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A COLLABORATIVE DESIGN METHOD FOR CIVIL AIRCRAFT BASED ON AN ENDURING AND EVOLUTIONARY AUTHORITATIVE SOURCE OF TRUTH

Xiaojian SUN [1], Mingqiang LUO [1], Zhiyang CUI [1], Zhenpeng JI [1] & Hu LIU [1]

[1] School of Aeronautic Science and Engineering, Beihang University, Beijing 100191, China

Abstract

Civil aircraft conceptual design is characterized by multiple iterations, multiple solution trade-offs, and multidisciplinary coupling. A human-software-hardware hybrid collaborative design method is proposed for civil aircraft based on an enduring authoritative source of truth and an aircraft conceptual schema. A future civil aircraft is designed conceptually in a collaborative environment based on the method. The results show that the collaborative design method can improve design efficiency and shorten the development cycle.

Keywords: collaborative design, authoritative source of truth, civil aircraft, conceptual design

1. Introduction

The conceptual design phase is in the initial stages of civil aircraft design and the early stages of the entire civil aircraft lifecycle. Its characteristics are more free design variables, less accurate analysis, and less costly consumption[1, 2]. The early design stage considerably impacts subsequent design and other lifecycle phases. The cost consumption determined by conceptual design is significant, and the design results are more decisive for preliminary design and detailed design results. The fidelity of the conceptual design results determines the civil aircraft design results. The conceptual design is characterized by multiple solution trade-offs, multiple iterations, and multidisciplinary coupling. Aircraft design is mainly based on system engineering[3, 4]. Model-based systems engineering (MBSE) and collaborative design can help solve a highly coupled design process, complex collaboration, and low design efficiency.

MBSE is the formalized application of modeling to support system requirements, design analysis, verification, and validation activities beginning in the conceptual design phase and continuing throughout development and later life cycle phases[5, 6]. First, MBSE can help solve model and interface inconsistency and clarify model management by formalized modeling. Second, the shift from document-centric to model-centric can help improve design efficiency and information transfer efficiency, increase the frequency of design iterations, and enhance the fidelity of design results. Finally, conceptual design is the beginning stage of civil aircraft design and covers most of the disciplines required in the design phase. After formalized modeling, it can be used as a pilot application and best practice as a basis for entire lifecycle MBSE implementation applications. NASA has successfully applied the MBSE method in several aircraft and satellite conceptual design projects, such as the Europa project and CubeSats[7–11]. The model-based collaborative hardware environment is the critical infrastructure setting for MBSE, where designers can design their aircraft.

In order to promote interdisciplinary cooperation between research institutes, the German Aerospace Center (DLR) has been building the Common Parametric Aircraft Configuration Schema (CPACS) since 2005[12]. CPACS is implemented as a Schema Definition (XSD) for the Extensible Markup Language (XML). CPACS defines the elements, attributes, and structure of all information that may be used in the conceptual design of an aircraft. It allows for the effective linking of any interdisciplinary analysis capabilities. It enables the simple processing of CPACS models and the implementation of discrete MDO architectures supported by a suite of software[13, 14]. DLR conducted an aircraft collaborative design environment based on CPACS to complete the preliminary aircraft design[15], a low-fidelity physics-based aerospace toolkit[16], and a collaborative conceptual design of a mid-range aircraft[17]. In recent years the DLR has used CPACS as the infrastructure for AGILE 4.0 and carried out next-generation aircraft MDO work, resulting in Collaborative MDO Systems[18–22].

Collaborative design refers to sharing timely information required to leverage the necessary tools, skills, and workforce and facilitate collaboration across disciplines[12]. Civil aircraft design involves multiple people, roles, and disciplines, requiring a collaborative design approach as a foundation. Collaborative design can help address collaboration among designers, switching design roles, and cooperation among design disciplines. The collaborative design provides a common platform for communication between different analysis capabilities and their individual variable spaces. A standardized schema and an authoritative source of truth (ASoT) [23]are the foundational platforms for collaborative design. Designers interact with data through the ASoT, and the standardized schema defines the interface standards of data and models between disciplines. We believe that a solution for collaborative design and MBSE in civil aircraft conceptual design is to build an enduring and evolutionary ASoT. The ASoT and standardized schema based on a collaborative design hardware environment allow for civil aircraft conceptual design that can improve the efficiency of collaborative design to increase the fidelity of conceptual design across a wide range of design spaces when needed.

In this paper, we have formed a collaborative design integration method with MBSE as the traction and mutual support of humans, software, and hardware through the enduring and evolutionary ASoT and aircraft conceptual design schema that has been constructed. Relying on the Aircraft Digital Collaborative Innovation Center of Beihang University, we build a collaborative design environment that can support the development of civil aircraft conceptual design. Finally, the future civil aircraft conceptual design and its solution demonstrate the feasibility of the collaborative integration method and the collaborative design environment.

2. Model-driven Hybrid Collaborative Method and Its Basis

2.1 An enduring and evolutionary authoritative source of truth

The ASoT is one of the five goals of the U.S Department of Defense Digital Engineering Strategy[24]. The ASoT captures the technical baseline's current state and history [25]. It is the central reference point for models and data across the lifecycle. It contains formalized models and standardized data that can support the extraction and deposit of data and models in the design process. The ASoT provides traceability as the system of interest evolves, capturing historical knowledge and connecting authoritative versions of the models and data. Changes made to the ASoT propagate throughout the digital design model to all affected systems and functions. With the ability to trace, track, verify, validate, and visual display, the ASoT can provide a comprehensive digital representation and entire lifecycle traceability of the system of interest. The ASoT can enhance the efficiency of collaborative work, shorten the development cycle, and improve the development cycle product quality. The goal of the ASoT is to record the right models and data and deliver the right models and data to the right stakeholders for the right Systems Engineering practice at the right time[25].

