Optimization of Computer Aided Industrial Design System for Passenger Aircraft Cabin

Xiaodong Yuan[1] and Xi Niu[2*]

[1]School of Art Design, Zhengzhou University of Aeronautics, Zhengzhou, Henan 450046, China, yxd1982@zua.edu.cn
[2]School of Art Design, Zhengzhou University of Aeronautics, Zhengzhou, Henan 450046, China, Nudity1985@zua.edu.cn

Corresponding author: Xi Niu, Nudity1985@zua.edu.cn

Abstract. The airliner conceptual design system can assist designers to improve design quality, increase work efficiency, shorten design cycle and reduce research cost. In this paper, we update the basic parameter estimation module, cabin layout module and preliminary design module of wing and tail shape, and add the sensitivity analysis module of overall parameters to address the shortcomings of the existing airliner concept design system TADAO, such as insufficient technical route, weak design assistance capability, lack of theoretical derivation of some modules and weak system robustness. This paper summarizes a set of methods for preliminary estimation of basic parameters by referring to relevant aircraft general design literature and theoretical derivation, which can estimate the main basic parameters with fewer input parameters. By referring to relevant aircraft general design literature, a set of methods for preliminary design of wing and tail shape is summarized, which can be used for rapid shape design; by comparing different technical routes, a method for sensitivity analysis of general parameters is determined.

Keywords: CAD; Industrial Design System; Passenger Aircraft Cabin; Display Memory
DOI: https://doi.org/10.14733/cadaps.2022.54-64

1 INTRODUCTION

With the gradual advancement of design progress and refinement of design content, aircraft design can be divided into three interrelated and interdependent phases: Conceptual Design, Preliminary Design and Detail Design [1]. The main work of the conceptual design stage is to select the aircraft configuration and aerodynamic layout, choose the main parameters, choose the engine, preliminary design of aircraft components, draw three sketches, general layout, preliminary performance estimation, etc., and finally draw up a reasonable preliminary plan to meet the design requirements after comparing the plans. The early aircraft design work was mainly done manually by designers, and the auxiliary tools were extremely simple and limited, and the evaluation and optimization of parameters and the comparison and analysis of solutions were mainly done by using calculation manuals. The main process is Sketching, Sizing, Lofting and Evaluating [2]. Aircraft design is creative and scientific, and the determination of a solution often requires repeated iterations and multiple approximations, and the changes of design parameters will directly affect the weight characteristics, propulsion performance, and aerodynamic characteristics of the aircraft, etc. The traditional manual design analysis not only has a long design cycle, large workload, and high design costs, but also makes it difficult to achieve multidisciplinary optimization and obtain the optimal solution. With the continuous development of computer technology, many aircraft design departments at home and abroad have widely used computer-aided design (CAD), which not only facilitates the management and sharing of design data, but also cures the previous successful design experience and methods in the aircraft design system and forms a professional design process. The importance of computer-aided design can also be seen from the development of automotive, aerospace and management industries. It is believed that with the development of computer technology and the increasing demand for talents, the airliner concept design system will play a very important role in the civil aviation business in the future.

The development of aircraft conceptual design systems was started by Yang et al. [3], a preliminary design program for military aircraft developed by General Dynamics, and CAAD [4], a preliminary aircraft design and performance analysis program developed by Lockheed Georgia Research Laboratory. Francesca et al. [5] proposed a preliminary aircraft design. All programs and systems can achieve some basic functions, such as design of major aircraft components, aerodynamic analysis, thrust characteristic analysis, weight characteristic analysis and flight performance analysis, etc., but mainly for military aircraft, and due to the limitation of computer technology, they all lack a friendly graphical interface and weak human-computer dialogue function.

