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Research Article

Research on the Combination Optimization Method of Aircraft Climb Parameters Considering the Influence of Pollution Emissions

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In order to find the optimum climb parameters for decreasing aircraft pollution emissions, we establish a calculation model of aircraft pollutant emissions to thoroughly examine the economy of aircraft operation and its impact on the environment, based on the International Civil Aviation Organization reference emission data and Boeing Method 2 which can calculate pollutant emissions in different flight phases by correcting the ICAO emission data. Firstly, we propose the concept of integrated flight cost considering the effect of emissions and establish its calculation model. Secondly, we establish the climb speed optimization models based on the traditional flight cost and integrated flight cost. Then, we analyze the effect of climb performance on the integrated flight cost. Next, we establish a combined optimization model of indicated airspeed and thrust using the genetic algorithm. The model simulation and result analysis are carried out using a wide-body aircraft. Finally, we analyze the effect of the optimization parameters and the sensitivity of the pollution index. The results show that the decrease in the flight speed and thrust effectively reduces the cost of pollutant emission during flight. The combination of (V_c, T_r) with the smallest integrated flight cost reduces the integrated flight cost by 1.28% and emission cost by 4.56%.

1. Introduction

The emissions of aircraft in flight have a significant impact on the environmental degradation and have an increasing concern for the civil aviation departments. To estimate pollutant emissions, Sherry [1] proposed a method to improve the accuracy of airport emission inventory using disparate data sets at thrust reduction setting, based on the International Civil Aviation Organization's (ICAO) emission model. Wasiuk et al. [2] developed an aircraft performance tool to estimate global and regional commercial aviation fuel burn and emissions. Turgut et al. [3] evaluated NO_X emissions in vertical and horizontal directions during takeoff and climbing. Mitchell et al. [4] assessed the environmental effects of flight under the condition of speed limits during departure. Wei et al. [5] estimated pollutant emissions for civil aircraft during cruising, showing that CO_2 and NO_X are the main pollutants during flight. Han et al. [6] studied the emission characteristics of fine particles during takeoff. The above studies involved only the calculation of the pollutant emissions in flight, without taking into account the differences in the environmental impacts of different pollutants, and the trade-off analysis which considers pollutants and flight efficiency thoroughly.

Optimization of performance parameters effectively reduces the effects of flight on the environment during flight. Chen et al. [7] kept the balance of the relationship between the environmental impact and operating costs to decrease the impact of flight on the environment. Koudis et al. [8] used thrust reduction methods as a means to decrease airport pollutant emissions during takeoff. Schumann et al. [9] established a track optimization method for wake clouds and CO_2 to reduce the impact of flight on the environment by changing the altitude of the flight. Wei et al. [10] introduced the aircraft emission cost into the flight cost model and optimized the parameters during the cruise.

The climb is an important part of performance optimization. Antonakis et al. [11] conducted experiments for optimizing the aircraft climb path using particle swarm optimization, by which the time and fuel consumption will be reduced by 15% and 20%, respectively. Dalmau and Prats [12] evaluated the advantages of continuous climb operation during the cruise phase of flights, which saves fuel and trip time ranging from 0.5% to 2% and 1% to 5%, respectively. Lu and Nan [13] used an adaptive genetic algorithm to optimize the vertical trajectory of the aircraft climb phase taking time and fuel consumption into account. The above-mentioned studies considered only flight time and fuel consumption as optimization targets but not included the effect of flight on the environment. Turgut and Oznur [14] quantified the effect of climb angle on fuel consumption and nitrogen oxide emission which were increased, respectively, by 9–19 and 0.3–0.7 kg per degree of climb angle for the departure climb phase. However, climb parameters, such as speed and thrust, will affect the economy of flight and pollutant emissions as well.