The primary role of the ASoT is to manage models and data. The ASoT enables the dynamic evolution of the aircraft design process from a document-centric to a model-centric digital engineering design system. The information of document-based collaborative design flows between designers through documents using instant messaging, internal e-mails, and web drives. There is a lack of a system that can record and manage information in a unified way. Designers should get information based on the same information source. Some companies adopt Product Data Management（PDM) system to manage documents to make a PDM system a unified data source. However, the PDM system can be used as a pool of documents, and even though it can manage versions of documents, document-based co-design is still inefficient in delivering information through reports. The ASoT deconstructs an entire report into a collection of models and data by breaking down the models and data in the design process into granularity, analyzing the types and characteristics of models and data included in the collaborative design process, sorting out the essential elements and relationships of models and data, and targeting the management, storage, and browsing methods appropriate for each element. We will establish the appropriate management, storage, and browsing methods for each element. The design efficiency can be improved by transferring models and data with granularity. Based on fine-granularity models and data, design aids can be custom-developed to help designers handle design information. The ASoT enables teams to collaboratively access the latest or validated models while seamlessly integrating their work.

Collaborative design is flexible in that different models are used within each discipline at different stages, and the interfaces between disciplines are not set in stone. In the design process, the number of participants and the design complexity is increasing, the granularity of the models and data is refining, the number and types of models and data are changing, the data completeness is increasing, and the collaborative design has an enduring and evolutionary character. However, even if the models and data keep changing and evolving, their essential elements and relationships are enumerable. The models and data can be composed of combinations of essential elements and relationships. The ASoT contains models and data for the whole lifecycle of aircraft collaborative design. Its essential function is to identify the essential elements and relationships of the models and data. The ASoT consists of aircraft instances for collaborative design through enumerable essential elements and relationships. To support the enduring of models and data, the ASoT needs to support changes in interfaces and smooth transitions in design transitions and gates (Figure 1). An aircraft design schema helps the ASoT define essential elements and relationships by defining a metamodel of models and data. This clarifies the interfaces between professions and supports smooth transitions of models and data.

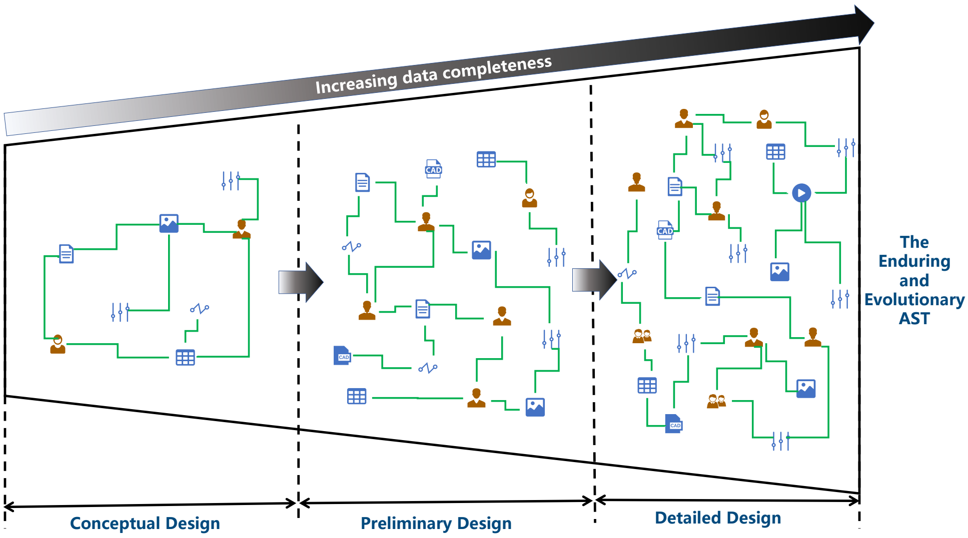

Figure 1 – An enduring and evolutionary authoritative source of truth.

2.2 An Aircraft Conceptual Design Schema

The **A**ircraft **C**onceptual **D**esign **S**chema (ACDS) is a standard specification of model and data in the ASoT and the basis for interoperability of collaborative work in conceptual design, which is a part of the civil aircraft design schema. The schema is an abstract collection of metamodels that identifies the types of information, the relationship of those elements, and the extensibility of including new and additional types of design information[26]. The schema defines the representation of all possible uses of models in aircraft design, including the definition of basic concepts, models, and design results in aircraft conceptual design. The schema helps designers express design documents as models and data with specific standards and create templates. The same templates (schema) can be used to represent different solutions for the same aircraft configuration in collaborative design, which helps designers manage models and data using the ASoT and facilitates the analysis of trade-offs among multiple solutions. The Schema establishes the interface between different disciplines to help designers reduce communication costs. By developing schema-document correspondence, models and data can be extracted from documents and automatically generated into standard formatted reports from the ASoT. By formalizing the design results within the concept design disciplines and standardizing the design interfaces, developing design tools with schema[13] can break through the information interaction between disciplines and improve the efficiency of collaborative operation.

There are three principles for building the ACDS: a) Following the existing design deliverables. Take each discipline's current deliverables and documents as the basis, sort out the deliverables in the document-centered design process, and digitize and model the results to realize the model-centered paradigm b) Emphasize data transferability. The goal of the schema is to transfer data between disciplines. Therefore, it is necessary to specify the current data transferred between disciplines as the basis for disciplinary interfaces. c) Supporting existing tools. Tools can help designers all the time and are both the model's exit and data's entrance. The schema should support the format of existing tools to help designers reduce workload and improve work efficiency.