From the 1970s to the 1980s, research institutions, aerospace manufacturers and universities cooperated vigorously to develop a series of more functional design and analysis software, which was not limited to military aircraft, but also included general aviation and transport aircraft, such as the General Aviation Integrated Program developed by NASA's Ames Research Center and the University of Minnesota OPDOT, a preliminary design optimization software for transport aircraft developed by GASP and Langley Research Center, most of these software have design, analysis, optimization and graphic display functions, and strong human-machine dialogue functions. In the 1990s, some professors of aviation schools also developed some aircraft design and analysis software based on their writings on aircraft design by Mykhaskiv et al. [6], an interactive analysis and optimization software for commercial aircraft projects developed by Dr. Aage et al. [7], an advanced aircraft analysis software developed by DAR founded by Dai et al. [8]. The aircraft concept design system RDS developed by Conceptual Research, Inc. founded by Raymer, etc. These software not only play a supporting role for research and teaching, but also develop into more influential commercial software. In the 21st century, with the rapid development of computer technology, computer-aided aircraft design has also been further developed. Urbahs et al. [9] developed the aircraft preliminary sizing tool Pre STo based on his lecture notes for the Green Freighter project, but only the general parameter preliminary estimation module, the cabin layout module and the wing and tail design modules have been developed so far. The European Commission has also proposed to build a computer environment for integrated and integrated optimization methods for aircraft CEASIOM [10]. The development of the main aircraft design and analysis systems is shown in Figure 1.

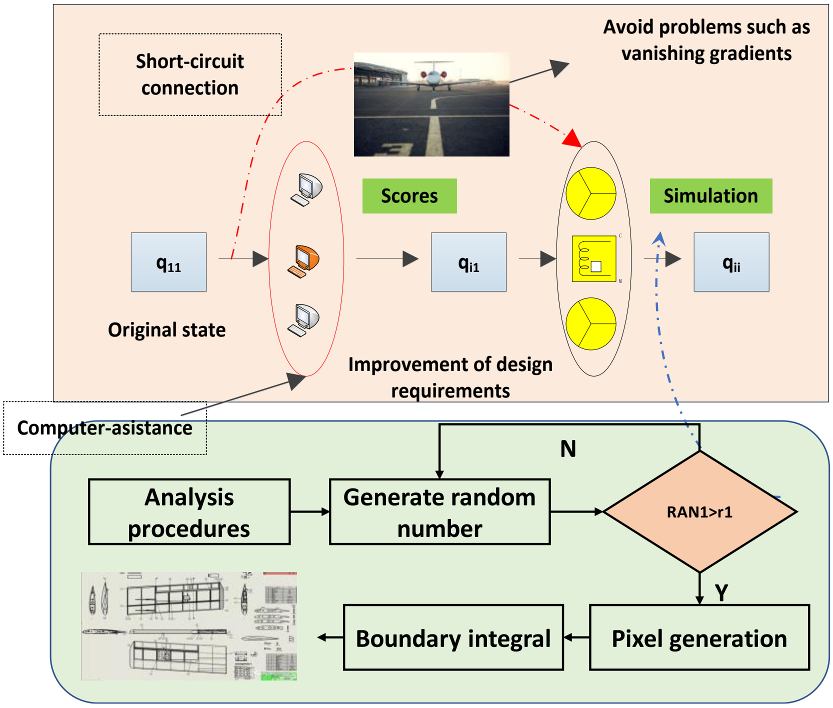

Figure 1: Major Aircraft Design Analysis Systems.

The importance of airliner concept design is self-evident, and it will affect the whole life cycle cost of the aircraft. The airliner concept design system can well assist the designers to obtain the optimal solution. This paper addresses the shortcomings of the existing airliner concept design system TADAO, such as insufficient technical route, weak design assistance capability, lack of theoretical derivation in some modules and weak system robustness, and updates its basic parameter preliminary estimation module, cabin layout module and preliminary design module of wing and tail shape, and adds the overall parameter sensitivity analysis module. This paper summarizes as follows. By referring to relevant aircraft overall design literature and theoretical derivation, a set of basic parameter preliminary estimation method is summarized, which can calculate the wing loading, thrust-to-weight ratio and weight characteristics by only inputting the commercial load, range, flight performance requirements, and fewer predicted parameters. Based on this method, a calculation module with good user interface is developed by applying MATLAB programming technique. The calculation example shows that the overall main parameters determined by the calculation module are in general consistent with the reference model.

