An Analytical Method for the Trade-off Between Comfort and Economy of Aircraft based on the Weight of Fuselage Structure

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Abstract. Both comfort and economy need to be considered in aircraft design, and fuselage structural weight, as one of the key design parameters, has a significant impact on both. The aim of this study is to explore an analysis method based on fuselage structural weight to balance comfort and economy, and to provide guidance for optimising aircraft design. Through literature study and methodological research, this paper proposes a systematic analysis framework covering the definition of comfort indicators, analysis of economy-related indicators, and analysis of the overall trade-off of indicators. Finally, by analysing the impact of different comfort indicators on weight, and thus on aircraft economy, the trade-offs between comfort and economy indicators are discussed, and a methodology for trade-offs in the design of future aircraft indicators is proposed.

Keywords: comfort of aircraft, weight of fuselage, DOC, economy of aircraft

1 Introduction

Comfort and economy in aircraft design have always been important aspects to consider in design. With the continuous development of the aviation industry and the advancement of technology, passengers are demanding more and more comfort, while airlines need to reduce operating costs to remain competitive. Against this background, how to achieve economy while ensuring comfort has become a top priority in civil aircraft design. However, how to make a trade-off between the two requires relevant methodological research.

Different parameters are often chosen as benchmarks for the comprehensive evaluation of aircraft characteristics, for example, The direct operating cost (DOC) is chosen as the evaluation criterion in Markus Kaufmann' work[1]. DOC has been used for the evaluation of a design solution in terms of cost and weight, which captures all costs that arise when the aircraft is own. It takes into account manufacturing cost, non-destructive testing cost and the lifetime fuel consumption based on the weight of the aircraft.

In the trade-off evaluation of comfort and economy indicators, although the improvement of comfort can improve passenger satisfaction and thus indirectly improve the economic efficiency of airlines, it is difficult to link comfort directly to DOC, while

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structural weight, as a key factor affecting aircraft performance and fuel efficiency, is directly related to comfort and economy. Weight can be used as a link to connect all the parameters together, which is why aircraft manufacturers are placing great emphasis on weight management in their aircraft[2]. Therefore, in this paper, weight is chosen as the dependent variable, and the cost of structural weight brought by comfort improvement and the impact on economy are discussed in depth, while a set of index evaluation system is constructed specifically for comfort and economy, and the method of comfort and economy trade-off analysis is explored to find the best design solution.

2 Comfort and Economy trade-off Methodology

In this study, we constructed a set of analysis methods for the comprehensive assessment of comfort and economy. Firstly, we screened the comfort indicators related to the air-frame design as a characterization of the comfort of the aircraft, and analyzed the impact of the changes in these indicators on the weight of the fuselage structure one by one. Secondly, we will define the correlation between weight and economic metrics, thus correlating comfort metrics and economic metrics through weight. Finally, we will develop a system of metrics evaluation, including a comprehensive evaluation of fuel efficiency and operational profitability analysis, as shown in Figure 1, to give the final trade-off optimization of the aircraft design.

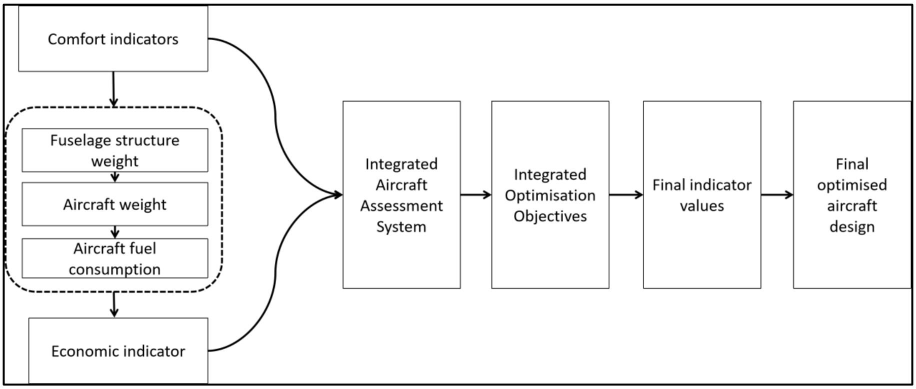


Fig. 1. Flowchart for trade-off analysis.