Boeing Method 2 (BM2), also known as "Boeing Fuel Flow Method 2" (BFFM2), was proposed by the Boeing Company to predict the emission indexes in a subsonic cruise condition, without the need to get access to any engine proprietary data. It can be used to calculate emissions indices based on fuel flow and ICAO certification data [15]. On the basis of the ICAO's reference emission data and Boeing method 2 (BM2), the calculation model of pollutant emission cost was established first, and then, the integrated flight cost calculation model that includes emission cost was established. Second, the climb performance optimization method of typical aircraft was established, and the effects of climb speed and thrust on flight cost were analyzed. Third, the optimization model of the combination of indicated airspeed and thrust was established using the genetic algorithm which aimed at minimizing the integrated flight cost. The model simulation and result analysis were carried out based on a wide-body aircraft. Finally, according to the concept of pollutant emission price index, the effect of the integrated flight cost was analyzed.

2. Calculation of the Integrated Flight Cost

2.1. Calculation of Flight Cost. The formula for flight cost includes time cost and fuel cost, which is written as follows [16]:

$$C = C_T + C_F, \tag{1}$$

where C_T is the total time cost (in ￥) and C_F is the total fuel cost (in ￥).

The cost index CI is defined as

$$\mathrm{CI} = \frac{C_t}{C_f}, \tag{2}$$

where C_t is the time cost (in ￥/min) and C_f is the fuel cost per kg.

Substitution of Equation (2) in Equation (1) gives

$$C = C_f \cdot (\mathrm{CI} \cdot t + F), \tag{3}$$

where t is the flight time and F is the fuel consumption (kg).

The aircraft performance parameters and flight cost calculation process during the climb are shown in the following figure. According to the input parameters, including engine parameters, airspeed, engine thrust percentage, aircraft mass, temperature deviation, and altitude integration step, the performance parameters and flight cost in the phase of the climb can be calculated. The flight cost calculation process during the climb is shown in Figure 1.

The traditional flight cost calculation model includes only two factors—time and fuel consumption—and it does not involve the cost of environmental impact induced by pollutant emissions in flight.

2.2. Calculation of Nitrogen Oxide Emissions. The emission of engine pollutants depends on the type of engine, fuel consumption, and emission index. Table 1 presents the basic emission indices at four typical flight stages of a PW4077–2PW061 engine, according to the reference emission model of ICAO.

We can infer from Table 1 that the CO_2 emission index is independent of the flight stage. For NO_X, we use the BM2 method to modify the aircraft emission index using correction and interpolation based on the data in the table [18]. The three steps to correct pollution emission indices are described as follows.

2.2.1. Calculation of Reference Fuel Flow. The data in Table 1 were obtained from the engine test under the conditions of International Standard Atmosphere (ISA), sea level, and different work speeds. Therefore, for a specific flight environment, the actual fuel flow of the aircraft should be converted into the reference fuel flow under the above conditions. The equation is written as

$$W_{\mathrm{ff}} = \frac{W_f}{\delta}\theta^{3.8} e^{0.2M^2}, \tag{4}$$

where W_{ff} is the corrected fuel flow in ISA at sea level (kg/h), W_f is the actual fuel flow (kg/h), δ is the ratio of static atmospheric pressure to atmospheric pressure at sea level, θ is the ratio of static temperature to air temperature at sea level, and M is the aircraft flight Mach number.

2.2.2. Calculation of the Reference Emission Index. From Table 1, we understand that atmospheric and flight conditions affect the fuel flow, and hence, the reference emission index is calculated by interpolating the reference fuel flow obtained from Equation (4).

2.2.3. Calculation of Actual Emission Index. The value of the NO_X emission index is also affected by flight altitude, aircraft speed, atmospheric temperature, and humidity. For the specific flight environment, the reference emission index