2 DEVELOPMENT OF PRELIMINARY DESIGN MODULES FOR WING AND TAIL SHAPES

2.1 Preliminary Design Method of Wing Shape

The choice of relative wing thickness is usually related to the speed of flight. The dividing line between low and high subsonic speeds can be described as when it is more advantageous to use a swept-back wing, but it is difficult to give a Mach number for this boundary because it also depends on the cruise lift coefficient, the level of airfoil technology, etc. According to the literature, this dividing line is approximately 0.6 M around, as shown in Figure 2.

(1) low subsonic speed

First of all, it is necessary to introduce the concepts of critical Mach number and drag divergence Mach number. The incoming Mach number at a point on the wing when the speed of the aircraft has just reached the speed of sound is called the critical Mach number, denoted by Mcr, while the drag divergence Mach number is the incoming Mach number at which the surge drag rises rapidly, denoted by MDD. The difference between Boeing and Airbus is about 0.08. In this paper, we consider that the drag divergence Mach number MDD is slightly larger than the cruise Mach number M. The user can input the difference △MDD, which is usually between 0 and 0.05.

(2) The relative thickness of the wing t/c is given by

$$t / c = M_{DD} / M_{CR} - 0.05 \tag{1}$$

The effective resistance dispersion Mach number MDD,eff is.

$$M_{DD,eff} = M_{DD} \frac{C_l}{M_{CR}} \tag{2}$$

Therefore, at low subsonic speeds, the relative thickness of the wing t/c can be expressed as

$$t / c = M_{DD} \frac{C_l}{M_{CR}} - 0.05 \tag{3}$$

(3) high subsonic speed

The relative wing thickness t/c, 1/4 chord swept-back angle q, effective drag divergence mach number MDD and cruise lift coefficient CL, C are related as follows

$$t / c = 0.3q \frac{5 + M^2{}_{DD,EFF}}{5 + (K_M - 0.5C_{L,C})^2} \tag{4}$$

(4) Distribution of relative thickness along the wing span

The above relative thickness is the average value, in fact, the thickness of each occupied position of the wing is largely determined by the three-dimensional flow field, accurate calculation requires more advanced aerodynamic software, while in the conceptual design stage can be based on the method of preliminary estimation, the average value of relative thickness t/c with the relative thickness of the exposed wing root (t/c)r, the relative thickness of the wing tip (t/c)t is related to the following equation.

$$t / c = 0.3(t / c)_r + 0.7(t / c)_r \tag{5}$$

2.2 User Interface for Preliminary Wing Shape Design Module

The GUIDE module of MATLAB is used to develop a calculation module for the preliminary design of the wing shape. The GUI of this calculation module includes a graphical display area, parameter input and output areas, and a control button area, as shown in Figure 3.

Project name and parent input parameters: Used to display the project name and parent input parameters. Graphic display area: used to display the top and front view of the wing.

Input and output area: the input parameters section is used to input the wing design parameters, airfoil parameters, aileron parameters and boost device parameters, where the white parameter input box means that the parameter needs to be input by the user, click on the help button "?" on the right side of the parameter. The gray parameter input box means that the parameter can be calculated by the program to get the reference value, click the help button "?" on the right side of the box to display the specific reference value. The data is only a reference for the user, and the user can modify it according to the design requirements.

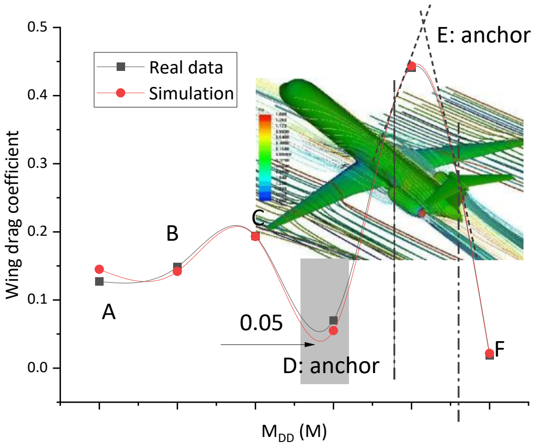

Figure 2: Critical Mach number and drag divergence Mach number.

