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Multidisciplinary Design Optimization of UAV Considering Development Costs

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Abstract

The paper establishes a multidisciplinary design and optimization framework that aims at minimizing Unmanned aerial vehicles (UAV) development costs. This framework integrates development costs as an equally important factor alongside weight and aerodynamic disciplines within the UAV design process. The OpenMDAO paradigm is employed to facilitate a standalone design and optimization application. A comprehensive multidisciplinary analysis module is developed, encompassing initial geometrical sizing, weight analysis, aerodynamic performance evaluation, and estimation models for development costs. The effectiveness of the framework is validated through a low-cost, high-performance UAV case study. The results demonstrate that neglecting the influence of UAV development costs would be imprudent. By appropriately adjusting design parameters using the optimization algorithm, significant reductions in UAV development costs can be achieved with minimal performance losses.

Keywords

UAV, Development Costs, Multidisciplinary Design and Optimization, Design Application

1. Introduction

Unmanned aerial vehicles (UAVs) are high-performance, information-based weapon systems developed by fully leveraging the outcomes of the information technology revolution. The research and development of UAVs has become a prominent feature in the advancement of high-tech weaponry in the contemporary era. It is estimated that 70% to 80% of a project's costs are determined during the development stage; Therefore, conducting cost analysis as early as possible in the design process is critically important. Currently, there is limited research on incorporating costs as a design factor within the design and optimization processes, and a lack of simple and user-friendly design optimization frameworks exists. This situation necessitates in-depth research to explore the coupling between UAV design processes and development cost analysis.

In terms of UAV design processes and optimization, Andras *et al.* [1] proposed and validated a CAD-based conceptual design framework for UAVs, employing commercial CAD tools as a parametric geometric engine to provide models required for various aspects of multidisciplinary analysis. Pedro *et al.* [2] optimized the aerodynamic characteristics of the initial UAV design by evaluating the drag and lift coefficients through theoretical and experimental methods. The results indicate that modifying design parameters can alter the aircraft's aerodynamic performance, and simple tools can be employed to study these effects. Emilio Botero *et al.* [3] utilized the open-source platform SUAVE to analyze, optimize, and design a series of small UAVs. This tool, written in Python, has been shown to be useful for UAVs based on fixed wings, rotors, and intermediate configurations, verifying the feasibility of using a Python-based design framework in UAV design and optimization. However, in this field, relatively little research has considered cost as an important design factor in the design process.

Regarding the estimation of UAV development costs, Chen *et al.* [4] obtained principal components using P-value analysis and grey relational analysis. Based on these principal components, they established corresponding linear regression and BP neural network models. Through sensitivity analysis, they determined the linear regression model as the final cost prediction model for general aviation aircraft development. Xie *et al.* [5] proposed a combined model of the GM (0, N) model and BP neural network algorithm, effectively integrating the simulation capabilities of BP neural networks with the advantages of the GM (0, N) model in generating information under conditions of limited samples and insufficient data. These studies treat cost as the research object but do not incorporate cost as a design factor into the design process. Therefore, constructing a design optimization framework that optimizes development costs is highly necessary.

In this paper, UAV development costs are treated as a design factor of equal importance to aerodynamics and weight, and are integrated into the design process. The Partial Least Squares (PLS) regression method is employed to model UAV development costs. Based on the open-source optimization tool OpenMDAO, a multidisciplinary design and optimization (MDO) framework is constructed using Python, with development costs as the optimization objective. This framework provides an effective methodology for the cost-effective design of UAVs.

2. Design Process and Optimization Framework

In response to the UAV overall parameter optimization problem mentioned in the previous section, we propose a design process and optimization framework. The first step involves establishing a multidisciplinary analysis model, which includes modules for geometry, weight, aerodynamics, and cost. Unlike traditional optimization problems, cost analysis is integrated as a performance metric for UAVs and incorporated into the design optimization process. Using OpenMDAO, the design variables, constraints, and objective functions are defined. The optimization algorithm is then applied to compute the values of the objective functions and the constraints. The design process and optimization framework are illustrated in **Figure 1**.