3 Screening of Aircraft Comfort Indicators

3.1 Analysis of Cabin Comfort Elements

With the popularity of air travel, passengers' demand for flight comfort is getting higher and higher. Flight comfort is not only related to passengers' flight experience, but also affects the airlines' advantage in competition. Bouwens’s work has presented an airplane cabin environment wheel, where the aircraft comfort metrics are categorize and the factors influencing them are given under each category[3]. By drawing on his work,in this paper the main elements of aircraft comfort are sorted out in the following parts:

- Cabin space: including cabin width, seat width, seat pitch, etc., which directly affects the passenger's range of motion and comfort.
- Internal noise level: including the average decibel value of noise in the cockpit, peak noise, noise duration, etc. Excessive noise level will affect passengers' auditory comfort quality.
- In-cabin pressure level: including the maximum cockpit pressure level, the rate of change of cockpit pressure, which directly affects passengers' breathing and physical health.
- Air quality: including air freshness, temperature uniformity level, air humidity, etc., which has an important impact on passenger comfort.
- Cabin service quality: including entertainment facilities, catering services, cleaning services, etc., all of which affect the overall flight experience of passengers.

3.2 Construct a Hierarchical Model

Based on the above analyses, we take the corresponding design factors as specific evaluation indicators, and from this, we establish a structural hierarchical model as shown in Fig. 2.

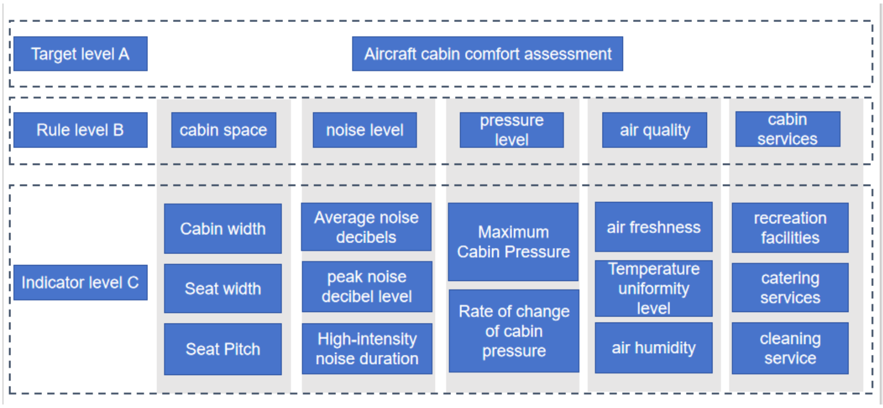


Fig. 2. Structural hierarchical model.

3.3 Calculate the Individual Weights of the Evaluation Factors Using the AHP Method

Based on Fig. 1, the evaluation system is constructed using the AHP method[4-5], with 5 evaluation factors at the criterion level and 14 evaluation factors at the sub-criterion level. The scale method is used as the standard of comparison, and two-by-two comparisons are made.

We can construct a judgement matrix C based on the parameter c_{ij},which means the importance of factor i relative to factor j:

$$C = \begin{bmatrix} c_{11} & c_{21} & \cdots & c_{1j} & \cdots & c_{1n} \\ c_{21} & c_{22} & \cdots & c_{2j} & \cdots & c_{2n} \\ \vdots & \vdots & \vdots\ \vdots & & \vdots & \vdots \\ c_{i1} & c_{i2} & \cdots & c_{ij} & \cdots & c_{in} \\ \vdots & \vdots & \vdots\ \vdots & & \vdots & \vdots \\ c_{n1} & c_{n2} & \cdots & c_{nj} & \cdots & c_{nn} \end{bmatrix} \tag{1}$$

The relative importance of two elements is taken between 1 to 9 on a 9-level scale (as shown in Table 1), which has the following characteristics: when i = j, $c_{ij} = c_{ji}$; when i ≠ j, $c_{ij} = 1/c_{ji}$.

Table 1. Values of relative importance of factors

Relative importance	**Value**
Extremely unimportant	1
Very unimportant.	2
Not important.	3
Slightly unimportant	4
Same importance	5
Slightly important	6
Important	7
Very important.	8
Extremely important	9

Take the largest eigenroot of the matrix C to be λ_{max} , and set the weight vector of the factors

$\mathbf{W}=(\omega_1, \omega_2, \omega_3, \ldots, \omega_n)^T$, then we have

$$C \times W = \lambda_{max} \times W \tag{2}$$

Using canonical column averaging, the elements of **C** are normalized by columns with the following method:

$$\overline{c_{ij}} = c_{ij} / \sum_{k=1}^{n} c_{kj} \tag{3}$$

we obtain the matrix $\overline{\boldsymbol{C}}=\overline{[c_{ij}]}$.