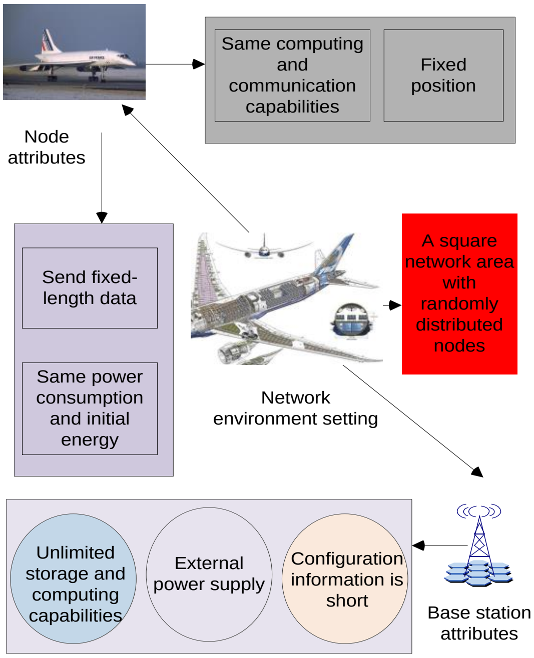

Figure 3: Preliminary wing shape design interface.

The output parameters include the tank volume check, the user can click whether to set the outer section tank, inner section tank and central tank to meet the available tank volume is larger than the required tank volume. Control button area: click "Import" button to import existing input files; "Confirm Input" button to confirm the input parameters and prepare for drawing; "Draw" button.

The "Draw" button allows you to draw the top and front view of the wing and the corresponding wing shape. If the parameters are modified, you can click the "Confirm Input" and "Draw" buttons again to redraw the figure. After finishing the drawing, the "Save View" button allows you to save the view to a user-specified path, the default being the current working directory. The "Save Data" button saves the data file to the path specified by the user, the default path is the import file directory. Click the "Exit" button, a dialog box will pop up to determine the exit of the program, click "Yes" to exit the program. The above functions can be implemented using MATLAB's data reading and writing, plotting, and message dialog functions. The tailplane is the airfoil that ensures the stability and maneuverability of the aircraft. In the overall design stage, because there is not enough data about weight distribution and rotational inertia, the information is difficult to collect and the scatter is large, so the analysis and calculation of the dynamic stability and maneuverability of the aircraft is quite difficult, therefore, the tail design is often based on the requirements for the static stability of the aircraft, and in the final stage when the overall design plan is basically completed, then the dynamic characteristics of the aircraft are comprehensively In the final stage of the overall design plan, the dynamic characteristics of the aircraft are analyzed, calculated and tested, and if problems are found, improvements are made again.

3 SYSTEMATIC OPTIMIZATION OF OVERALL CABIN PARAMETER SENSITIVITY OF PASSENGER AIRCRAFT

The overall parameter sensitivity refers to the overall parameters in a certain range of changes, the degree of change in the performance indicators, the analysis results are expressed in the form of single-parameter trend diagram and multi-parameter carpet diagram. Changes in the overall parameters can be described as "a hair to move the whole body", usually causing changes in a number of other parameters and performance indicators, and the trend and rate of these changes are often not the same, or even the opposite. Therefore, the analysis of parameter sensitivity is very necessary. Parameter sensitivity analysis has the following two main roles: (1) to provide a basis for the selection of the overall parameters. Usually, the design point of the program should be selected in the performance index changes more slowly, so as to avoid deviating from the design point when the performance will produce drastic changes, so that the program has robustness. (2) To provide a reference for the improvement or modification of the design scheme. The overall parameter sensitivity analysis can clearly express the position of the design point of the scheme in the design domain, and quantitatively indicate the impact of parameter changes on the aircraft indicators, so as to indicate the direction for parameter modification and scheme determination. In this chapter, an easy-to-use overall parameter sensitivity analysis module with good user interface is developed by applying MATLAB programming technology by integrating both the passenger aircraft overall comprehensive analysis program and the proxy model.