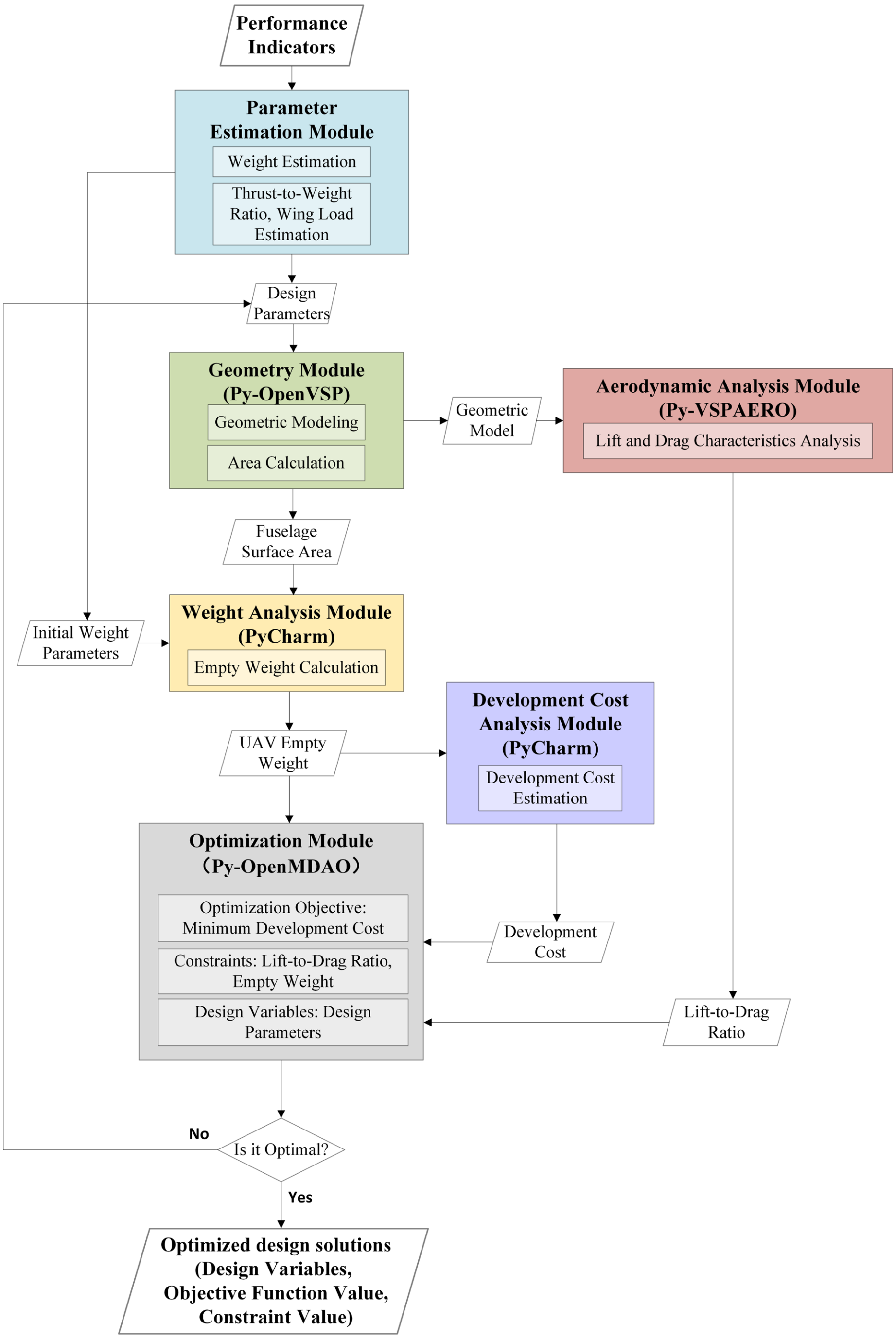

Figure 1. Design process and optimization framework.

2.1. UAV Design Process

The UAV design process investigated in this paper primarily focuses on the conceptual design stage. The key tasks involve: Initially determining the primary parameters of the UAV, preliminarily establishing the geometric parameters of each component, and formulating the initial conceptual scheme of the UAV. Firstly, based on the performance index of the UAV, estimates are made for its maximum take-off weight, fuel weight, and other relevant data. By plotting a boundary diagram for the UAV within feasible limits, both thrust-to-weight ratio and wing load are determined; Subsequently obtaining engine thrust and wing area requirements according to their respective definitions. The fuselage length is estimated using an empirical formula from literature [6], while selecting an appropriate length-diameter ratio determines fuselage width. Thus concludes preliminary estimations for basic geometric parameters of the UAV. A conceptual model for the UAV scheme is obtained which will be utilized for subsequent multidisciplinary analysis and optimization.

2.2. Optimization Problem

This paper investigates the economic-based design optimization of low-cost UAVs, focusing on determining a reasonable design scheme and overall parameters for given UAV performance indicators. In the overall UAV design process, two key components are the aerodynamic performance analysis and weight analysis. Therefore, in this study, the lift-to-drag ratio is used to evaluate the UAV's aerodynamic performance, while the basic empty weight serves as the output for the weight analysis. The problem of determining the overall parameters can be formulated as an optimization problem. The three main elements of the optimization model are design variables, constraints, and the optimization objective.

Optimization objective: $\min C_{development}(X)$

Constraints: $s.t.(L/D) \geq 8$

$W_{empty} < 3$

Design variables: $X = \{L_f, AR, \varphi, S_{wing}, \lambda\}$

Optimization objective: The objective is to minimize the UAV's development cost.

Constraints: The constraints are the UAV's lift-to-drag ratio and the basic empty weight.

Design variables: The design variables include the geometric parameters of the UAV, such as fuselage length(L_f), wing aspect ratio(AR), wing taper ratio(λ), wing sweep angle(φ), and wing area(S_{wing}).

2.3. Optimization Algorithm

Sequential Least Squares Quadratic Programming (SLSQP) is an iterative algorithm designed to solve constrained nonlinear optimization problems. As a special case of the Sequential Quadratic Programming (SQP) method, SLSQP combines least squares techniques with quadratic programming to address nonlinear issues, enabling it to manage both linear and nonlinear equality and inequality constraints.

SLSQP is primarily employed to solve constrained minimization problems, with the goal of identifying design variables that minimize the objective function while adhering to a set of equality and inequality constraints. The algorithm's approach resembles that of SQP, wherein the problem is iteratively linearized or approximated as a quadratic programming problem. However, SLSQP distinguishes itself by utilizing least squares methods to handle constraints and the objective function.

The main steps of the algorithm are as follows:

Step 1**: *****Initialization***

SLSQP primarily solves nonlinear optimization problems with constraints, which can be formulated in the standard form as:

$$\min C_d(X) \tag{1}$$

where $C_d(X)$ is the UAV's development cost, subject to the following constraints:

Empty weight constraints:

$$W_{empty}(X) < 0 \tag{2}$$

Lift-to-drag ratio constraints:

$$(L/D)(X) \geq 0 \tag{3}$$

Select initial design variables X_0, such as the UAV's geometric parameters (wing area, fuselage length, etc.). Define the objective function $C_d(X)$, which represents the UAV's development cost. Assume this function depends on the design variables X. Define inequality constraint functions. Initialize Lagrange multipliers μ_0 to handle the inequality constraints.

Step 2**: *****Construct the Lagrangian Function***

SLSQP utilizes the Lagrange multiplier method to handle constrained problems. The Lagrangian function $\text{Lagrange}(X,\mu)$ is constructed, incorporating only the inequality constraints W_{empty} and (L/D).

$$\text{Lagrange}(X,\mu) = C_d(X) + \mu_1 W_{empty}(X) + \mu_2 (L/D)(X) \tag{4}$$

where: μ_1 corresponds to the Lagrange multiplier of the lift-drag ratio constraint (L/D). μ_2 corresponds to the Lagrange multiplier of the empty weight constraint W_{empty}.

Step 2: Linearize the Objective Function and Constraints

At the current iteration point X_k, perform a second-order approximation of the objective function $C_d(X)$ and a first-order linearization of the constraints:

Objective function approximation using Taylor series expansion:

$$C_d(X) \approx C_d(X_k) + \nabla C_d(X_k)^T (X - X_k) + \frac{1}{2}(X - X_k)^T H(X_k)(X - X_k) \tag{5}$$

where $\nabla C_d(X_k)$ is the gradient of the objective function at x_k, and $H(x_k)$ is the Hessian matrix (the second-order derivative matrix).

Linearization of the constraints:

$$\begin{aligned} W_{empty}(X) &\approx W_{empty}(X_k) + \nabla W_{empty}(X_k)^T (X - X_k) \\ (L/D)(X) &\approx (L/D)(X_k) + \nabla (L/D)(X_k)^T (X - X_k) \end{aligned} \tag{6}$$

where:

$\nabla W_{empty}(X_k)$ and $\nabla (L/D)(X_k)$ are the gradients of the lift-to-drag ratio and empty weight constraints at the current design point, respectively.

Step 3*: *Construct and Solve the Quadratic Programming Subproblem

In each iteration, construct a local quadratic programming (QP) problem to update the design variables *X*:

Objective:

$$\min \nabla C_d(X_k)^T d + \frac{1}{2} d^T H(X_k) d \tag{7}$$

subject to the linearized constraints:

$$\begin{aligned} &\nabla W_{empty}(X_k)(X_k)^T d + W_{empty}(X_k)(X_k) < 0 \\ &\nabla (L/D)(X_k)^T d + (L/D)(X_k) \geq 0 \end{aligned} \tag{8}$$

By solving this quadratic programming subproblem, obtain the update d_k for the design variables.