Models and data are the objects managed by the ASoT, and the ACDS is the standard for models and data. By defining the ACDS, the ASoT can standardize the expression of aircraft design solutions. In other words, by defining granular models and data expressions, The ACDS becomes the basis for the ASoT to express models and data. The ACDS expresses models and data for requirements analysis and architecture design, initial sizing and conceptual sketch, overall layout, airframe arrangement, propulsion, aerodynamics, weights, performances, and cost analysis. Based on enumerable essential elements and relationships, the ACDS disassembles the model and data into a metamodel through a multi-layer definition of Metamodel-Conceptual Schema-Instance Schema. The metamodel means elements and relationships. The structure of ACDS is shown in figure 2. The conceptual schema can be instantiated into an instance schema by populating it with solution data, which can be used to represent an aircraft design solution instance. The conceptual schema is a collection of metamodel that expresses the deliverables of a particular working scenario in the aircraft conceptual design. The ASoT manages models and data by instance schema, enabling version management and data viewing.

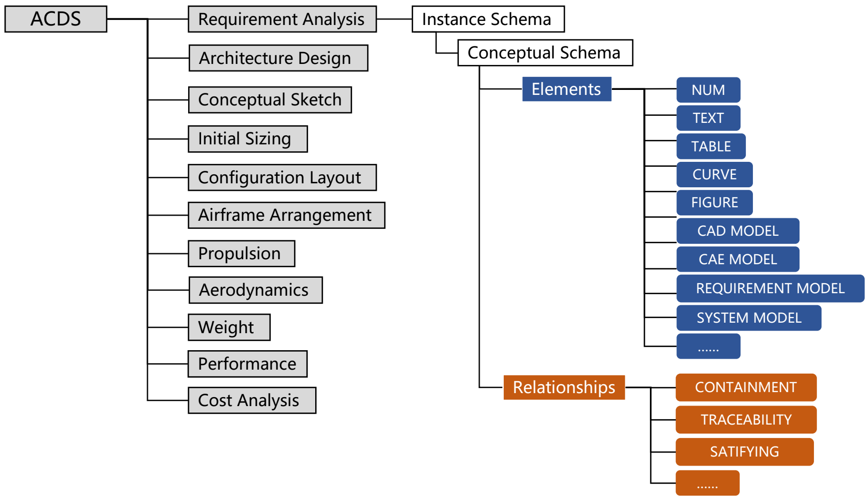

Figure 2 – The structure of ACDS.

The basis of all design data and models can be attributed to the combination of "elements" and "relationships." An "element" is the basic model that can exist on its own and can become a model on its own, or it can form a model together with other "elements" through a "relationship". A "relationship", which represents the connection between two "elements", is an abstract language that expresses the relationship between data and model. Due to the increasing data integrity at different stages of collaborative design, extensible types are designed to cope with essential elements and relationships.

The ACDS elements are numbers, curves, tables, text, figures, CAD model, CAE model, requirement model, and system model. Text is the information that can be expressed by only a short string, which is used to express the sketch description and other information; numbers are the model parameters that can be expressed by only floating or integers, which are used to express a large number of single design parameters; the table is a set of data and strings in the form of a table, which can reflect the emergence of these data and strings through the table, and is often used to express weight tables; curve is used to express multi-dimensional curves such as aerodynamic data, power data, performance data, etc.; the requirements model expresses the aircraft design requirements; the system model defines the aircraft functional architecture design model by SysML (Systems Modeling Language).

The relationships are containment, traceability, and satisfying relationships. A containment relationship defines one or more elements containing another element to construct a hierarchical relationship. A traceability relationship defines those or more arbitrary elements of a model that need to be traced back to a requirements model. A traceability relationship asserts that the arbitrary element will satisfy a requirement. A satisfying relationship defines those ones or more arbitrary elements that satisfy a requirement model, and a satisfying relationship requires a determination of whether the requirement is met.

We construct the ACDS containing "Name", "Parent", "Type", "Value", "Unit", and "Note". The "Name" indicates the name of the model, The "Parent" indicates the relationship to which the design model belongs, The "Type" indicates the element type, and The "Value" indicates the design model or the data itself, which can be a number, text, model path, table path, etc., The "Unit" is the unit of data, and The Note is the note of the model. The "Unit" uses the International System of Units. It can support the expression and delivery of the conceptual design from requirement analysis and architecture design, system conceptual design, digital integration, and testing. Table 1 shows the part of the Configuration Layout conceptual schema in the ACDS. The configuration layout has the role of the top and bottom of the aircraft conceptual design. It is based on general parameters and conceptual sketches, and there are many data types. It involves the parameters and models of the aircraft design, such as three-view drawing, wing, tail, fuselage, landing system, and nacelle.

Table 1 – Part of Configuration Layout Conceptual Schema of the ACDS.

Name	Parent	Type	Value	Unit	Note
Layout Description		TEXT	**TBD**		**TBD**
Three-view Drawing		FIG	**TBD**		**TBD**
Wetted Area		NUM	**TBD**	m^2	**TBD**
Wing		CLASS			**TBD**
Span Length	Wing	NUM	**TBD**	m	**TBD**
Root Chord	Wing	NUM	**TBD**	m	**TBD**
……	……	……	……	……	……
V-Tail		CLASS			**TBD**
Span Length	V-Tail	NUM	**TBD**	m	**TBD**
Root Chord	V-Tail	NUM	**TBD**	m	**TBD**
……	……	……	……	……	……
Wing Type		CLASS			**TBD**
Parameters	Wing Type	TABLE	**TBD**	-	**TBD**
……	……	……	……	……	……
3D Model		CAD	**TBD**		**TBD**

***TBD** means To be defined. In order to transform the conceptual schema into an instance schema, designers need to fill in the design result or file path at **TBD**

The schema serves as a bridge between the ASoT and collaborative design, supporting collaborative design to interact with the ASoT for data and models quickly. The compatibility between design software and schema can be extended through software interface development to facilitate designers to operate different hardware and software environments to form automated calculations. Based on schema and the ASoT, there are two design modes for collaborative design, as shown in figure 3. Mode 1 is when the designer populates the design data with a conceptual schema and submits it to the ASoT through a parsing tool. Once the model and data are submitted to ASoT, other designers can view and download the model and data. Mode 2 is when the design tool generates a schema-compliant file and automatically submits it to ASoT. The model and data in ASoT can be generated/downloaded as a schema-compliant file to other design tools. These two design modes are the basis for a model-driven collaborative design.

