Research on Aircraft/Engine Integrated Method of Civil Aircraft Products Development Oriented to System Engineering

Yu Jinhai¹,a, Fu Jilei²,b*, Lu Yi¹,c, Fu Shan³,d, Huang Dan⁴,e, Zhang Xin-Ai⁵,f

¹,²School of Aeronautics and Astronautics SJTU Shanghai, China
²,³,⁴School of Electronic Information and Electrical Engineering SJTU Shanghai, China
⁵Shanghai Aircraft Design and Research Institute COMAC Shanghai, China
⁶yujinhai@comac.cc, b* Corresponding author: leopoldwalden@gmail.com,
luyi1@sjtu.edu.cn, sfu@sjtu.edu.cn, huangdan@sjtu.edu.cn, zhangxinai@comac.cc

Abstract—This research proposes an aircraft/engine integrated design system construction method for civil aircraft based on system engineering oriented to large civil aircraft airworthiness certification. The aircraft/engine integrated design system of civil aircraft based on the “mapping model” highlights the logical completeness of the development evidence. This research contains two types of core design evidence: 1) design data of aircraft/engine integrated system; 2) aircraft/engine integrated system confirming and verifying data. The mapping model corresponds to the constraints of airworthiness regulations on the aircraft/engine integrated system design in three aspects: requirements analysis and confirmation, functional design, and design execution and verification, which promotes design data and airworthiness compliance evidence build in parallel.

1. INTRODUCTION

In the traditional aircraft design process, due to the failure to fully capture the requirements of stakeholders, lack of design experience, and other reasons, the requirements capture is incomplete. All the above reasons result in frequent design changes, extended development cycles, and a rapid increase in development funds. When the R&D personnel put forward the design, even they draw on the opinions of relevant experts and consider them as comprehensively as possible, they will still encounter some new problems after putting them into production. Especially after the actual operation of those developed aircraft independently, the insufficient design of some details will cause many inconveniences to the relevant operators. Therefore, system engineering methodology should be particularly emphasized when doing forward design in the civil aircraft design process.

The development of civil aircraft is an extremely complex system engineering. As a complex product, civil aircraft has the characteristics of complex product composition, complex customer requirements, complex product technology, complex project management, and complex manufacturing process. The management and implementation of the complex product development of civil aircraft is a process that requires long-term practice and continuous improvement. It requires a comprehensive solution to technical, software, and management issues related to product development. Complex products are typical hierarchical structures. Each layer contains many subsystems and functional components.
addition, the application software inside the product also increases the complexity of its development. From the perspective of collaboration in development, companies need to establish a complete and reliable information exchange mechanism among suppliers, integrators, R&D institutions, and users to coordinate complex product development[2].

Carrying out the forward design based on requirements can significantly reduce the later development costs, speed up the development progress, and ensure that the designed products meet the requirements and expectations of stakeholders such as airlines and certification authorities. Therefore, this paper proposes an aircraft/engine integrated design method based on system engineering. By implementing this design method, we expect to minimize the repetition in the aircraft integrated design process, improve design efficiency, and reduce unnecessary design costs.

2. SYSTEM ENGINEERING IN THE OVERALL DESIGN OF CIVIL AIRCRAFT

2.1. Definition and Characteristics of System Engineering

Modern system engineering originated in the 1930s. After experiencing different stages as the system analysis method invented by RAND Corporation, the publication of “System Engineering Methodology”[3], the establishment of NCOSE, and the name change of NCOSE For INCOSE, the theoretical system of modern system engineering has tended to perfect. It has been successfully applied in the construction of large complex systems such as aerospace engineering, marine engineering, and rail engineering. The implementation of modern system engineering makes the entire complex project development risk-controllable, cost-affordable, stable, and orderly.

According to the literature[3], there are three representative definitions of system engineering:

- System engineering is a discipline that focuses on the whole (system) rather than the design and application of various parts. That means looking at the entirety of the problem, taking into account all aspects and all variables of the problem, and linking social and technical aspects.
- System engineering is a top-down iterative process of synthesizing, developing, and running real systems, meeting all system requirements in a near-optimal manner.
- System engineering is an interdisciplinary method that enables the system to implement successfully.