Step 4*: *Update the Design Variables

Update the design variables X using the obtained update d_k:

$$X_{k+1} = X_k + d_k \tag{9}$$

Here, X_{k+1} is the new design scheme for the next iteration.

Step 5*: *Update the Lagrange Multipliers

Update the Lagrange multipliers μ_1 and μ_2 according to the Karush-Kuhn-Tucker (KKT) conditions to ensure the feasibility of the inequality constraints:

If g(X_k) is inactive (*i.e.*, the lift-to-drag ratio constraint is not tight), set $\mu_1 = 0$.

If h(X_k) is inactive (*i.e.*, the empty weight constraint is not tight), set $\mu_2 = 0$.

Step 6*: *Check Convergence

Verify whether the convergence criteria are satisfied:

Change in development cost: $\left|C_d(X_{k+1}) - C_d(X_k)\right|$ is sufficiently small.

Change in design variables: $\|X_{k+1} - X_k\|$ is sufficiently small.

Constraint satisfaction: All constraints are met, *i.e.*, $(L/D)(X_{k+1}) \geq 0$ and $W_{empty}(X_{k+1}) < 0$.

If the convergence criteria are satisfied, terminate the algorithm; otherwise, return to Step 2 and continue iterating.

Step 7*: *Output the Optimization Results

Upon convergence of the iterative process, output the optimized design variables X^*. At this point, X^*represents the optimal UAV design that minimizes the development cost while satisfying the lift-to-drag ratio and empty weight constraints.

In optimization algorithms, SLSQP is a robust and efficient choice. It performs well when addressing multi-constraint optimization problems, particularly those involving high-dimensional, nonlinear objective functions and complex constraints. Additionally, in practical applications, SLSQP demonstrates relatively fast convergence and effectively handles the feasibility of constraints. SLSQP is widely applied in multidisciplinary optimization (MDO), particularly in the aerospace field [7]-[9].

3. Multidisciplinary Analysis Models

3.1. Geometry Module

OpenVSP is developed from the Rapid Airplane Modeler (RAM) software for rapid aircraft modeling. Its early versions utilized a Command User Interface (CUI) for interaction; however, as the user base expanded, it gradually evolved into a Graphical User Interface (GUI). Additionally, it supports script-driven operation, which serves as the technical foundation for OpenVSP's extensibility. This paper employs Python to invoke the API for conducting parametric modeling and aerodynamic analysis.

Utilizing the open-source parametric geometric modeling software OpenVSP [10], a three-dimensional model for the conceptual design is established. The geometric module's inputs consist of geometric parameters, which are encoded into Python scripts. By invoking the API, the three-dimensional shape of the conceptual design is generated, along with the output of relevant data such as reference area and wetted area.

3.2. Weight Module

The weight composition of the UAV is shown in **Figure 2**. The primary distinction from conventional military aircraft is the reduction of crew and operational items, so the operating empty weight defined in this context is typically equal to the basic empty weight. The basic empty weight of the UAV comprises the weight of the airframe structure, propulsion system, and system equipment.

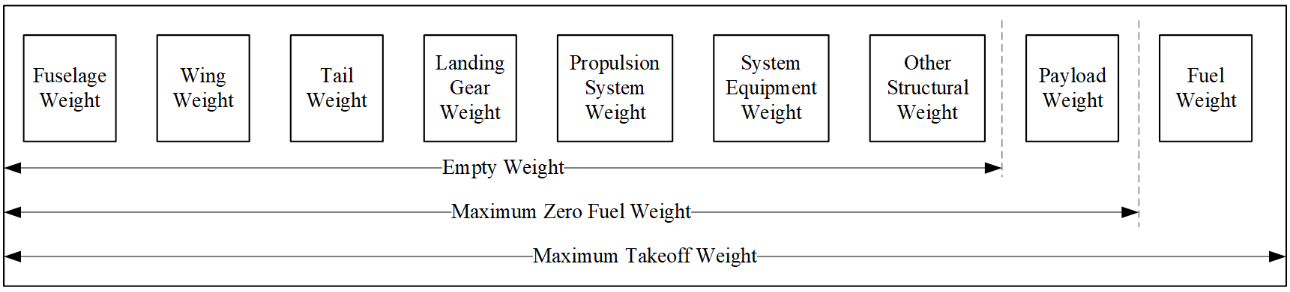

Figure 2. UAV weight composition.

1) Fuselage Weight

The volume of the pressurized section of military aircraft is relatively small compared to the non-pressurized section, allowing it to be simplified as a non-pressurized fuselage. The design criteria for such fuselages primarily consider the bending moment of the rear fuselage associated with the design cruise speed. The estimation formula for the structural weight of a non-pressurized fuselage is [11]:

$$W_f = 0.044 k_7 V_D^{0.74} \left(\frac{L_T}{2D} \right) \left[S_f^{0.07} + \frac{0.22 S_f^{0.45} N^{0.32}}{V_D^{0.35}} \right] S_f \tag{10}$$

In the equation: V_D is the maximum design speed at sea level; L_T is the tail moment arm length, defined as the distance between the quarter-chord points of the wing and tail; for non-tail configurations, it is defined as the distance between the quarter-chord points of the wing and control surface; D is the fuselage width; S_f is the fuselage surface area; N is the design limit maneuvering factor; and k_7 is a complexity factor based on different types of aircraft and design characteristics, with the calculation formula as follows:

$$k_7 = k_8 + 0.2\varepsilon + 0.4\alpha + k_9\delta + 2.7k_{10} + 0.1\eta + 0.3\omega \tag{11}$$

where:

k_8—For medium to large military aircraft, it is taken as 1.8; for twin-engine general aircraft or engine-mounted configurations, it is taken as 2.0; for single-engine light aircraft with a wetted area less than 20 m², it is given by

$2.0 + 1.5\left(20 - S_f\right) / S_f$

k_9—For main landing gear connected to the wing and retracted into the fuselage, it is taken as 0.35; for main landing gear connected to the fuselage and retracted into the fuselage, it is taken as 0.7.

k_{10}—The ratio of weapon bay length to fuselage length.

ε—Taken as 1 when the engine is embedded in the fuselage, and 0 in other cases.

α—Taken as 1 when the intake duct is located on the fuselage, and 0 in other cases.

δ—Taken as 1 when the main landing gear intrudes into the fuselage structure, and 0 in other cases.

η—Taken as 1 for carrier-based aircraft, and 0 in other cases.