3.1 Technology Line

Parameter sensitivity analysis uses two technical routes: (1) invoking the overall comprehensive passenger aircraft analysis program; (2) firstly, using the overall comprehensive passenger aircraft analysis program as the analysis model, establishing a proxy model of the overall comprehensive passenger aircraft analysis program through experimental design and approximation methods, and then invoking the proxy model. The calculation flow of the two technical routes is shown in Figure 4.

When the first technical route is adopted, due to the limitation of the overall comprehensive analysis procedure of passenger aircraft, it is necessary to provide interfaces for modifying parameter variables and technical variables, which is more cumbersome to operate; in the calculation process, it is necessary to discrete the input variable interval into several points and go through several loops to traverse all single and double parameters, which takes too long to run, thus limiting the number of parameters and only pre-setting single parameters and a limited number of double. The practicality is not good because only single parameters and limited combinations of double parameters can be set in advance. In addition, because of the large number of iterations in the calculation process, the calculated values may have numerical noise, so the generated graph lines are not smooth enough.

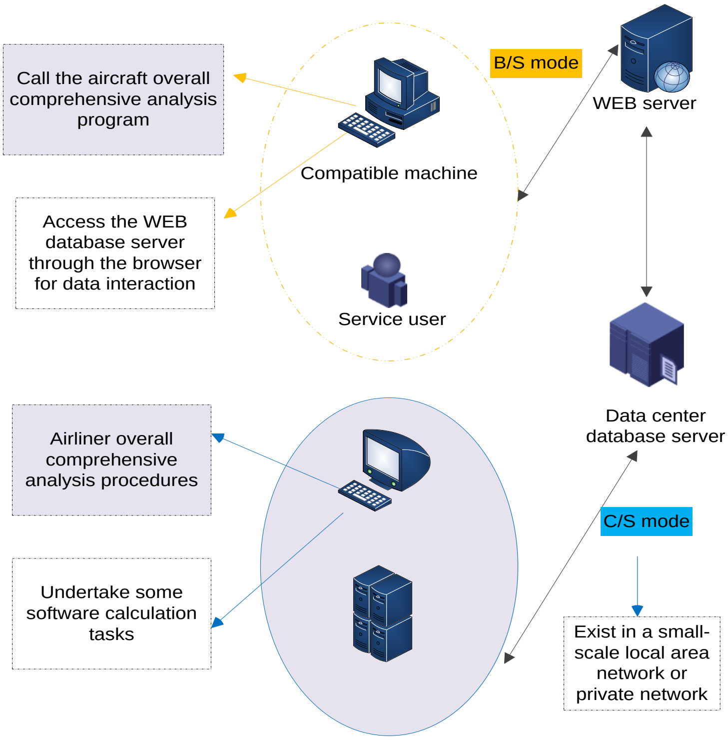

Figure 4: Parameter sensitivity analysis flow chart.

When the second technical route is adopted, the established proxy model is invoked during the plotting, the response is real-time and the running time is short, so when the two-parameter carpet plot is drawn, the user can freely choose the combination of the two parameters and can adjust the sparsity of the carpet plot; in addition, because some data noise is filtered out in the process of establishing the proxy model, the generated plot lines are smoother, as shown in Figure 5. Comparing the two technical routes, the method of invoking the proxy model not only simplifies the process, reduces the running time and increases the combination of input parameters, but also generates a higher quality of the generated plot lines, so this technical route is used for the parameter sensitivity analysis.

3.2 System Optimization of the Wing

Taking the wing area S and the maximum static thrust T at sea level as input parameters and the takeoff field length sTOFL as output performance index parameters, this is used as an example to illustrate the method of drawing a two-parameter carpet diagram.