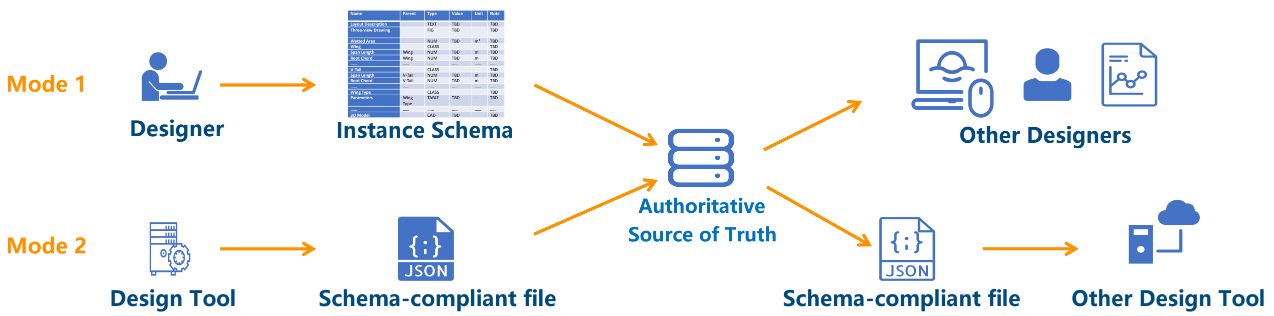

Figure 3 – Two Design Modes Based on the ASoT and Schema.

ACDS is similar to CPACS. However, The essential requirement of CPACS is that tools can automatically read and process an incoming CPACS file. The essential requirement of ACDS is that users can interpret the data set. Due to the nature of XML files, CPACS has the advantage of expressing numerical, textual, tabular, and curvilinear data, which are represented by arrays and vectors compared to ACDS, and are very convenient for ex-pressing multi-dimensional tables such as aerodynamics and performance. ACDS is flexible and extensible and can express arbitrary types of data and models. The open schema supports the completion of elements and relationships as they are added during the design process.

2.3 Model-driven Hybrid Collaborative Method

In the beginning, civil aircraft conceptual design was realized by MDO (multidisciplinary design optimization) technology with a single person and machine, which can be referred to as the first generation of collaborative design. MDO can quickly obtain the optimal solution for an aircraft design solution under the influence of a range of parameters in a short period. However, MDO is generally done by a single person using a single computer, which requires the designer to have profound skills in multiple disciplines and cannot maximize the wisdom of other designers. The fidelity of disciplinary models is generally low to achieve fast iteration and optimization. The high-fidelity design results cannot be achieved. Meaningfully, MDO defines a fixed interface between disciplines, which is the basis for collaborative design.

Gradually collaborative design is developed into a distributed conceptual design for multiple people and machines, which can be referred to as the second generation of collaborative design. The 2nd generation collaboration design assigns work to multiple people, allowing each person's expertise to be fully utilized and the accuracy of the solution to be achieved through high-fidelity modeling. After multiple iterations of design, the aircraft solution can be optimized. However, multiple iterations are less efficient and more stressful for engineers. On the other hand, the lack of testing means makes it impossible to simulate and verify the design results.

Now we propose a model-driven human-software-hardware hybrid collaborative design (Figure 4). Hybrid collaborative design requires clear input and output interfaces, and the model-based approach can help build the underlying technical support. Third-generation collaborative design automates design tools (software) in some disciplines, reduces designer involvement, and can shorten the design cycle. At the same time, the third generation of collaborative design can incorporate hardware such as flight simulators to enable flight-after design. The hybrid collaborative design not only supports system-level verification, such as flight simulators but also supports system validation, such as the system of system simulation.

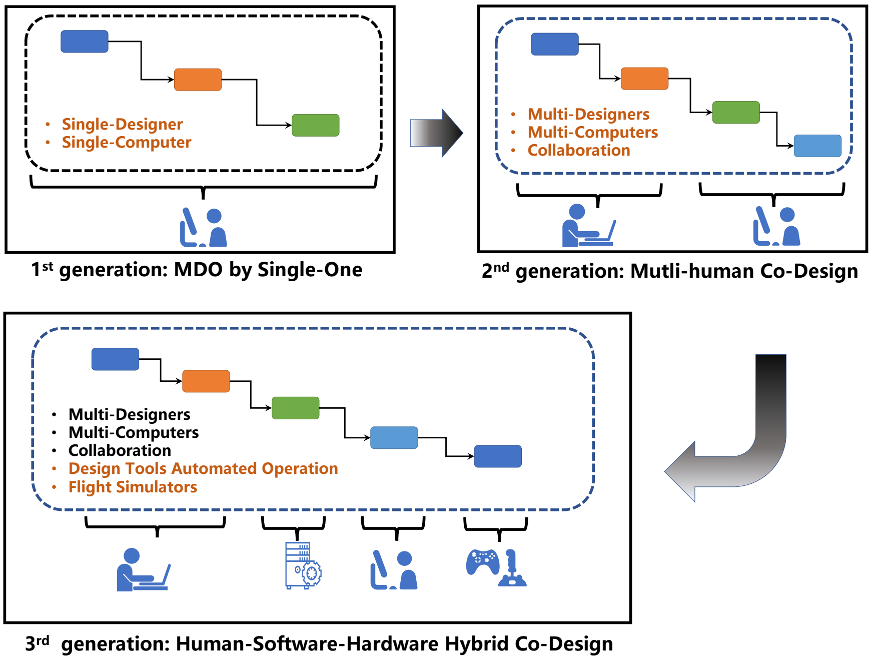

Figure 4 – Evolution of generations of Conceptual Design.