ω—Taken as 1 for truss-supported wings, and 0 in other cases.

2) Wing Weight

The main structure of the wing refers to the wing sections that bear the loads. The primary components of the box section include beams, spars, skins, and ribs. The estimation formula for the weight of the wing's main structure is:

$$W_{IPS} = \left(m_c + m_r \right) W_{TO} \tag{12}$$

$$m_C = 1920 A^{1.5} S^{0.5} \overline{N}\ r\ (1 + \lambda) \sec\phi \sec\varphi / \tau f_a \tag{13}$$

$$m_r = \frac{3S^{1.25}\tau^{0.5}}{M_{TO} A^{0.25}} \left[(1 - 0.34\lambda + 0.44\lambda^2) + 2.2\tau \left(\frac{S}{A}\right)^{0.5} (1 - \lambda + 0.72\lambda^2) \right] \tag{14}$$

In the equation: W_{TO} is the maximum takeoff weight; m_c is the weight coefficient for the box section skin and beam web; m_r is the weight of the main wing ribs; A is the wing aspect ratio; S is the wing reference area; λ is the taper ratio; ϕ is the effective sweep angle (at the quarter-chord line); φ is the structural sweep angle (generally approximated as equal to ϕ; τ is the relative thickness at the wing root; f_a is the allowable working stress of the wing material.

The above weight calculation formula does not account for weight increases due to factors such as the connection structures between the wing and other components, structural openings, variable sweep, and wing folding, nor does it include the weight of secondary structures such as flaps and ailerons. Therefore, it requires correction. The values of the correction factors C_1, C_2, and C_3 are obtained from the literature [6]. The total weight of the wing structure is:

$$W_w = \left(C_1 + C_2 + C_3\left(m_C + m_r\right)\right)W_{TO} \tag{15}$$

3) Tail Weight

The tail weight typically accounts for less than 3% of the total aircraft weight, but it significantly impacts the longitudinal position of the center of gravity. The primary factors influencing tail weight are the tail area and the maximum design speed.

The estimation formula for the weight of a single vertical tail is:

$$W_v = 0.065 k_{12} V_D S_h^{1.15} \tag{16}$$

In the equation, S_h is the vertical tail area; V_D is the maximum design speed at sea level;

The value of k_{12} depends on the tail configuration type: for vertical tails not mounted on a horizontal tail, it is taken as 1; for T-tail configurations, it is taken as 1.5.

4) Landing Gear Weight

According to statistical data, the weight of the landing gear assembly generally accounts for 3% to 5% of the maximum takeoff weight and 8% to 15% of the total aircraft structural weight. The weight of the nose landing gear constitutes 15% of the total landing gear assembly weight, while the main landing gear accounts for 85%.

5) Propulsion System Weight

The propulsion system weight refers to the total weight of the complete propulsion system, including the short nacelle and engine accessories, calculated as shown in the following equation:

$$W_{PP} = n C_{eng} W_{eng} \tag{17}$$

In the equation: n is the number of engines; C_{eng} is the propulsion system installation coefficient; W_{eng} is the bare engine weight, which can be provided by the supplier. The installation coefficient depends on the type of UAV and is taken as 1.4.

6) System Equipment Weight

The onboard systems mainly include the fuel system, flight control system, hydraulic system, avionics system, power system, anti-icing system, and auxiliary power system. Fixed equipment primarily consists of kitchens, restrooms, and other supply equipment, which can be disregarded for UAVs since there are no personnel onboard. The fuel system has already been accounted for in the propulsion system weight module. The total weight of the onboard systems, excluding the fuel system, W_{sys} can be expressed as:

$$W_{sys} = C_{sys} W_{TO} \tag{18}$$

In the equation, C_{sys} is the sum of the coefficients of the onboard systems relative to the maximum takeoff weight. It can be calculated by summing the weight coefficients for each onboard system of the UAV using empirical formulas, as detailed in the literature [11].

3.3. Aerodynamic Module

Currently, there are numerous common aerodynamic analysis methods. Based on computational accuracy, these can be categorized into low-accuracy engineering estimation methods, medium-accuracy rapid numerical methods, and high-accuracy numerical solutions of the Euler equations and Navier-Stokes equations. As computational precision increases, the time cost also rises correspondingly. During the preliminary optimization phase of an aircraft, considering both computational speed and accuracy, rapid numerical methods are primarily selected for aerodynamic analysis. The vortex lattice method is a classic approach within medium-accuracy rapid numerical methods for calculating aircraft aerodynamic characteristics. It is based on the lifting surface theory and is a practical numerical computation method. This approach has advantages such as clarity of physical quantities, rapid computation, high accuracy, and ease of implementation through programming.

Mainstream open-source software based on the vortex lattice method includes AVL, VLM, and Tornado. The parametric modeling software OpenVSP (Open Vehicle Sketch Pad), used in this study, integrates an aerodynamic analysis program based on the vortex lattice method within its VSPAERO analysis module and provides engineering algorithms for viscous corrections. Using the API interface of VSPAERO, aerodynamic characteristic analysis of the UAV is performed in Python, resulting in the lift and drag characteristics of the UAV.

3.4. Development Cost Module

The cost of UAV development refers to the expenses necessary for completing the entire project, encompassing activities such as design, prototype sampling, trial production, and test verification conducted from project initiation to completion.

Based on domestic aviation equipment development practices, management of development funding, and statistical analysis of development costs for hundreds of types of aviation equipment in the United States, the primary factors influencing aviation equipment development costs include the level of new technology content, technology maturity, operational capability, development workload, number of prototypes, quality of prototypes, and development cycle.

In the early stages of development, the equipment development plan is not specific enough to utilize engineering estimation methods for calculating development costs. For estimating the total development costs, this paper employs a parametric method, taking into account factors such as equipment weight and development cycle. For the overall estimation of development costs, the partial least squares regression method is selected based on the aforementioned introduction and literature review.

Using the original data from literature [12] for partial least squares regression fitting, the regression equation obtained is:

$$\begin{aligned} y = &-8943713.731 + 140083.2912x_1 + 134906.3058x_2 \\ &-128289.2566x_3 + 9345.2726x_4 + 87169.3217x_5 \\ &-140706.8749x_6 - 170687.4218x_7 \end{aligned} \tag{19}$$

The fitted regression equation was tested, and the results are shown in **Table 1**. The results demonstrate that the estimation model achieves a prediction accuracy of 98.9%, confirming its effectiveness in accurately estimating the development cost.

Table 1. Regression model prediction effect.

Actual Value (Million CNY)	Predicted Value (Million CNY)	Relative Error
7675.6	7596.29	1.03%

4. Design and Optimization Case Study

4.1. Design and Optimization Process

Assuming the performance requirements of a certain low bypass ratio, UAV are as shown in **Table 2**.