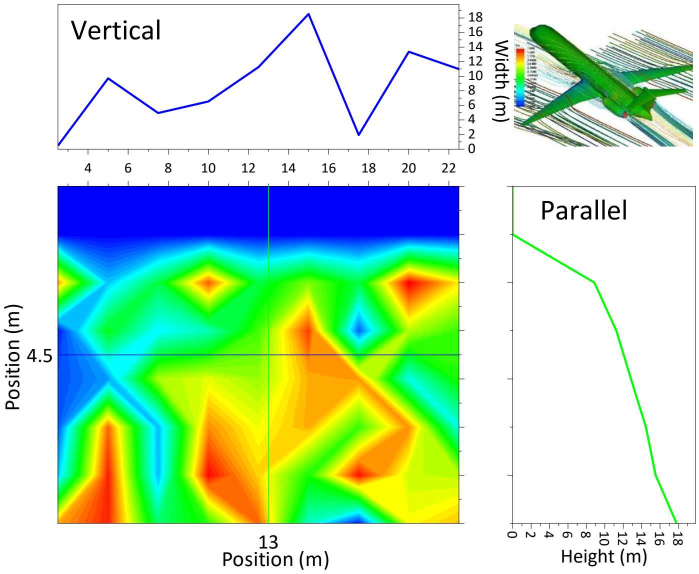

Figure 5: Plot lines generated by invoking the proxy model.

Assuming that the variation interval of T is T1~TP, which is divided into P parts, and the variation interval of T is T1~TQ, which is divided into Q parts, a matrix of two-parameter numerical coordinates, denoted as X0, can be obtained as shown in Eq.

$$X_0 = \begin{bmatrix} (T_0,Q_0)\cdots(T_q,Q_0) \\ \vdots \quad \ddots \quad \vdots \\ (T_0,Q_t)\cdots(T_q,Q_t) \end{bmatrix}_{q*t} \tag{6}$$

Then, according to the proxy model calculation (other parameters are still the values of the design point), each two-parameter numerical coordinate can be found a takeoff field length, and finally the data of takeoff field length in the form shown in Eq. is a Q × P matrix, which is denoted as R.

$$R_0 = \begin{bmatrix} (P_0,Q_0)\cdots(P_q,Q_0) \\ \vdots \quad \ddots \quad \vdots \\ (P_0,Q_t)\cdots(P_q,Q_t) \end{bmatrix}_{q*t} \tag{7}$$

A mapping from X0 to X is thus constructed, and a two-parameter carpet map can be generated by plotting the data points at the corresponding positions of the matrices X and Y and then connecting the lines.

Taking a 250-seat class of a two-aisle airliner as an example, the single-parameter trend and two-parameter carpet plots generated by the module are shown. As can be seen in Figure 6, for this airliner, the optimal wing area for direct operating cost is 360m2, while the design point is closer to the optimal point, mainly because the wing area is also limited by other design requirements. As shown in Figure 7, the larger the wing area, the shorter the takeoff field length, and its optimal wing area is not 360m2, which is illustrating the significance of parameter sensitivity analysis to assist designers in weighing the parameters.

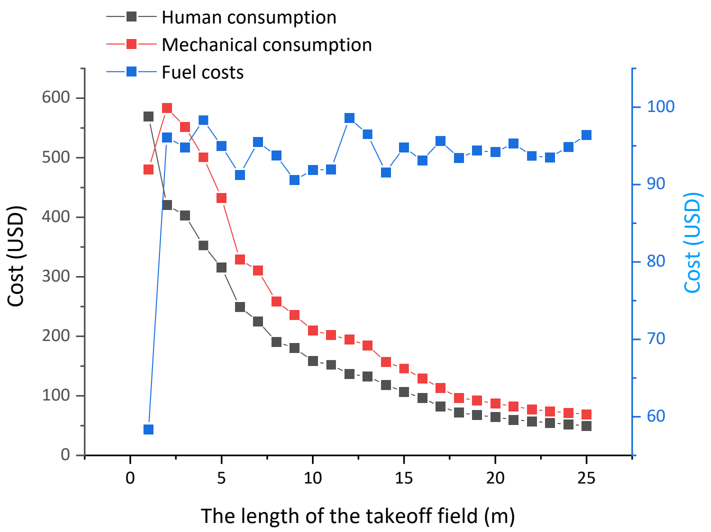

Figure 6: Impact of wing area on direct operating costs.