System engineering focuses on defining customer requirements and related functions in the early stages of the development cycle and documenting them; then carry out design synthesis and system confirmation when considering the complete issues such as operation, cost, schedule, performance, training, assurance, testing, manufacturing and exiting problem. The purpose of system engineering is to provide high-quality products that meet users' requirements while considering the business and technical requirements of all users.

System thinking and global perspectives in system engineering enable system designers to understand how the system operates in the background environment, how the system itself operates, and how to manage the system. The three-dimensional structure of system engineering proposed by Hall in 1969, which is specified to the logical dimension, working dimension, knowledge dimension, further deepened the multi-angle and global concept of system engineering. Among them, the logic dimension deepens the application of operations research; the work dimension regulates the design, manufacture, and operation of engineering projects; the knowledge dimension emphasizes the application of various technologies and knowledge in product development. System engineering will organize and standardize the realization, operation, and maintenance of hundreds of large-scale complex systems in the interdisciplinary field in terms of space and time so that the system can be developed in an orderly manner following the definition of the life cycle framework in various constraints.

Ellipse model was proposed in the MIL-STD-499A standard issued by the US military in 1974. The ellipse model has three steps: requirements analysis, function analysis & allocation, and synthesis. Through these three steps, the technical process and technical management process are connected in series. In this model, engineers need to perform multiple, two-way iterations between the functional architecture and the physical architecture until all functions and architectures are verified. The advantage
of the ellipse model is to give the essential elements of classic system engineering concisely. The disadvantage is that the system analysis and control in technical management activities are not described in detail.

Kevin Forsberg and Harold Mooz established the V model proposed in 1978. The V model emphasizes the role of verification and testing at various stages. The V model relates to the process of system decomposition and system integration through testing. In the V model, from the component level to the system confirmation, each level of testing must refer to the original specification document to ensure that the designed components, subsystems, and systems always meet the system requirements. The V model is used to visualize system engineering, especially in the demonstration and design stages. The V model emphasizes the necessity of confirming and verifying requirements with users in requirements analysis. It also emphasizes defining the verification plan in the early stages and continuous risk assessment throughout the whole development process. The core of the V model describes the baseline evolution process from user requirements identification to system architecture design. The V model very accurately expresses the system evolution process from requirements analysis to system decomposition to system integration, making system engineering visible and easy to manage. Domestic and foreign aviation products, especially avionics systems, mostly adopt V Model development based on the above advantages. After the V model was proposed, it was still continuously improved and perfected. In 1991, Kevin Forsberg and Harold Mooz proposed a double V model[4,5]. The double V model adds a dimension, emphasizing concurrency opportunities and risk management, emphasizing integration, verification and confirmation planning, and solving problems through verification. After the double V model is proposed, the visualization model of system engineering has been quite mature and perfect.

2.2. Civil Aircraft Products and System Engineering

Commercial aircraft development is a complex system engineering. The system engineering method is an engineering management technology produced for the development and integration of complex systems, which can achieve the overall optimal project. The application of the system engineering method is an inherent need for commercial aircraft development. At present, system engineering has become a general method for guiding the development of commercial aircraft in the industry. Major civil aircraft manufacturers, industry associations, and related agencies have compiled a large number of guidance methods and standards around system engineering applications. For example, SAE ARP4754A “Guidelines for the Development of Civil Aircraft and Its Systems” is an important practical guide in the field of aviation. It integrates system engineering and safety design into the process of civil aircraft development and airworthiness certification. System engineering has been widely used in the development of international aircraft and has achieved remarkable results. It has been summarized and improved in the best practice experience of giant companies such as Boeing, Airbus, and MiG. As mentioned earlier, system engineering, as an effective method, has fundamental guiding significance for civil aircraft system formation.