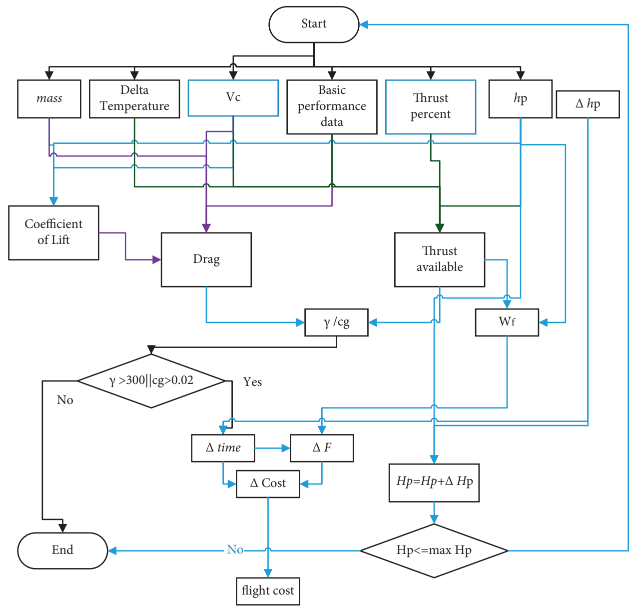

Figure 1: Flow chart of flight cost calculation in the climb.

Table 1: Basic emission indices of a PW4077–2PW061 engine.

Mode	Power setting (%F)	Time (min)	Fuel flow (kg/h)	CO_2 index (kg/kg) [17]	NO_X index (kg/kg)
Takeoff	100	0.7	10868.4	3.155	0.0398
Climb out	85	2.2	8827.2	3.155	0.0325
Approach	30	4.0	2937.6	3.155	0.0113
Idle	7	26.0	835.2	3.155	0.0042

should be converted into the actual emission index according to the following equation [15]:

$$E_{I,N} = E_{\mathrm{RI}} \frac{\delta^{0.51}}{\theta^{1.65}} \exp\left[19.0\left(0.0063 - \frac{0.622\Phi P_v}{P - \Phi P_v}\right)\right], \quad (5)$$

where $E_{I,N}$ is the actual emission index of NO_X (kg/kg), Φ is the atmospheric relative humidity, P is the local static pressure at a given altitude (Pa), and P_v is saturated vapor pressure (Pa). Then, the emissions of NO_X can be calculated from the following equation:

$$S_{NO_X} = E_{I,N} \cdot F, \quad (6)$$

where S_{NO_X} is the emissions of NO_X (kg).

The total emission cost C_p is defined, on the basis of traditional flight cost, as

$$C_p = C_{CO_2} \cdot S_{CO_2} + C_{NO_X} \cdot S_{NO_X}, \quad (7)$$

where C_p is the total emission cost (¥/kg), C_{NO_X} is the emission cost of NO_X per unit mass (¥/kg), and C_{CO_2} is the emission cost of CO_2 per kilogram (¥/kg).

2.3. Calculation of the Integrated Flight Cost Considering the Influence of Emissions. To measure the impact of aircraft emissions on the external environment, the emission factors were included in the flight cost to obtain the integrated flight cost.

$$C' = C_T + C_F + C_p. \quad (8)$$

The pollutant emission price indices, including CO_2 price index PI_{CO_2} and NO_X price index PI_{NO_X}, which indicate the ratio of CO_2 price and NO_X price to fuel price, respectively, are defined as

$$PI_{CO_2} = \frac{C_{CO_2}}{C_f}, \quad (9)$$

$$PI_{NO_X} = \frac{C_{NO_X}}{C_f}. \quad (10)$$

Substitution of the above equations in Equation (9) gives

$$C' = C_f\left(\mathrm{CI} \cdot t + F + PI_{CO_2} \cdot S_{CO_2} + PI_{NO_X} \cdot S_{NO_X}\right). \quad (11)$$

Based on the Intergovernmental Panel on Climate Change's estimation of emission index and its impact, EUROCONTROL's cost-benefit analyses provided an international overview of aircraft emission shadow prices [19], as shown in Table 2.

3. Effect of Climb Performance on the Integrated Flight Cost

3.1. Effect of Climb Speed. Figure 2 shows the results of flight costs, emission costs, and integrated flight costs at different airspeeds, taking a certain aircraft as an example. The cost

Table 2: Overview of emission costs of different pollutants (¥).