Table 2. Performance requirements.

performance requirements	Value
Combat Radius (km)	2500
Mission Payload (kg)	550
Cruise Altitude (m)	12000
Cruise Speed (Mach)	0.8
Minimum Turn Radius (km)	4.5
Service Ceiling (m)	14000
Takeoff Distance (m)	700
Landing Distance (m)	700

Before performing overall parameter estimation, some empirical parameters need to be preliminarily estimated. The aerodynamic parameters involved in constraint analysis are the zero-lift drag coefficient (C_{D0}), the induced drag factor (K_1), and the maximum lift coefficient. For subsonic aircraft, the C_{D0} value for the UAV in this study is taken as 0.018. The maximum lift coefficients for takeoff and landing are set to 1.6 and 1.8, respectively, and the UAV's aspect ratio is 5, from which the induced drag factor (K1) can be calculated. Based on the UAV performance requirements, a specific model of low bypass ratio turbofan engine is adopted, with a sea-level thrust of approximately 5 tons and a bypass ratio of 0.56. Based on the above analysis, the input parameter values for the parameter estimation module are shown in **Table 3**.

The above parameters are input into the parameter estimation module, and the program calculates the boundary charts, initial weight estimation data, and geometric parameters. The interface is shown in **Figure 3**.

Table 3. Initial estimated input values for parameters.

Parameter Name	Value
Bypass Ratio	0.56
Cruise Mach Number	0.8
CD0	0.018
Combat Radius (km)	2000
Turn Radius (km)	4.5
Takeoff Lift Coefficient	1.6
Landing Lift Coefficient	1.8
Cruise Altitude (km)	12
Payload Weight (kg)	1000
Aspect Ratio	5
Takeoff Distance (m)	700
Landing Distance (m)	700
Weight Fraction in Climb Stage	0.985
Weight Fraction in Cruise Stage	0.843
Weight Fraction in Loiter Stage	0.99
Weight Fraction in Landing Stage	0.83

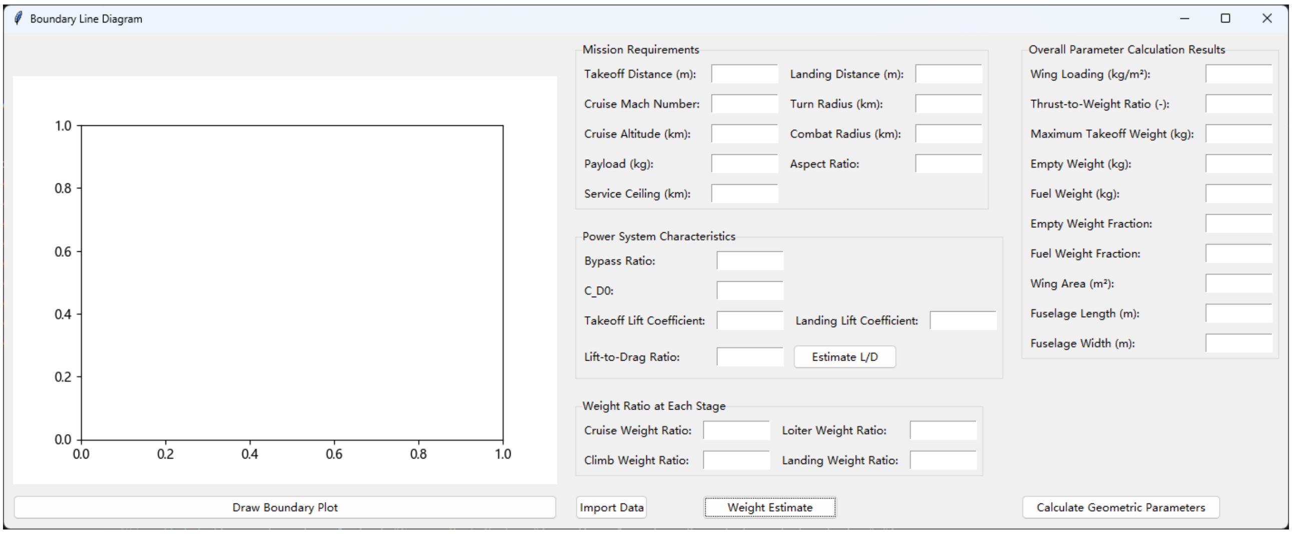

Figure 3. Parameter estimation module interface.

The results are presented as shown in **Table 4**.

Table 4. Output of the parameter estimation module.

Parameter Name	Value
Wing Loading (kg/m^2)	226.13
Thrust-to-Weight Ratio	0.32
Maximum Takeoff Weight (kg)	3293.70
Empty Weight (kg)	1324.86
Fuel Weight (kg)	1418.83
Empty Weight Fraction	0.40
Fuel Weight Fraction	0.43
Wing Area (m^2)	14.57
Fuselage Length (m)	9.16
Fuselage Width (m)	1.14

The estimated maximum takeoff weight of the UAV is 3293.7 kg, with an empty weight of 1324.86 kg and a fuel weight of 1418.83 kg. The empty weight fraction is 0.4, and the fuel fraction is 0.43. The wing loading is 226.13 kg/m^2, and the thrust-to-weight ratio is 0.32. Based on the definitions of wing loading and thrust-to-weight ratio, the reference wing area is 14.57 m^2, the fuselage length is 9.16 m, and the fuselage width is 1.14 m.

The geometric parameters are input into the geometry module to obtain the UAV's geometric model. **Figure 4** shows the interface of the geometry module. The input parameters are shown in **Table 5**. The outputs of the geometry module are the UAV geometric model files and the fuselage surface area. The calculated fuselage surface area is 20.42 m^2.

Table 5. Inputs of the geometric module.

Parameter Name	Value
Fuselage_width (m)	1.14
AR	5
Wing_Area (m^2)	14.57
Sweep (˚)	35
Wing_Taper	0.4
Fuselage_length (m)	9.16
Tail Area (m^2)	2.9
Tail_Taper	0.5

Import the model generated by the geometry module, set the Mach number to 0.8 and the angle of attack to 2 degrees. By running the VSPAERO vortex lattice method, the lift-to-drag ratio of the UAV is calculated to be 14. **Figure 5** illustrates the interface of the aerodynamic module.