At present, there is no systematic identification method for the identification of civil aircraft stakeholders. Most of them use non-quantitative brainstorming methods and Delphi methods. This is not conducive to the accurate operation of civil aircraft. Stakeholders. Therefore, in recent years, relevant domestic researchers have gradually applied the US Defense Architecture (DoDAF) method in system engineering to the construction of various civil aircraft scene models. On this basis, the identification of stakeholders in the operation phase of civil aircraft. DoD Architecture Framework Working Group pointed out that the DoDAF technical framework in the US Department of Defense is currently an effective means of constructing aircraft scene models. DoDAF uses the form of views to apply to top-level operational requirements, equipment functional requirements, and functional decomposition of aviation equipment. In the field of civil aviation, FAA also draws on DoDAF multi-view analysis technology, and also uses DoDAF’s OV, SV, TV view and other architectural tools in the planning and design of the US National Airspace System NAS to describe national aviation Operating scenarios between various systems in the airspace.
More and more attention has been paid to the application of system engineering in the field of civil aircraft development in recent years\cite{6}. The application of system engineering in overall design can provide theories and methods for the integrated design of this project, and can fully capture the various interests at the beginning of the design. Through the system engineering method, the aircraft/engine integrated design requirements can be fully converted into the top-level design requirements. The requirements can then be converted into top-level design constraints of aircraft/engine integrated design, including safety, comfort, economy, environmental protection, and other constraints. And all these constraints can be further transferred to general constraints, aerodynamic constraints, maintenance constraints, structural constraints, reverse constraints, etc.

3. The Mapping Model of Aircraft/Engine Integrated Design and System Engineering System.

3.1. Stakeholder Requirements Capture

The characteristics of integrating large bypass ratio engine and aircraft are reflected in the relatively small variable range (parameter design space), the constraint space subjected to various engineering constraints, and the influence of both design optimization based on typical mission voyages and the aerodynamic efficiency under non-design condition. Early design methods and design processes relied heavily on wind tunnel tests. The design specifications were summarized based on test data and flight data. But due to the influence of Reynolds number on interference effects, wall effects, temperature, and flow field quality, the design boundaries given in existing design manuals are usually more conservative and are more suitable for the installation of small and medium bypass engines. However, the valid part of the design guidelines summarized in the early design manuals makes it possible to establish a comprehensive parameterized model based on CATIA that contains design constraints. They can play the role of constraint checking during the design iteration process and become a design optimization.

The establishment of a comprehensive parameterized model is a technical route with good application prospects proposed in this study. Relying on the existing CATIA model and integrating design information in addition to geometric information, including airworthiness constraints and historical experience, it can reduce numerical simulation on invalid design, improving design efficiency, and design quality.

The overall aircraft/engine integrated design is based on user requirements and fully captures stakeholders’ requirements. The main stakeholders of this project are shown in Figure 1.
Based on the identification as mentioned above of stakeholders, combined with the characteristics of this project, relevant scene analysis was carried out to identify the design requirements of various stakeholders in the corresponding scene. The main scenarios for identifying specific stakeholders are shown in Figure 2.

![Figure 2. Aircraft/engine integrated design scenario.](image)

3.2. System Engineering Mapping Model

This research proposes an aircraft/engine integrated design of civil aircraft based on system engineering\(^7\), aiming to anticipate that the initial design of aircraft based on forward design can fully capture the requirements of various stakeholders and convert the requirements of stakeholders into top-level design requirements. These top-level design requirements need to be confirmed and allocated during the design process\(^8,9\). In the end, the requirements are mapped to the physical domain in the aircraft/engine integrated design plan, and the requirements of stakeholders are confirmed in the plan. The captured aircraft/engine integrated design requirements can be verified by numerical simulation, wind tunnel tests, and other means. The idea of aircraft/engine integration design based on system engineering is shown in Figure 3.

Finally, the specific constraints will be from general constraints, aerodynamic constraints, maintenance constraints, structural constraints, system constraints, and backstepping constraints. The requirements obtained from other aspects are allocated to the wing, suspension, engine, and other physical domains to be realized, and finally, the requirements are verified in the design synthesis.
4. AIRCRAFT/ENGINE INTEGRATED DESIGN PROCESS

As mentioned in the previous chapter, aircraft/engine integrated overall design starts from user requirements, experience comprehensively analyzing of stakeholders’ requirements, and top-level design requirements. And finally, these top-level design requirements need to be confirmed and allocated during the design process. Figure 4 shows the overall design process of the model-based Aircraft/engine integrated design.

The overall design process of Aircraft/engine integration is mainly divided into three stages: requirements analysis, design synthesis, confirmation, and verification. In the early stage of the overall design process, the designers mainly based on the capture of the requirements of various stakeholders to extract the requirements for the aircraft/engine integrated design. Then, designers analyze and translate these requirements into design plans and tasks. Through the requirements analysis, the top-level requirements of the design are captured. Top-level requirements contain for example the engine
installation airworthiness requirements according to CCAR25-R4, FAR25, and CS25; the resistance reduction requirements considering the dynamic influence of the integrated design based on the difference between the resistance coefficient of the wing-body/hanger/nacelle which is designed individually and the resistance coefficient of the ventilated nacelle optimized by integrated aerodynamic design; laminar nacelle design requirements for reducing resistance; requirements for numerical simulation procedures; requirements for numerical simulation capabilities and push-resistance decomposition capabilities; requirements for calculation accuracy.