The average of the sum of the rows of C is $1/n\left(\sum_{j=1}^{n} \overline{c_{ij}}\right)$,then we have:

$$\omega_i = 1/n\left(\sum_{j=1}^{n} \overline{c_{ij}}\right) \tag{4}$$

In this way we obtain the vector of weights for each factor:

$$W=(\omega_1, \omega_2, \omega_3, \ldots, \omega_n)^T \tag{5}$$

3.4 Simplify Processes and Models

In order to ensure the reasonableness as well as the realisability of the methodological study, the above comfort indicators were screened, and the specific principles of indicator screening are as follows:

- Influence on passenger comfort: select the indicators that have the greatest influence on passenger comfort.
- Measurability: Select indicators that can be measured accurately, and at the same time, the indicators can be quickly evaluated and weight cost calculated by software, so as to facilitate comparative analysis.
- Data availability: Select data sources that are easily accessible and reliable to ensure the accuracy of the analysis.

Based on the above selection principles, in order to simplify the calculation and validate the overall process, the main indicators of comfort of civil aircraft are selected as three: fuselage width, noise and cockpit pressure.

- Fuselage width: Fuselage width affects the passenger's sense of space and seat comfort. A wider fuselage provides more headroom and seat pitch, enhancing passenger comfort.
- Internal Noise Level: Interior noise levels have a significant impact on passenger auditory comfort and quality of rest. Lower noise levels help to improve the passenger's flying experience.
- Cabin Pressure Levels: Cabin pressure levels affect passenger breathing, physical health and comfort. Appropriate cabin pressure reduces the physiological effects of flying at altitude on passengers and improves comfort.

The other indicator parameters can be gradually introduced later to further improve the trade-off analysis process.

4 Analysis of the Relationship between Aircraft Comfort Indicators and Fuselage Structure Weight

Based on the determination of the above aircraft comfort indicators, this paper carries out an analysis of the influence of these comfort indicators on the weight of the fuselage structure, so as to construct the relationship between the comfort indicators and the weight of the fuselage structure.

4.1 Relationship between Fuselage Width and Fuselage Structure Weight

Fuselage width is the distance inside the cabin of an aircraft in the lateral direction. A wider fuselage provides more headroom and seat pitch, enhancing passenger comfort. A wider fuselage requires more material, and a wider fuselage structure may require more complex design and reinforcement, such as an elliptical fuselage, all of which directly increase the structural weight of the fuselage.

As we all know that the fuselage structure weight is one of the most important parts for the aircraft take-off weight, and it is also a key factor which can reflect the aircraft structure advanced level, which affects directly the maximum take-off weight (MTOW). A lot of study has been made on fuselage structures' weight estimation.

Weight estimation methods for fuselage structures are generally empirical formula, semi-empirical formula and finite element analysis. In the aircraft conceptual design stage, if the input parameters are limited and the iteration time is required, the evaluation can be carried out by the first two methods, and if a detailed design plan is available, a detailed finite element model of the fuselage structure can be constructed for weight evaluation.

There are many different methods for estimating the weight of fuselage structures in conventional configurations, with different emphasis on the estimation process, so the average value is taken on the results of the multiple methods. The weight estimation methods for conventional configuration fuselage structure are given in the aircraft design manuals and other aircraft general design materials [6-12], and the weight estimation equations for the fuselage structure given by Professor Niu Chunyun [11] are as follows:

$$W_F = k_1 k_2 \times \{2446.4\left[0.5\left(W_{MTO} + W_L\right)\right]^{0.3} \times \left(1 + \frac{1.5\Delta p}{4}\right)^{0.5 S_g^{0.325}} \times \left[\left(H_F + B_F\right)\right]^{0.5 L^{0.6}} \times 10^{-4} - 678\} \tag{6}$$

L:overall fuselage length ft

W_{MTO} :Designed maximum take-off weight lb

W_L :Design landing weight lb

H_F :Maximum height of fuselage section ft

B_F :Maximum width of fuselage section, ft

Δp :design cabin differential pressure,lbf/(in^2)

S_g :Total fuselage wetted area, which excludes the area where the fuselage meets the wings and tail ft^2

k_1 :The value is taken as 1.05 when the main landing gear is mounted on the fuselage and 1.0 when the main landing gear is mounted on the wing

k_2 :1.1 for engine on fuselage and 1.0 for engine on wing.