Pollutants	Medium	Low	High
CO_2 (per ton)	274.0	91.4	456.3
NO_X (per kg)	33.3	11.6	55.0

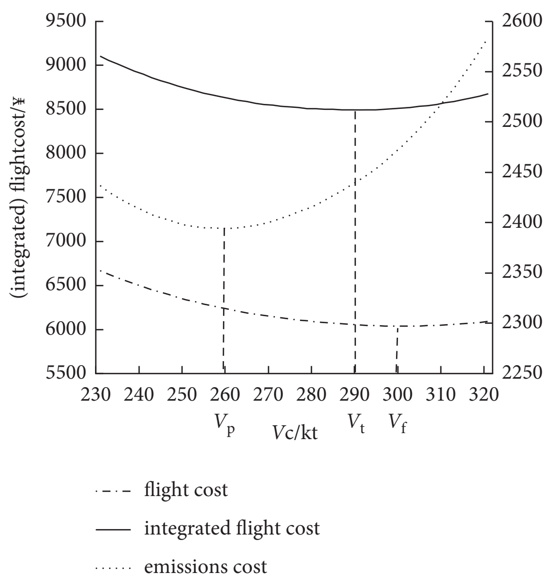

Figure 2: Variation of cost with V_c.

index was set to 30, for the same aircraft and engine type as a reference. Other calculation conditions are as follows: the climb altitude ranges from 10,000 to 25,000 ft, the fuel price is 6000 ¥/t, the initial climb weight is 200,000 kg, the ambient temperature is 0°C, $PI_{CO_2} = 0.094$, $PI_{NO_X} = 16.46$, and the climbing strategy is constant. Under such conditions, the airspeed climbs at a speed range from 200 to 350 kt.

From Figure 2, the optimum speeds at different cost indicators are as follows: the optimum speeds of the flight cost V_f are higher than the optimum speeds of the integrated flight cost V_t which is higher than the optimum speeds of emission cost V_p. When the speed is lower, the corresponding fuel flow and the emission index of NO_X are smaller. Consequently, the emissions and emission cost of NO_X are also lesser. Climbing at a higher speed also indicates that airspeed takes less time, so the flight cost becomes lesser.

3.2. Effect of Climb Thrust. Table 1 demonstrates that thrust has a significant effect on the emission index of NO_X, and hence, it should be taken into account when analyzing the emission cost of pollutants. The flight cost and pollutant emission cost under different thrust conditions were calculated and analyzed, and the results are shown in Figure 3.

The specific conditions used to calculate the flight cost are as follows: the climb speed is 280 kt; the value of the ratio of actual thrust to rated maximum climb thrust (T_r) ranges from 75 to 100%; the climb altitude is 10,000–25,000 ft.

Figure 3 indicates that the flight cost and integrated flight cost decrease with increasing T_r, whereas the emission cost changes in the opposite way. The fuel flow and the emissions of NO_X are in accordance with thrust. Hence, we conclude that when the thrust is lower, the emission cost is lesser. Furthermore, at this moment, the longer the flight time is, the higher the flight cost becomes.

4. Combination Optimization of Airspeed and Thrust

4.1. Combination Optimization Model. From the above analysis in Section 2, considering the effect of climb speed and thrust on flight cost, we optimize the performance parameters using the genetic algorithm, obtaining the combination of climb speed and thrust (V_c, T_r) with the minimum integrated flight cost.

The actual flight needs to fulfill certain requirements for speed and thrust. The conditions for control variables were set according to the basic performance parameters and actual operation requirements of the aircraft.

$$\begin{aligned} 200 \le V_c \le 350, \\ 0.75 \le T_r \le 1. \end{aligned} \tag{12}$$

The control variables (V_c, T_r) were encoded by the float-point coding method. The length of each control variable was 1.

The fitness function was derived from the following equation:

$$f = C_f\left(\mathrm{CI} \cdot t + F + \mathrm{PI}_{CO_2} \cdot S_{CO_2} + \mathrm{PI}_{NO_X} \cdot S_{NO_X}\right). \tag{13}$$

The roulette method was used to select parents for individuals that meet the above constraints, and the probability of selection was 0.5. The probability of parents to cross and mutate was 0.6 and 0.05, respectively.