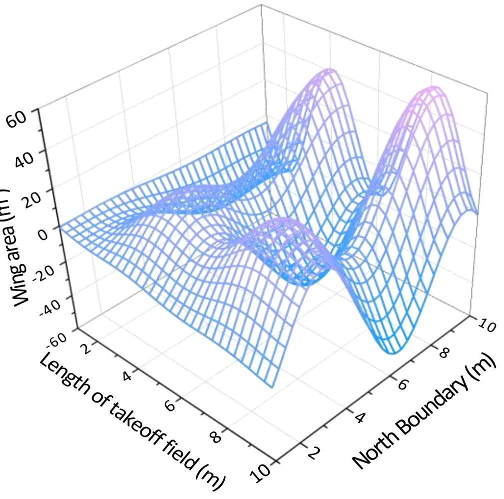

Figure 7: Effect of wing area on takeoff field length.

Aircraft cabin facility design is a crossover and fusion of scientific and artistic approaches. The scientific method and the artistic method have the same purpose, and the complementarity and symbiosis of science and art can create a more imaginative, safer, more economical, more ecological and more artistic way of life and environment. Herbert Alexander Simon, the "father of design", proposed that product design is the "science of creating artificial objects" based on rational engineering and multidisciplinary intersection. There are two parallel tendencies in the development of product design in Germany: one is the thinking mode that emphasizes rationality, systematization and logic; the other is the opposite of humanization and humanistic design concept. The artistic form of a product is not a matter of simple proportional harmony in the geometric sense, but is created and appreciated through intuitive understanding. Herbert Reed in "Art and Industry - Principles of Industrial Design" proposed that the shape of products designed for people embodies three forms: the formal factors of size and proportion, the expressive factors of emotion and reason, and the perceptual and unconscious factors.

Therefore, the efficacy of the artistic and aesthetic form of aircraft cabin facility modeling design is an infectious feeling, and this infectiousness may be both intuitive and rational. Aircraft cabin facilities modeling design features.

First of all, it is necessary to meet the strict airworthiness requirements and technical standards. The strict safety requirements of aircraft necessarily require designers to understand the basic test system airworthiness standards and technical standards of aircraft cabin facilities such as flammability test, mechanical performance test, static and dynamic destructive force test, etc., and also pay attention to the latest airworthiness announcements for a long time. Currently, most domestic civil aircraft cabin facilities have only obtained CAAC airworthiness certificate, and few companies have obtained FAA or EASA certification.

The characteristics of many kinds, small batch, customization and high complexity. Civil aviation aircraft cabin facilities mainly cover seats and their parts, luggage racks, galleys, lavatories, checkrooms, dining carts, video players, aviation headphones, life jackets, lifeboats, curtains, porthole panels and many other types; China's civil aviation and circular industry is developing fast, but started late, the demand for aircraft cabin facilities has the characteristics of small batch; industry domestic airlines huge aircraft cabin facilities replacement is mainly to import Customization is the main focus, because of its high complexity of research and development, manufacturing, and safety indicators, especially the leased aircraft will be replaced with OEM pieces or products with foreign certification when the lease is returned. The characteristics of many types of aircraft cabin facilities, small batch, customization, and high complexity require more systematic cabin facility innovation design theory to cope with.

Reflect the diversity of good design. The diversity of passengers' functional needs must also require aircraft cabin facilities to reflect the diversity of good design, the characteristics of today's international aircraft cabin facilities design: first, to ensure safety, pay attention to comfort; second, the diversity of passenger demand for aircraft cabin facilities design tends to personalization, functional diversification; third, industrial design, ergonomics, cabin safety and other multidisciplinary knowledge cross-study makes Third, the interdisciplinary knowledge of industrial design, ergonomics and cabin safety makes the design of aircraft cabin facilities more systematic.

4 CONCLUSIONS

The sensitivity analysis of overall parameters conducted in this paper has the following two technical routes (1) directly invoking the passenger aircraft overall comprehensive analysis program for the analysis; (2) firstly, using the passenger aircraft overall comprehensive analysis program as the analysis model, establishing the proxy model of the passenger aircraft overall comprehensive analysis program through experimental design and approximation methods, and then invoking the proxy model. Through analysis and comparison, (2) is adopted, which not only simplifies the process, reduces the running time and increases the combination of input parameters, but also generates higher quality graph lines, which can analyze the sensitivity of different overall parameters and provide the basis for program design and improvement and modification. The modules are developed based on MATLAB environment, users do not need to install too much third-party software, and the robustness of the system has been greatly improved. The basic parameter preliminary estimation module and the cabin layout module are used to teach the overall design of flight vehicle course in Nanjing University of Aeronautics and Astronautics, and their effectiveness and accuracy are further confirmed by the response of students and teachers.