The third generation of collaborative design is based on the schema of data standards within disciplines and interface standards between disciplines to achieve collaborative access to ASoT by designers, software, and hardware. The ASoT is the model and data exchange center. The data of people, software, and hardware of each discipline in collaborative design are submitted to the ASoT, and the ASoT records the version information and manages the models and data. ACDS provides machine-readable JSON versions to facilitate the writing and reading of models and data by design tools and hardware. ACDS provides a human-readable version of Excel/Files, which can be parsed into JSON files using parsing tools for easy identification by ASoT uniformly. Humans, software, and hardware in the design ecosystem can access the interface of the ASoT, generate data according to schema within the discipline design, and exchange data between disciplines according to the schema, forming a model-driven hybrid collaborative method. Figure 5 shows this method, including Human-in-loop, Software-in-loop, and Hardware-in-loop.

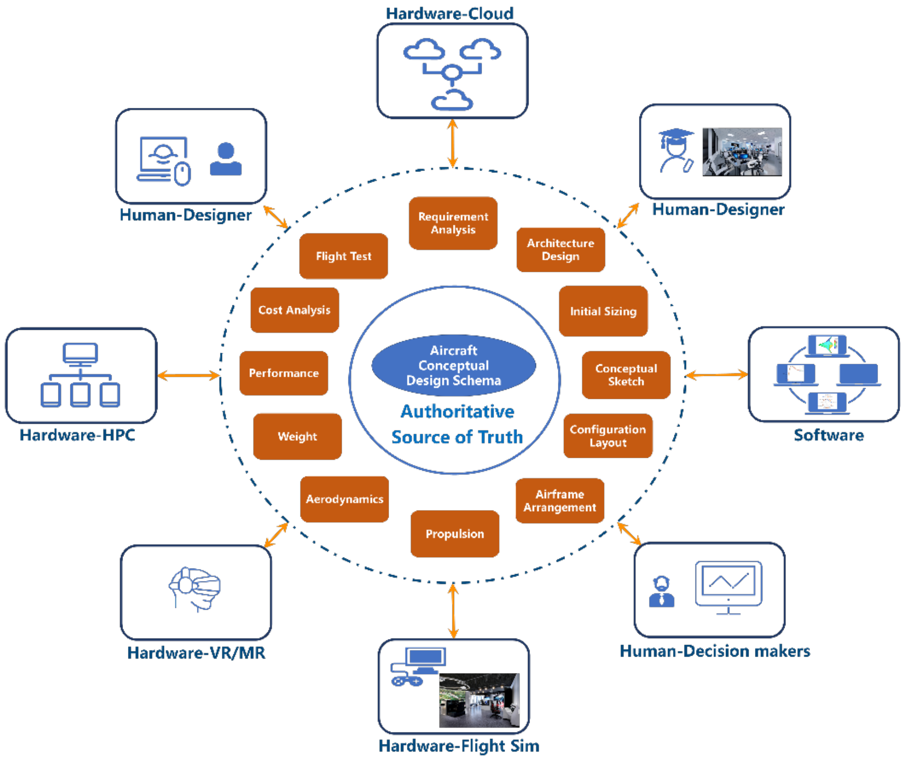

Figure 5 – Model-driven Hybrid Collaborative Method.

Human-in-loop means that designers work collaboratively with the ASoT. Humans play a decisive factor in collaborative design. In general, humans are involved in the whole process of collaborative design, performing functions such as building design solutions, operating design tools such as software and hardware to form design models and data, viewing design models and data, generating and archiving reports, and using experimental tools to evaluate the performance of solutions. Humans in collaborative design include designers, decision makers, and other stakeholders. Designers form formal models and data to submit to the ASoT, and other designers can access the correct models and data from the ASoT. Decision-makers can view the design progress and baseline through the ASoT, and other stakeholders can access the ASoT by specific views.

Software-in-loop means that the design tool can generate schema-based models and data after secondary development. There is a wide range of software in collaborative design. To achieve various design objectives, design tools in every discipline are different from other disciplines and can generate different types of metamodels. ACDS helps designers to normalize the models and data generated by these tools. These tools are secondarily developed when necessary to form schema-compliant models and data. Likewise, the software can be adapted to upload models and data to the ASoT automatically. Of course, the software needs to be able to log into ASoT through a Web port and gain access to the appropriate projects and humans. Like humans, the software is used throughout the collaborative design process. Since ACDS has defined the interface standards for upstream and downstream disciplines, some software in collaborative design can even have unattended computing capabilities. Once the upstream design results are entered into the ASoT, the downstream can access the input data and perform automatic calculations, and the results of the completed calculations can also be entered into the ASoT.

Hardware-in-loop means that some hardware, such as flight simulators, have been developed and can access the ASoT and directly use the models and data in the ASoT for operation. Hardware refers not only to the high-performance computers running the design tools but also includes test and verification equipment such as flight simulators, VR/MR (Virtual Reality/Mixed Reality) equipment, and small test stations. The purpose of the hardware is to verify the feasibility of the design solution and validate that the design solution meets the design requirements and stakeholder needs. These test hardware needs to be used by humans, who evaluate the design solution through real-world experience. After the design is formed, the flight simulator can be used for "fly before built." to shorten the development cycle and improve the efficiency of collaborative design. For example, the designer can feel the effect of the change in center of gravity position on the maneuvering efficiency by flying in a flight simulator.