Torenbeek[9]proposed the following equation for estimating the weight of the fuselage structure:

$$W_F = C_{shell} d_{fus}^2 \times \left(L_{fus} + L_{ref}\right) + \Omega_{fl}\, \mathrm{n}_{ult}^{0.5} \mathrm{d}_{fus} \mathrm{l}_{fus} \tag{7}$$

In the formula:

Reference length: $L_{ref} = 1.5m(5\,\mathrm{ft})$

Equivalent diameter: $\mathrm{d}_{fus} = 0.5\left(W_{fus} + h_{fus}\right)$

Fuselage correction factor for single deck cabins: $C_{shell} = 60N/m^3(0.38\,\mathrm{lbf/\,ft^3})$

Attachment device parameters: $\Omega_{fl} = 160N/m^2(3.3\,\mathrm{lbf/\,ft^2})$

It is also possible to introduce pressure-bearing and bending coefficients based on the coefficient method studied by Desktop Aeronautics, Inc [10], which is calculated as follows:

$$\mathrm{I}_p = 1.5\mathrm{E}\left(-3\right)*\mathrm{P}*\mathrm{B} \tag{8}$$

$$\mathrm{I}_b = 1.91\mathrm{E}\left(-4\right)\mathrm{N}*\mathrm{W}*\mathrm{L}/\mathrm{H}^2 \tag{9}$$

In the formula:
P: the maximum internal and external pressure difference, lb/ft^2
B: the fuselage width, ft
H: the height of the fuselage, ft
L: the fuselage length, ft
N: the overload coefficient at maximum zero oil weight.
W: the maximum zero oil weight minus the loaded weight on the wing.

4.2 Relationship between Internal Noise Level and Weight of Air-Frame Structure

Internal noise level is the intensity of noise in the cabin of an aircraft during flight, and lower noise levels help to improve the flight experience for passengers.

Noise reduction measures (e.g., use of soundproofing materials, specially designed panels, etc.) may increase the weight of the fuselage. In this paper, based on the experience accumulated in the calculation of the previous project, all the weight added by noise reduction is converted into the thickening of the fuselage structural wall panels, so as to construct a calculation model of the relationship between the internal noise level and the weight of the fuselage structure, as shown in the Fig 3 below.

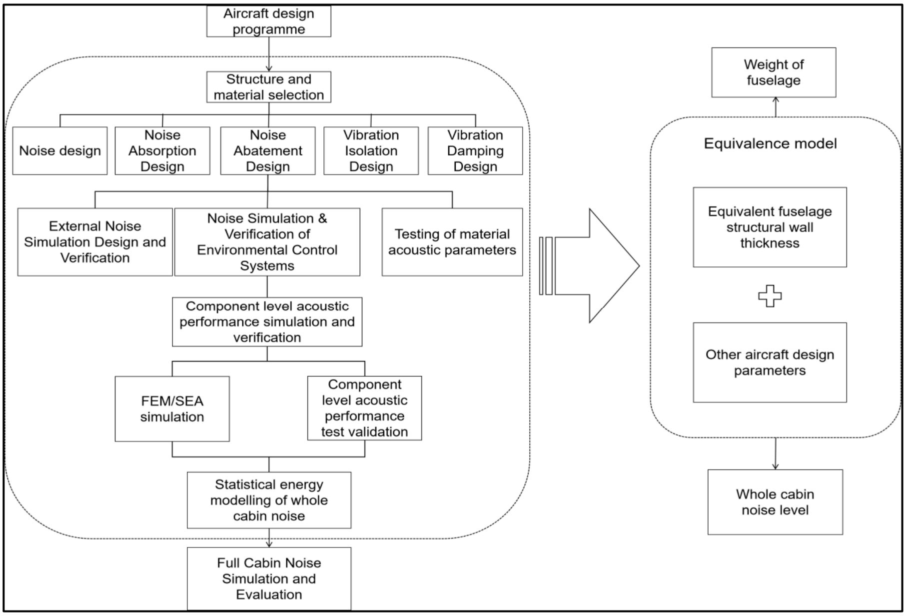


Fig. 3. Flowchart for equivalent fuselage weight estimation model based on cabin noise level.

4.3 Relationship between Cabin Pressure Level and Weight of Fuselage Structure

Cabin pressure level refers to the intensity of air pressure in the cabin of an aircraft during flight.

Appropriate cabin pressure levels reduce the physiological effects of high-altitude flight on passengers and improve comfort.