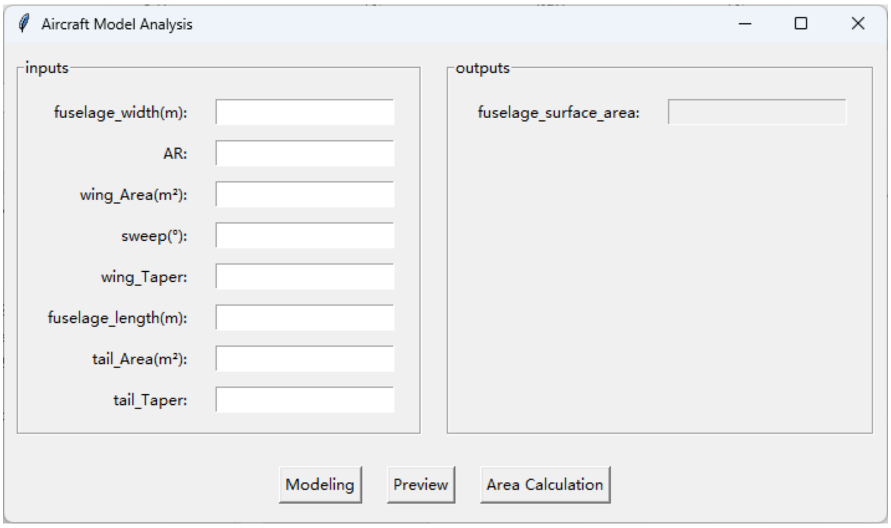

Figure 4. Geometry module interface.

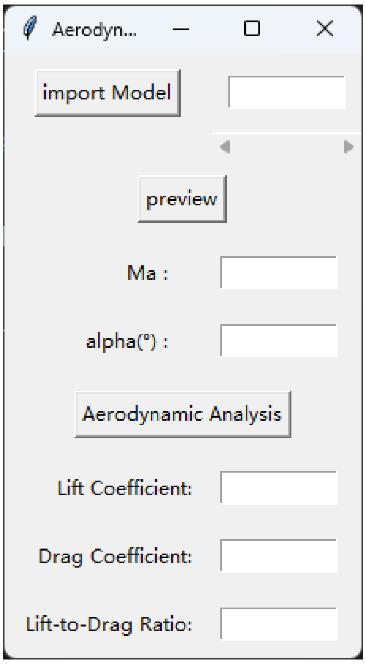

Figure 5. Aerodynamic analysis module interface.

Using the weight analysis program for iterative calculations, **Figure 6** shows the interface of the weight module. The input parameters are listed in **Table 6**. The UAV's maximum takeoff weight is found to be 3812.46 kg, with a fuel weight of 1212.91 kg and a zero-fuel weight of 2599.56 kg. The basic empty weight is 1599.56 kg, structural weight is 640.82 kg, landing gear weight is 171.56 kg, propulsion system weight is 350 kg, system equipment weight is 362.19 kg, and miscellaneous weight is 38.12 kg.

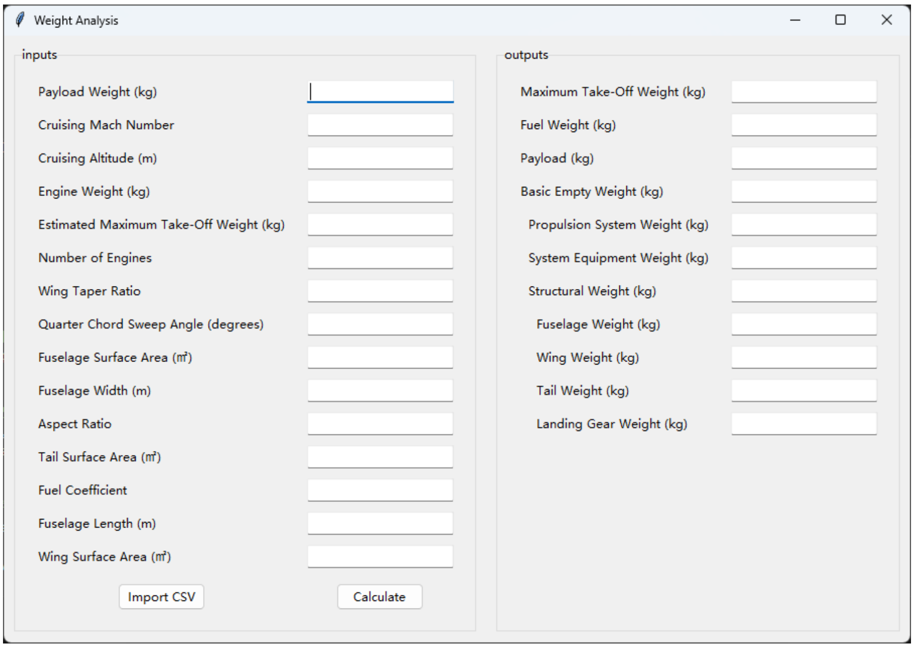

Figure 6. Weight analysis module interface.

Table 6. Inputs of the weight module.

Parameter Name	Value
Payload Weight (kg)	550
Cruising Mach Number	0.8
Cruising Altitude (m)	12000
Engine Weight (kg)	250
Estimated Maximum Takeoff Weight (kg)	3293.7
Number of Engines	1
Wing Taper Ratio	0.4
Quarter Chord Sweep Angle (degrees)	35
Fuselage Surface Area (m^2)	20.42
Fuselage Width (m)	1.14
AR	5
Tail Surface Area (m2)	2.9
Fuel Coefficient	0.43
Fuselage Length (m)	9.16
Wing Surface Area (㎡)	14.57

By using the development cost estimation module, as shown in **Figure 7**, with input parameters listed in **Table 7**, the calculated development cost is 358.51 million CNY.

Figure 8 shows the interface of the optimization module. The design variable ranges are set as shown in **Table 8**.

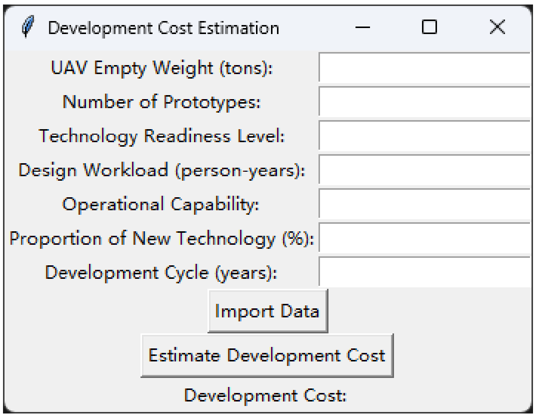

Figure 7. Development cost estimation module interface.

Table 7. Inputs of the cost estimation module.

Parameter Name	Value
UAV Empty Weight (t)	1.57
Number of Prototypes	3
Technology Readiness Level	7
Design Workload (person-years)	250
Operational Capability	38.6
Proportion of New Technology (%)	10
Development Cycle (years)	3

Table 8. Design variable ranges.

Design Variable	Value Range
Aspect Ratio	4 - 10
Fuselage Length (m)	5 - 20
Wing Sweep Angle (˚)	30 - 40
Wing Area (m^2)	10 - 20
Wing Taper Ratio	0.35 - 0.45

In the optimization module, the constraints were set as a lift-to-drag ratio greater than 8 and an empty weight less than 3 tons.