3. A Model-based Collaborative Design Environment

The Aircraft Digital Collaborative Innovation Center (ACIC) is a new generation digital engineering laboratory established by Beihang University based on co-build, co-win, and co-sharing principles. Its purpose is to build a systematic and digital collaborative design environment for future aircraft design and support the experimental and practical teaching of aircraft design-related courses. The ACIC has a distributed cross-campus hardware and software environment that covers an area of 700 square meters, including MBCoDE (Model-Based Collaborative Design Environment), MBCoVE (Model-Based Collaborative Visualization Environment), and MBCoTE (Model-Based Collaborative Test Environment). Figure 6 shows the layout diagram of the ACIC. ACIC's hardware operations are driven by models and data in the ASoT, aiming to create a model-based collaborative design environment.

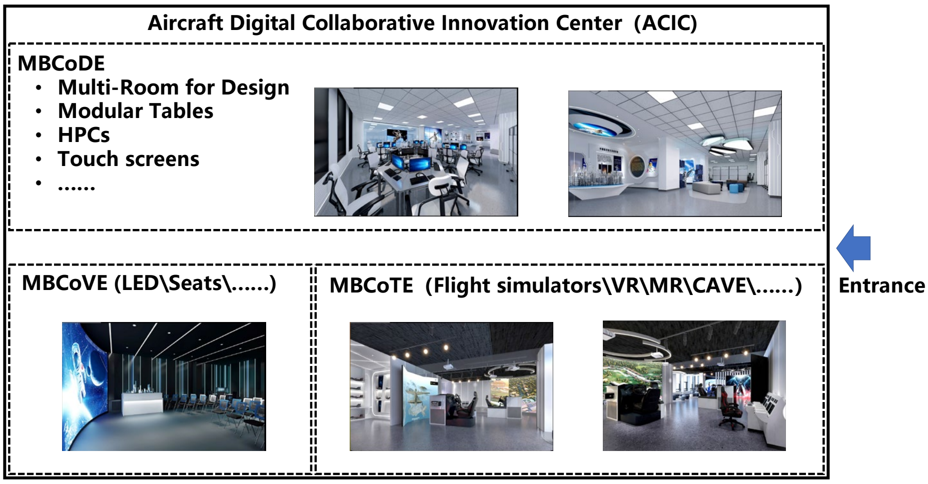

Figure 6 – Layout diagram of the ACIC in Beihang University.

3.1 MBCoDE

MBCoDE is the main working scenario for collaborative design. The hardware includes multiple HPCs (high-performance computers), touch screens, and multiple dividable rooms. These rooms are separated by removable panels, each with a touch screen and some modular conference tables. Several small meeting rooms can be combined into one large meeting room. MBCoDE can meet various scenarios of collaborative design, including individual work, IPT (Integrated Product Team) teamwork, small team brainstorming, and medium-sized meeting. The software includes the ASoT and design tools. The ASoT is deployed on a Linux server, and data is stored by NAS (Network Attached Storage). At the same time, the design tools are configured in HPCs and supercomputers, which are deployed in centralized server rooms and can be connected to MBCoDE via the Intranet. The hardware and software environments are connected to the ASoT through Intranet. The designer can do most of the work on the design solution in MBCoDE, accessing the ASoT through the high-performance computer and performing model-based design and simulation calculations. Designers can also take advantage of the touch screen and seminar anytime. Face-to-face communication facilitates the implementation and advancement of the project. Considering the impact caused by COVID-19, MBCoDE deployed a 1000Mbps network and teleconferencing equipment. Designers can work simultaneously over the Internet and access the ASoT and design tools. The work carried out by the designers in the MBCoDE includes requirements analysis, architecture design, conceptual sketches, initial sizing, configuration layout, airframe arrangement, propulsion, aerodynamics, weight, performance, and cost analysis.

3.2 MBCoTE

MBCoTE is equipped with three flight simulators, two CAVE (Cave Automatic Virtual Environment), and VR/MR equipment for virtual test flights and verification of design solutions.

Flight simulators help designers learn how to fly the aircraft; They can help designers experience the overall impact of changes in the center of gravity position and changes in aerodynamic coefficients on aircraft operations; They can be used for program improvement and adjusting design parameters to achieve better flight quality. CAVE and VR/MR equipment can be used for virtual assembly, for virtual verification of human-machine interaction such as virtual tests of maintainability and accessibility; they can perform virtual walkthroughs to enable designers to experience virtual scenarios of passenger cabins, cargo holds, escape facilities, ground services, etc.; they can be used for virtual training to help designers experience aircraft operations and maintenance.

Like MBCoDE and MBCoVE, MBCoTE's hardware is integrated with the ASoT, where models and data from the ASoT drive the flight simulator operation, providing 3-D models and scenarios to the CAVE and VR/MR equipment. The model-driven test environment helps designers get quick feedback on design results, reducing design costs and cycles. The impact of any small design parameter changes on the final design quality can be realized by combining MBCoDE and MBCoTE, which the ASoT and hybrid collaborative method support. The work carried out by the designers in the MBCoTE includes systems definition such as requirements analysis and architecture design, systems test and verification such as flight simulation and virtual training. The work carried out by the decision makers in the MBCoTE is a variety of virtual experiences.