Tailoring the system engineering process based on the overall aircraft/engine integrated design, mainly includes the following aspects:

1) Requirements management
   It is actually an activity of systems engineering, which exists throughout the life cycle of the project. Requirements management (RM) is iteratively identified and refined from the top-level requirements to the low-level requirements associated with it and is consistent with the functional baseline and architecture while synthesizing all the system solutions of concern. The tools used by RM are:
   - Requirements tool architecture, including requirements documents, traceability mechanism, allocation mechanism, verification, traceability evaluation, compatibility.
   - Requirements management software.
   - Requirements database.

2) Functional analysis
   In FAA system engineering, functional analysis is a process of system engineering. Through functional analysis, the requirements of stakeholders are transformed into an orderly and traceable functional architecture. This process generates a framework of requirements and physical architecture. Typical files for this process are the interface control file ICD. The FA process mainly has the following five items:
   - Define top-level functions
   - Logical relationship of collating function
   - Top-down decomposition function
   - Functional decomposition evaluation
   - Functional analysis baseline file

3) Design synthesis
   Design synthesis is the process of implementing the logically and functionally organized requirements into the physical architecture in the form of optimal design schemes, including people, products, and processes. Typical files of this process are work breakdown structure WBS, architecture module diagram ABD, and schematic diagram SBD. The tools include SBD and computer-aided design software and hardware.

4) Trade-off analysis
   The system engineering elements used to balance among many technical solutions are key tools for designing work to meet stakeholders' requirements with the highest cost performance. The tasks include:
   - Determine the scope and principles
   - Define evaluation criteria and additional factors
   - Choose an alternative
   - Elimination of alternatives
   - Evaluation options
   - Sensitivity analysis
   - Results review and conclusion

5) Analysis and integration
   The integrated process ensures that the results provided by each analysis can reach the required level of authenticity, accuracy, and timely results. The process of analysis integration is:
   - Identify and analyze requirements
• Make sure using the right tools
• Ensure that appropriate analytical techniques are applied
• Make sure the input is correct
• Perform analysis
• Verify integration results

6) Confirmation and verification

The “double V” process is the core process of system engineering. The confirmation process determines that the executed project is correct, and the verification process ensures that the project is executed correctly.

5. CONCLUSION

In the process of aircraft/engine integrated development, foreign mainstream civil aircraft have effectively reduced the development cycle, cost, and risk of civil aircraft products through the integration of system engineering theories and methods. This research proposes a set of methods for building an aircraft/engine integrated design system based on system engineering. The design system, based on the requirements of airworthiness regulations, establishes the relationship between the aircraft/engine integrated design process and the airworthiness verification process. The design system outputs structured design evidence to ensure that the aircraft/engine integrated design process provided to the airworthiness authority has complete logic, rigorous evidence, and traceability.

Based on the “double V” model under the system engineering theory, this paper analyzes the development process of conformity evidence, and the aircraft/engine integrated system. In this research, the work can be concluded as parts below: clarifying the definition of system engineering and product development, and the system engineering tool of complex products represented by the aircraft/engine integrated system; constructing the mapping model of aircraft/engine integrated and system engineering system; building an aircraft/engine integrated design system based on the “mapping model” to ensure the logical completeness of design evidence. The whole design system includes two types of core design evidence: 1) Aircraft/engine integrated system design data; 2) Aircraft/engine integrated system confirmation and verification data. The mapping model corresponds to the design constraints of aircraft/engine integrated system based on the airworthiness regulatory requirements in aspects of requirement analysis & confirmation, functional design, and design execution & verification. All the work above improve the traceability of the design process and refine the degree of design data.

ACKNOWLEDGMENT

This research was sponsored by the Civil Aircraft Special Scientific Research Project initiated by the Ministry of Industry and Information Technology and the Startup Fund for Youngman Research at SJTU of China (SFYR at SJTU).

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