4.2. Realization Flowchart Based on the Genetic Algorithm. The integrated cost under the given temperature deviation, aircraft quality, fuel price, cost index, and emission index was calculated. To obtain the minimum integrated cost, the genetic algorithm was used to optimize the combination of (V_c, T_r). Figure 4 shows the specific optimization process.

First, the given calculation conditions were introduced. The control variables (V_c, T_r) were then coded, and the population was initialized. Second, the fitness function was calculated by calling the integrated cost calculation model. The pollutant emissions can be obtained based on the calculation formulas and models used in this study. The flight cost, emission cost, and integrated flight cost were obtained, as well as thus the fitness value. Third, after selection, crossover, and mutation, the population was updated. Furthermore, the current algebra was evaluated. Finally, by repeating the second and third steps until reaching the setting algebra, the combination of minimum fitness value (V_c, T_r), which was also the best optimization result, can be obtained.

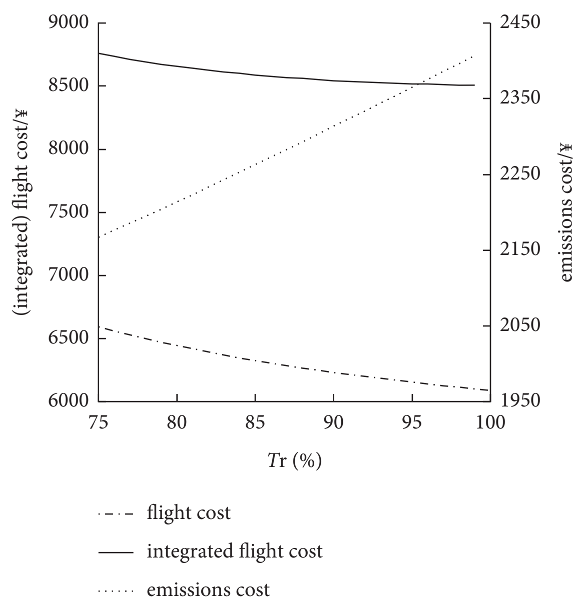

Figure 3: Variation of cost with T_r.

4.3. Analysis of Optimization Results. The optimization method was simulated for a wide-body aircraft as an example. The calculation conditions are as follows: the temperature deviation is ISA + 0°C; the initial weight of the aircraft is 200,000 kg; the fuel price is 6000 ¥/*t*; the cost index is 30; $PI_{CO_2} = 0.094$; $PI_{NO_X} = 16.46$; the climb altitude is 10,000–25,000 ft; V_c ranges from 200 to 350; T_r ranges from 75% to 100%. Figure 5 shows the variation of the fitness function value with the algebra, using the genetic algorithm optimization. It illustrates that the optimal fitness is 10,850 ¥, and the function values begin to converge around the 150th generation. The final optimized (V_c, T_r) combination is (278, 86).

The combinations of the lowest integrated flight cost (V_c, T_r) and the lowest flight cost (V_c, T_r) are (278, 86) and (300, 100), respectively. Table 3 compares the climbing parameters in the above two methods.

Table 3 shows that the combination of the lowest integrated flight cost (V_c, T_r) reduces the emission cost by 4.56% and the integrated flight cost by 1.28%. Although the fuel increases, the emission cost decreases more, and thus, the total cost or the integrated flight cost decreases.

4.4. Influencing Factors of Optimization Parameters. When the price of pollutants is constant, the initial climb weight, temperature deviation, and cost index are the main influencing factors of the optimization parameters.

The typical calculation conditions are as follows: the ambient temperature is ISA + 0°C; the climb weight is 200,000 kg; the fuel price is 6000 ¥/*t*; the cost index is 30; $PI_{CO_2} = 0.094$; $PI_{NO_X} = 16.46$, the climb height is 10,000–25,000 ft; V_c ranges from 200 to 350 kt; T_r ranges from 75% to 100%.