3.3 MBCoVE

MBCoVE contains an 8K curved LED (light-emitting diode) screen of about 30 square meters, dozens of seats, and professional sound equipment, forming a meeting space. The LED screen has a basis for upgrading to a 3D screen. The main functions of MBCoVE are proposal presentations, large-scale seminars, and reviews. The LED screen can be connected to 4 computers simultaneously via network or HDMI. The LED screen can be connected to MBCoDE's HPCs or laptops for the whole design team to connect and discuss simultaneously. It can also be connected to other distributed environments through the Internet for online discussion. MBCoVE can be used as a seminar room for designers to communicate their plans. It can also be used as a design decision room to view the status of collaborative work, design parameter changes, labor division, and plan advancement in real-time through the monitoring panel function provided by ASoT. Alternatively, it can be used as a presentation and debriefing room for stakeholders to visit and take lessons.

In summary, ASoT and ACDS are the data bus between the collaborative design environment (MBCoDE, MBCoTE, and MBCoVE) and the design process(Figure 7). During the aircraft collaborative design process, models and data are delivered in ACDS-compliant files and managed by the ASoT. The combination of The Aircraft Digital Collaborative Innovation Center, the ASoT, and people forms a novel approach to collaborative design.

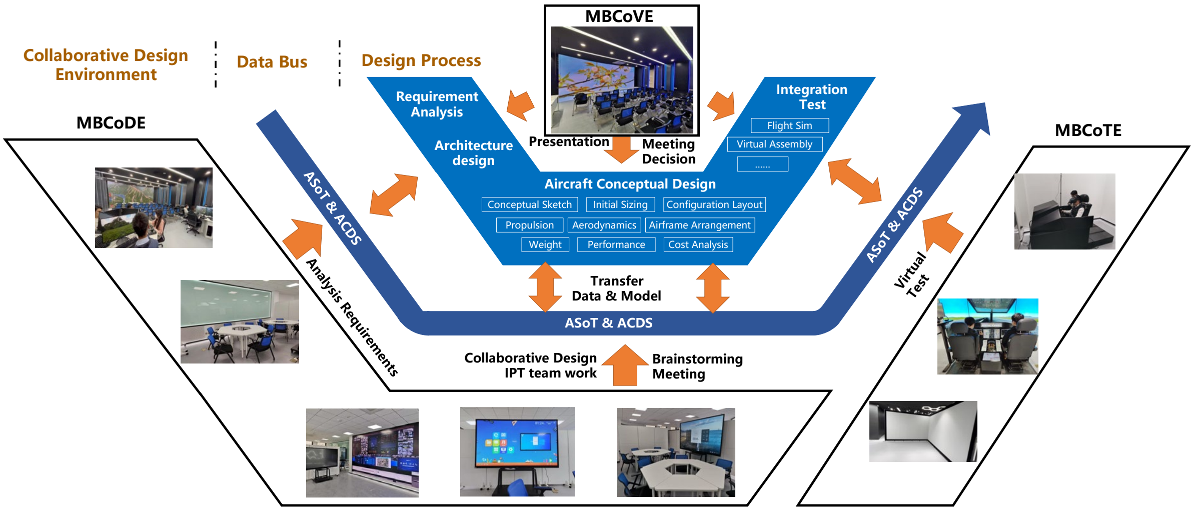

Figure 7 –Aircraft design with the ASoT, ACDS, and a collaborative design environment.

4. Experiences

We have relied on the enduring and evolutionary ASoT and the Aircraft Digital Collaborative Innovation Center to design and validate a future civil aircraft. The future civil aircraft is a long-range, twin/multi-engine, twin/multi-aisle 350-seat class advanced wide-body passenger aircraft scheduled to enter the market in 2035. We started with requirements analysis and architecture design, performed aircraft conceptual design and verification, and finally, digital integration and testing. Specifically, we include requirements analysis, architecture design, initial sizing, conceptual sketch, configuration layout, airframe arrangement, propulsion, aerodynamics, weight, performance, cost analysis, and flight simulation. Figure 5 shows design results for this future civil aircraft.