The design variables, constraint values, and objective function values before and after optimization are shown in **Table 9**.

The iterative changes of UAV parameters during the optimization process are shown in **Figure 9-11**. we observe that in the initial phase of the optimization module, various design points are explored, resulting in significant fluctuations in the UAV parameters. As the number of iterations increases, the search range of the optimization module gradually narrows. After reaching the optimal value, several subsequent attempts stabilize at the same value, indicating that the

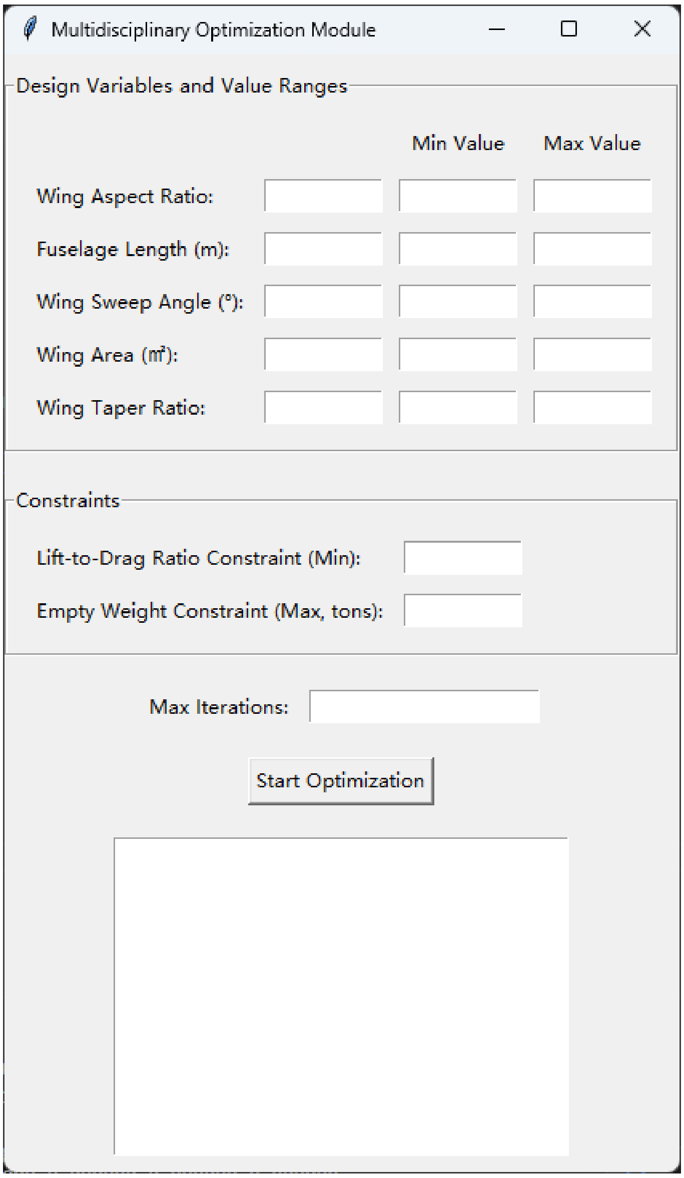

Figure 8. Optimization module interface.

Table 9. Comparison of parameters before and after optimization.

Design Variable	Initial value	Optimal value
Aspect Ratio	5	4
Fuselage Length (m)	9.16	9.41
Wing Sweep Angle (°)	35	34.62
Wing Area (m^2)	14.57	10
Wing Taper Ratio	0.4	0.45
Cost(million CNY)	358.51	245.33
Lift-to-Drag Ratio	12	10.31
Empty Weight(t)	1.57	1.35

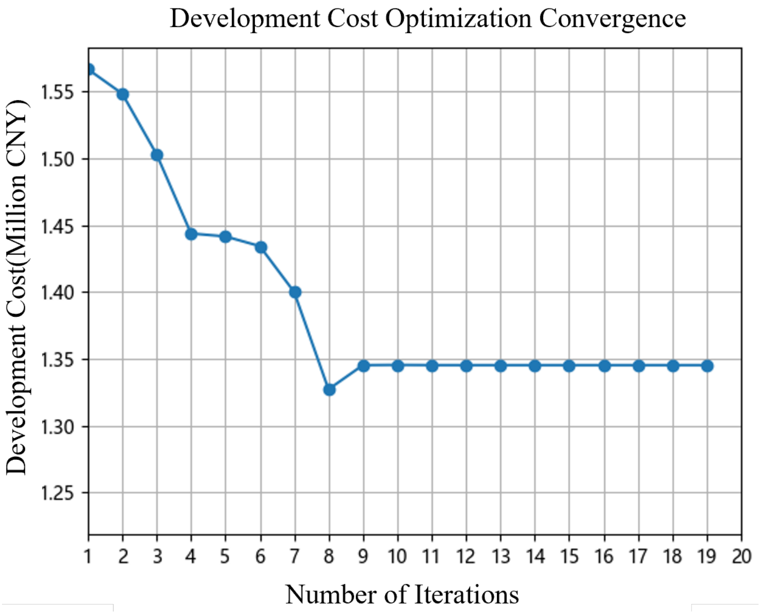

Figure 9. Convergence of development cost optimization iterations.

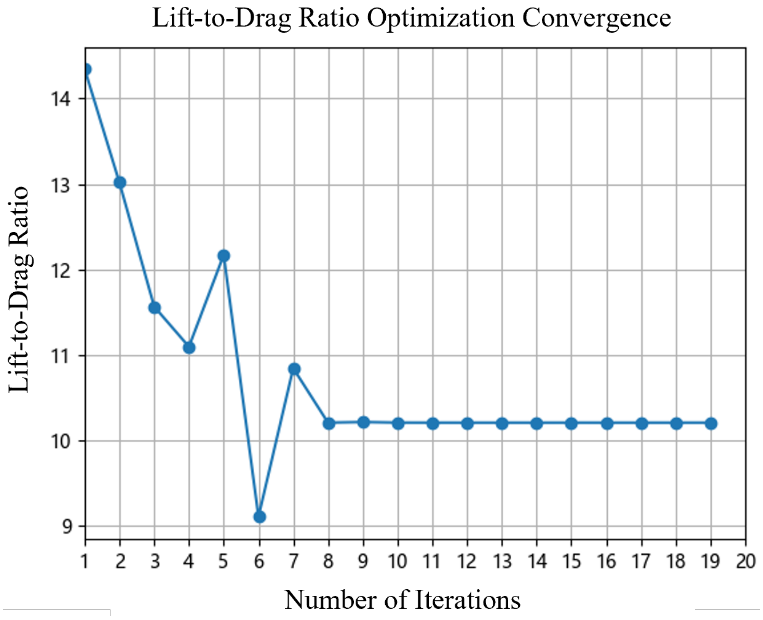

Figure 10. Convergence of Lift-to-Drag Ratio optimization iterations.

iteration has converged and the optimization process has concluded. The optimal value of the objective function has been obtained. The variation trend of UAV air weight and development cost exhibits a high degree of consistency, in accordance with the objective law. However, during the sixth iteration, the lift-drag ratio approaches its constraint lower limit while the development cost is not yet optimal. This indicates that there exists a complex relationship between the lift-drag ratio and development cost; achieving optimal cost does not necessarily entail reducing the lift-drag ratio to its lowest level.