In addition, this paper summarizes a set of cabin quick layout method with reference to the airworthiness regulations on cabin seats, emergency exits and aisle arrangement and the related aircraft general design literature, which can quickly arrange the seats, aisles, toilets, galleys and safety exits of different cabins to provide a reference for the safety, economy and comfort of passenger aircraft. Then a calculation module with good user interface is developed by applying MATLAB programming technology. The example verification shows that the passenger cabin laid out by this calculation module is basically consistent with the reference model.

Xiaodong Yuan, https://orcid.org/0000-0002-6030-794X
Xi Niu, https://orcid.org/0000-0001-6276-8371

REFERENCES

[1] Safety, M. J.-J.; Technology, F.: Testing the Process of Evacuation from the Passenger Aircraft with the Use of Computer Simulation, Safety & Fire Technology, 56(2), 2020, 22-39. https://doi.org/10.12845/sft.56.2.2020.2

[2] Gnadt, A.-R.; Speth, R.-L.; Sabnis, J.-S.; Barrett, S.-R.-H.: Technical and Environmental Assessment of All-Electric 180-Passenger Commercial Aircraft, Progress in Aerospace Sciences, 105, 2019, 11-30. https://doi.org/10.1016/j.paerosci.2018.11.002

[3] Yang, Q.; He, L.; Liu, X.; Yang, Z.: Computer-Aided Industrial Development Path Optimization: A Case from "Optics Valley of China", Cluster Computing, 22(4), 2019, 8869-8878. https://doi.org/10.1007/S10586-018-2002-9

[4] Morra, L.; Coccia, N.; Cerquitelli, T.: Optimization of Computer Aided Detection Systems: An Evolutionary Approach, Expert Systems with Applications, 100, 2018, 145-156. https://doi.org/10.1016/J.ESWA.2018.01.028

[5] Francesca, D.; Crescenzio, S.; Bagassi, S.; Asfaux, N.; Design, L.-J.: Manufacturing. Human Centred Design and Evaluation of Cabin Interiors for Business Jet Aircraft in Virtual Reality, International Journal on Interactive Design and Manufacturing (IJIDeM), 13(2), 2019, 761–772. https://doi.org/10.1007/s12008-019-00565-8

[6] Mykhaskiv, O.; Banović, M.; Auriemma, S.; Mohanamuraly, P.; Walther, A.; Legrand, H.; Mü ller, J.-D.: NURBS-based and parametric-based shape optimization with differentiated CAD kernel, Computer-Aided Design and Applications, 15(6), 2018, 916-926. https://doi.org/10.1080/16864360.2018.1462881

[7] Aage, N.; Andreassen, E.; Lazarov, B.-S.; Sigmund, O.: Giga-voxel computational morphogenesis for structural design, Nature, 550(7674), 2017, 84-86. https://doi.org/10.1038/nature23911

[8] Dai, J.; Wei, M.; Xie, Q.; Wang, J.: Aircraft seam feature extraction from 3D raw point cloud via hierarchical multi-structure fitting, Computer-Aided Design, 130, 2021, 102945, https://doi.org/10.1016/j.cad.2020.102945

[9] Urbahs, A.; Urbaha, M.; Carjova, K.; Koruba, Z.: Technological solutions for the computer-aided design and manufacturing of a remotely piloted aircraft, Procedia Computer Science, 149, 2019, 390-397. https://doi.org/10.1016/j.procs.2019.01.153

[10] Kishalov, A.-E.; Lipatov, V.-D.; Soloviev, P.-V.: Modeling and computer-aided design of combustion chambers for aircraft engines and gas turbine plants using an expert system, Journal of Physics: Conference Series, 1679(2), 2020, 022040. https://doi.org/10.1088/1742-6596/1679/2/022040