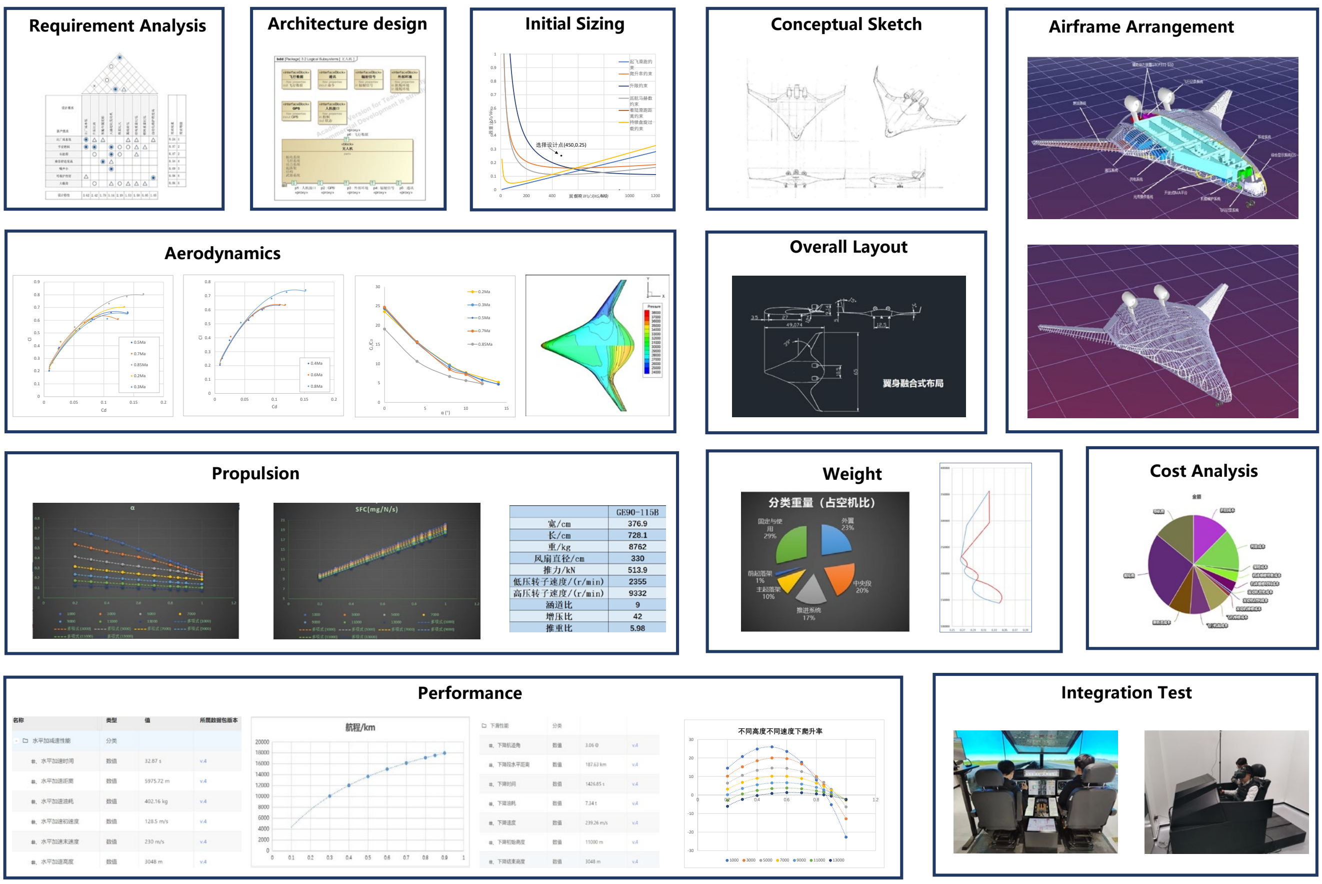

Figure 5 – Future Civil Aircraft Design.

All models and data from requirements analysis to flight simulation are presented in the schema.

The design process data and baseline data are stored in the ASoT. We use the ASoT as the center of collaborative design work, and the entire design process is carried out in the Aircraft Digital Collaborative Innovation Center. We carry out collaborative work through a model-based approach without needing reports, presentation documents, and design in the MBCoDE environment. Nodes such as Weight rely on the Software-in-Loop method, enabling unattended computation and automatic weight analysis and computation after its upstream nodes have completed their computation. Small-scale seminars are conducted through MBCoDE's touch seminar screen, while large-scale seminars are conducted through MBCoVE. After the design is formed, the model and data are submitted to the ASoT in the format specified by the schema. The model and data can be loaded directly into the flight simulator of MBCoTE, realizing "fly before built."

We conducted a complete conceptual design of the future civil aircraft, and the design results showed that the design solution could better validate the design requirements. The design cycle was shortened by several weeks compared to the same period in the previous one, and the design efficiency was improved.

The following lessons have been learned from using the model-driven hybrid collaboration method for the aircraft design process.

a. ACDS should start small. Some of the requirements of ACDS are different from traditional design process deliverables and need to be continually honed with the designer. It is possible to start with a particular discipline to try out and modify and keep expanding the use and acceptance of ACDS.

b. Patience is needed to promote the use of the ASoT. The ASoT is a new software system, and its design and operation must continuously improve. When designers make suggestions, the software developers of the ASoT should listen to the suggestions with an open mind, analyze the problems, give feedback about solutions, and make changes to the software system after receiving positive answers. There will be very many issues to be modified before the official launch.

c. Personnel coordination. The persons involved in collaborative design are all undergraduate students conducting design for the first time. They need to be motivated by specific methods to help them establish the habit of communication.

d. Helping designers reduce their workload. We have developed several design aids for the ASoT to help designers generate, submit, and download models and data for the ASoT. These tools include four types: a) plug-ins embedded in the design tool to generate ACDS-compliant models and data directly from the design tool, to submit the models and data to the ASoT, and to download the required data from the ASoT to the design tool to carry out the design directly. This tool helps designers to reduce the process of data request and extraction. b) Generic parsing tool. This tool can be used in Windows Explorer to help designers parse files in ACDS-supported formats and submit them to the ASoT, with a preview function during submission. c) Browser-based webpages. Helps designers, decision makers, and other stakeholders to view models and data of current design status, collaborative design progress and staff division, design parameter sets, and historical project data. d) Message tool. This tool can help stakeholders such as designers, decision makers, or the ASoT push messages. The message push includes upstream model and data update reminders, requirement verification and traceability reminder, and approval reminder.

5. Conclusion

Based on the enduring and evolutionary authoritative source of truth and the civil aircraft conceptual schema, a human-software-hardware hybrid collaborative method is formed, which helps to improve the efficiency of collaborative design. The hybrid collaborative method is designed in three sections: human-in-loop, software-in-loop, and hardware-in-loop. Relying on the Aircraft Digital Collaborative Innovation Center of Beihang University, a future civil aircraft conceptual design was carried out. The design results verified the design requirements, shortened the design cycle, and improved the design efficiency.

The design case proves that the hybrid collaborative design method, which is based on the ASoT and relies on the Aircraft Digital Collaborative Innovation Center constructed in this paper, can reduce the problems of inconsistent models and confusing interfaces in civil aircraft conceptual design, improve the design efficiency and information transfer efficiency, increase the credibility of design results, and help realize the transfer from document-centered traditional design to model-centered digital design.

6. Contact Author E-mail Address

Corresponding author: Mingqiang Luo: e-mail: luomingqiang_buaa@163.com

Submission author: Xiaojian Sun: e-mail: sunxiaojian0202@163.com

7. Copyright Statement

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