The geometric shapes before and after optimization are shown in **Figure 12**.

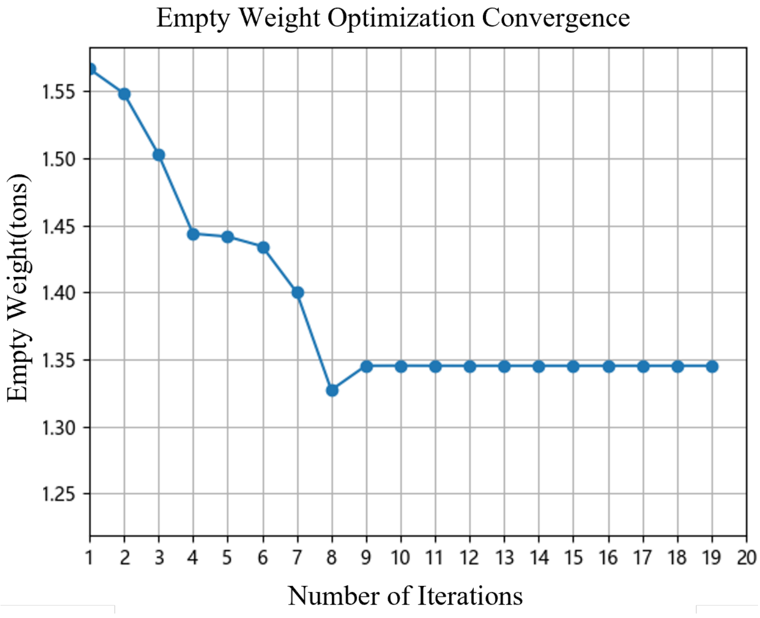

Figure 11. Convergence of empty weight optimization iterations.

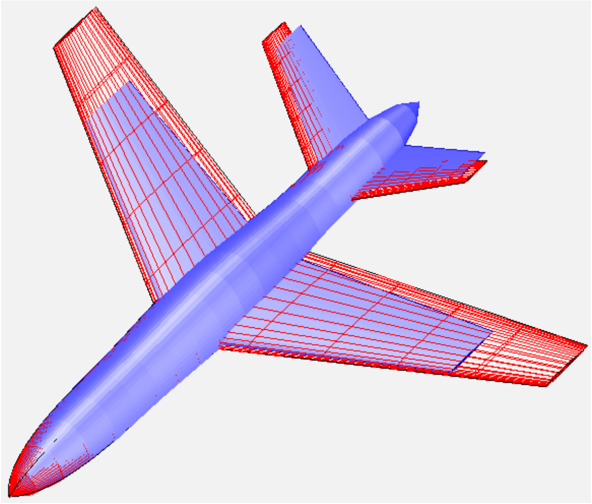

Figure 12. Comparison of geometric shapes before and after optimization.

The red wireframe model represents the UAV's geometric shape before optimization, while the blue solid model represents the geometric shape after optimization. By overlapping them within the same coordinate system in the figure, the changes in the UAV's geometry before and after optimization become more apparent. From the figure, it can be observed that compared to the initial model, the optimized UAV has an increased fuselage length and a reduced wing area.

4.2. Results and Discussion

The optimization results indicate that the development cost of the optimized design is reduced by 31.55% compared to the initial design, while the empty weight is reduced by 0.22 tons, and the lift-to-drag ratio is only reduced by 1.69. This demonstrates effective control over the UAV development cost with minimal aerodynamic performance loss. The reduction in wing area after optimization is the main factor contributing to the decrease in the lift-to-drag ratio. However, the smaller wing area also resulted in a reduction in the UAV's empty weight, which in turn impacted the development cost. On balance, the benefits outweigh the drawbacks. From the optimization iteration chart, it is evident that at the initial stage, the optimizer explored various design points, leading to significant fluctuations in the UAV's development cost. As the number of iterations increased, the objective function gradually stabilized, and the optimization process converged to a value near equilibrium. The objective function reached its minimum value at the 8th iteration, with optimization converging at the 10th iteration.

5. Conclusions

The present study developed a multidisciplinary design and optimization (MDO) framework aimed at minimizing development costs. In this framework, development costs were considered equally important as weight and aerodynamic performance, integrating UAV cost analysis into the design process. The open-source optimization tool OpenMDAO was utilized to implement this framework. A Partial Least Squares (PLS) regression model was established to estimate development costs, which underwent validation to ensure its accuracy met the required standards. Additionally, UAV geometry and aerodynamic analysis modules were developed based on the open-source tool OpenVSP. Furthermore, a user-friendly design optimization program was written in Python to facilitate the entire process, from the initial estimation of UAV parameters to conceptual design optimization. Through a comprehensive case study design process, it was demonstrated that the MDO framework presented in this study effectively controlled development costs by adjusting design parameters during the conceptual design phase while considering constraints such as empty weight and lift-to-drag ratio. This demonstrates the feasibility of incorporating development cost as a significant factor within the overall aircraft design process.

The optimization results of the case demonstrated that controlling development costs led to a reduction in the lift-drag ratio due to decreased wing area, thereby impacting the aerodynamic performance of the UAV. However, these factors were not simply opposing forces; rather, it was crucial to identify an optimal balance point among aerodynamics, weight considerations, and development costs. Additionally, selecting appropriate constraints and optimization ranges for design variables became essential in meeting specific design requirements.

In this paper, the Sequential Least Squares Quadratic Programming (SLSQP) algorithm was used to solve the optimization problem. This algorithm is capable of solving optimization problems with continuously differentiable objective functions in the presence of equality and inequality constraints. However, as the complexity of the multidisciplinary analysis model increased, the optimization speed significantly decreased. In the future, surrogate models can be considered to improve the optimization iteration speed and further refine the UAV design and optimization framework. This paper chose the Partial Least Squares Regression method to establish the development cost estimation model. This method had good predictive performance for small sample problems. However, due to the limited and disorganized data currently available on UAV development costs, better methods can be sought in the future to process the data and establish more accurate predictive models.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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