Figure 6 shows the effect of the initial climb weight on the optimization parameters, i.e., V_c and T_r. The climb weight ranges from 200,000 to 230,000 kg. Other calculations are the same as typical calculation conditions.

Figure 6 illustrates the optimum speed and the optimum thrust as a function of flight weight. It is clearly shown that an increase in aircraft weight increases the optimum speed and the optimum thrust for minimal integrated flight cost and flight cost. This is because when the speed and thrust are constant, the flight cost and emission cost increase with the weight. By increasing the speed and thrust, the flight cost can be reduced.

Figure 7 shows the effect of external temperature deviation on the optimization parameters. The temperature deviation ranges from −10°C to 30°C, and other calculation conditions are the same as typical calculation conditions.

As shown in Figure 7, the optimum speed and thrust decrease with the increase of temperature only accounting for flight cost. While when considering the integrated flight cost, the optimum speed and thrust decrease proportionally at lower temperatures, with the temperature ranging from −10°C to 20°C, but begin to increase at higher temperatures. The emission of NO_X increases with increasing temperature. Lower airspeed and thrust lead to lower emission cost and integrated flight cost. As the temperature reaches 30°C, under the same conditions, the fuel cost increases sharply. Therefore, high airspeed and thrust are very important to reduce flight cost.

Figure 8 shows the effect of cost index CI on optimization parameters. CI ranges from 0 to 100, and other calculation conditions are the same as typical calculation conditions.

As shown in Figure 8, for minimal integrated flight cost and flight cost, the optimal thrust and airspeed increase with increasing CI. Since the proportion of time cost to the integrated flight cost increases with increasing CI, increasing the airspeed and thrust to reduce the integrated flight cost is very important.

4.5. Impact Analysis of Pollutant Emission Price Index. With the rapid growth of civil aviation transportation, the impact of aircraft emissions on the environment has drawn increasing attention from all walks of life, and the emission price of pollutants has gradually increased. Therefore, it is imperative to analyze the effect of the pollutant emission price index on the optimization parameters. Since the emission index of CO_2 is constant and the influencing factors are the same as fuel consumption, it is not analyzed in detail in this work.

With other calculation conditions unchanged, the combination of V_c and T_r related to the minimum integrated flight cost under different NO_X emission prices was calculated, and the results are shown in Figure 9.

It can be seen from Figure 9 that, for minimal integrated flight cost, the optimal V_c and T_r decrease with increasing PI_{NO_X} and finally decrease slowly. But the flight cost is not affected by PI_{NO_X}. With the increase in PI_{NO_X}, the NO_X cost per kilogram increases, and hence, the emission cost also increases accordingly. By reducing the thrust and speed, the fuel flow and NO_X emission can be reduced, which in turn reduces the emission cost.

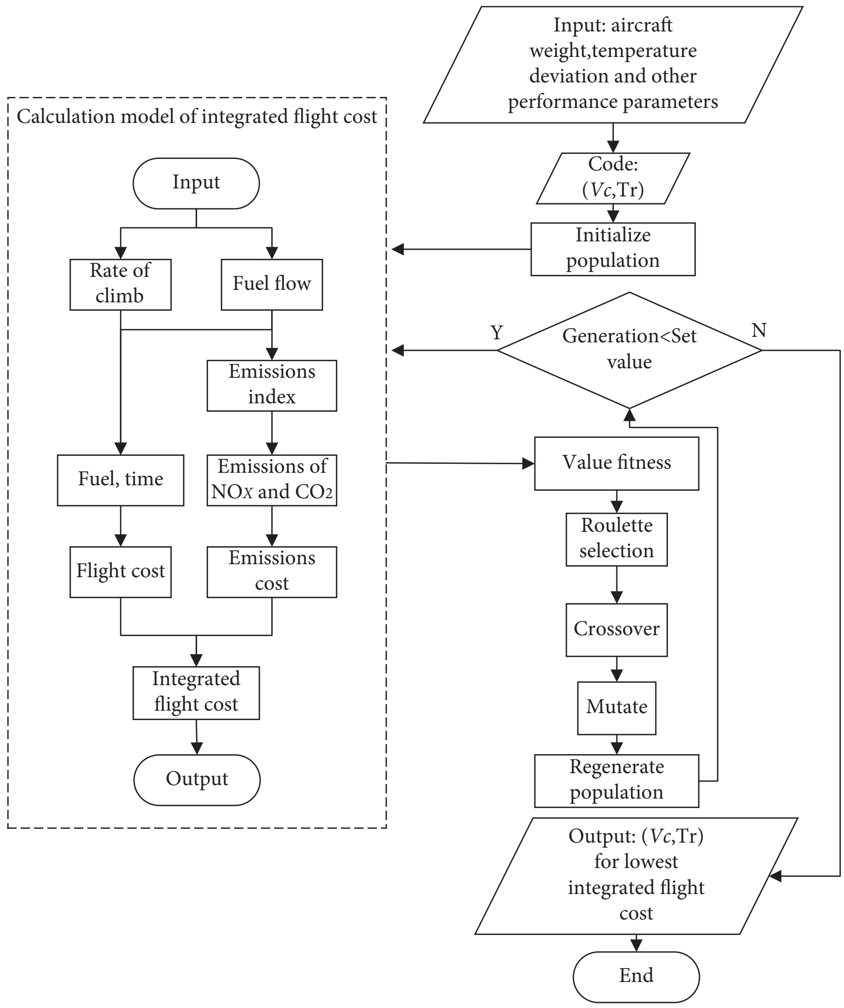

Figure 4: Flowchart of optimization calculation of comprehensive cost based on the genetic algorithm.

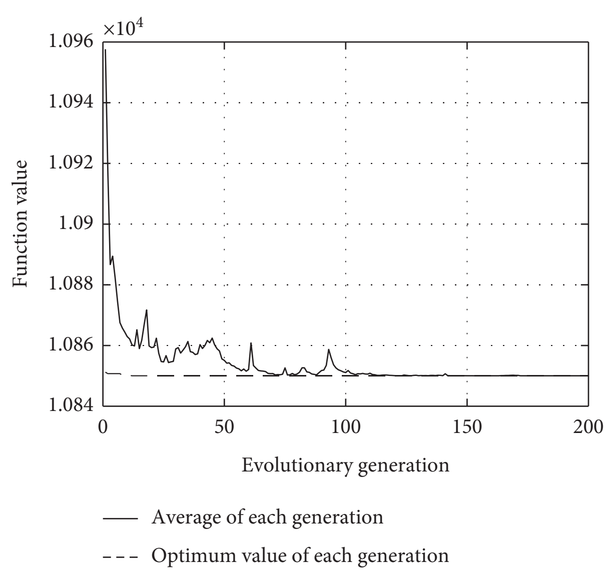

Figure 5: Variation of the fitness function with the algorithm.

Table 3: Comparison of climbing parameters.

Value of combination parameters	Integrated flight cost (¥)	Flight cost (¥)	Emission cost (¥)	Fuel (kg)
(278, 86)	10850	6124	4726	903
(300, 100)	10991	6039	4952	879
Deviation ratio (%)	−1.28	1.40	−4.56	2.73

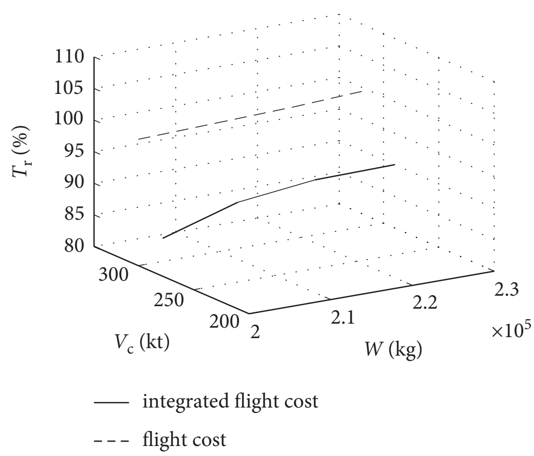

Figure 6: Effect of flight weight on optimization parameters.

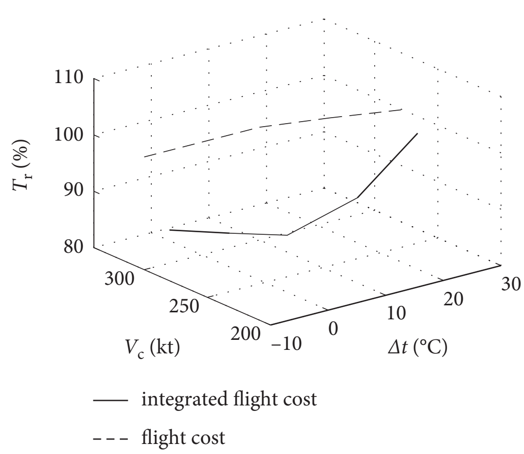

Figure 7: Effect of temperature on optimization parameters.

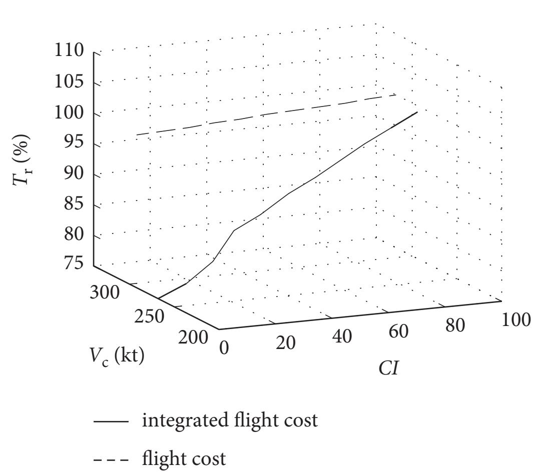

Figure 8: Effect of CI on optimization parameters.

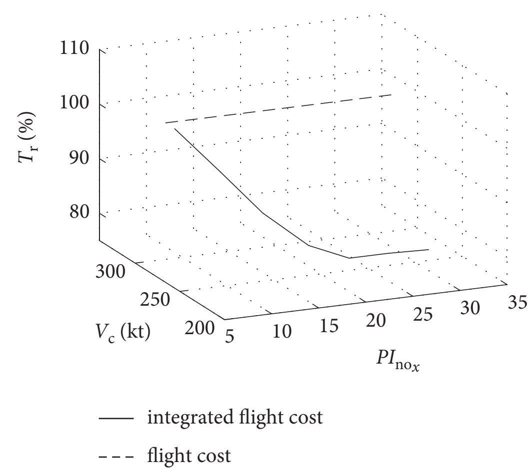

Figure 9: Effect of PI_{NO_X} on optimization parameters.

5. Conclusions

In this study, we established an airspeed–thrust combination optimization model based on the integrated flight cost, according to the ICAO reference emission data and BM2 method. In addition, the concept of emission price index was proposed. The model was evaluated and simulated using a typical aircraft type. We conclude the following:

(1) The combination optimization model of climb parameters based on the integrated flight cost is more scientific and reasonable than the traditional economic climb model. The optimal combination (V_c, T_r) with the minimum integrated flight cost reduces the integrated flight cost by 1.28% and the emission cost by 4.56%.

(2) The climb parameters of aircraft have a significant impact on pollutant emissions. The optimal combinations of (V_c, T_r) are different for considering the integrated flight cost and only considering the flight cost.

(3) The optimal combination (V_c, T_r) with the minimum integrated flight cost is affected by some parameters including weight, temperature, CI, and PI_{NOX}. For minimal integrated flight cost, an increase in aircraft weight increases the optimum speed and the optimum thrust; the optimum speed and thrust decrease proportionally at lower temperatures, with the temperature ranging from −10°C to 20°C, but begin to increase at higher temperatures; the optimal thrust and airspeed increase with increasing CI but decrease with increasing PI_{NO_X}.

Data Availability

The results data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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