The physiologically optimal cabin pressure environment should be maintained as close as possible to the ambient conditions of one atmosphere at sea level. However, due to engineering constraints, in particular, the greater the pressure difference between inside and outside the cockpit, the greater the damage to the aircraft and occupants in the event of structural damage. Therefore, the cockpit must be designed according to the physiological requirements of the human body. Cockpit pressure environment physiological requirements mainly consider two aspects: one is to determine a reasonable pressure value, to reduce the impact of high-altitude hypoxia on the human body, followed by the prevention of high-altitude decompression sickness. The second is to control the rate of change of pressure, to avoid physiological damage caused by sudden changes in air pressure. Such as pneumatic lung damage and ear pressure damage.Cockpit pressure height limit is determined by human physiological requirements, cockpit pressure height of 2 438m (8 000ft) is to make people more comfortable pressure environment; cockpit pressure height of 4 572m (15 000ft) is a person can withstand the limit of external pressure, beyond the limit (for a certain period of time), people's respiratory difficulties, will lead to danger.

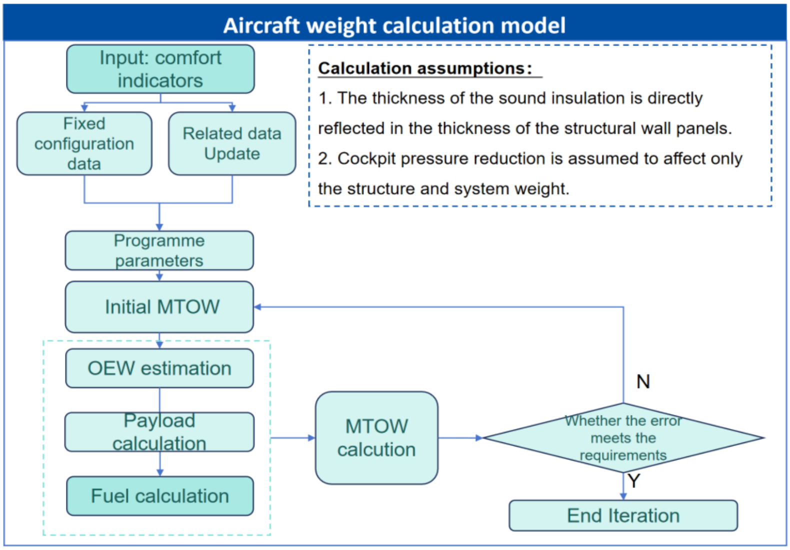
Airworthiness regulations require that the pressurised cockpit pressure altitude should not exceed 2438m during normal operation, and if the aircraft is operating above 7 620m, the cockpit pressure altitude should not exceed 4 572m under reasonably possible failure conditions.

Aircraft generally fly above 10 000m, and the cabin pressure is required to be below 8 000ft, so the fuselage structure needs to withstand the cabin pressurisation brought about by the differential pressure loads. The lower the cabin pressure altitude, the greater the pressure difference between the inside and outside of the fuselage, the greater the weight of the fuselage structure.

As with the fuselage width indicator, the weight of the fuselage structure at different cabin pressure levels can be evaluated by empirical formulas or modelling.

5 Modelling Of Weight Parameters between Comfort and Economy

By associating each comfort metric with the weight of the fuselage structure, constructing a model for estimating the weight of the fuselage structure, and placing it into the weight analysis model of the whole aircraft, it is possible to calculate the weight of the whole aircraft and the corresponding fuel efficiency, thus linking the combination of comfort metrics to the level of fuel consumption, which is showed in Fig 4. In the research process of this method, since the cruising speed is assumed to be the same for the same aircraft type, the fuel efficiency is defined as the fuel consumption per unit of time, and the fuel consumption is used as the evaluation index of economy.



Calculation assumptions:

1. The thickness of the sound insulation is directly reflected in the thickness of the structural wall panels.
2. Cockpit pressure reduction is assumed to affect only the structure and system weight.

Fig. 4. Aircraft weight calculation flowchart

In the conceptual design stage, the fuselage structure weight estimation formula given by Professor Niu Chunyun[13], or the fuselage structure coefficient method, can be used for the assessment of the fuselage structure weight, and then the amount of change in fuselage structure weight brought about by the change in the internal noise level can be used for weight correction. The overall weight assessment can be carried out directly through the model at the detailed design stage. With the accumulation of data at a later stage, big data can be applied to build computational models, improve and upgrade the computational process and computational software[14].

For this reason, the weight calculation model of the whole aircraft is updated and corrected, and the corresponding weight evaluation software of the whole aircraft is formed.

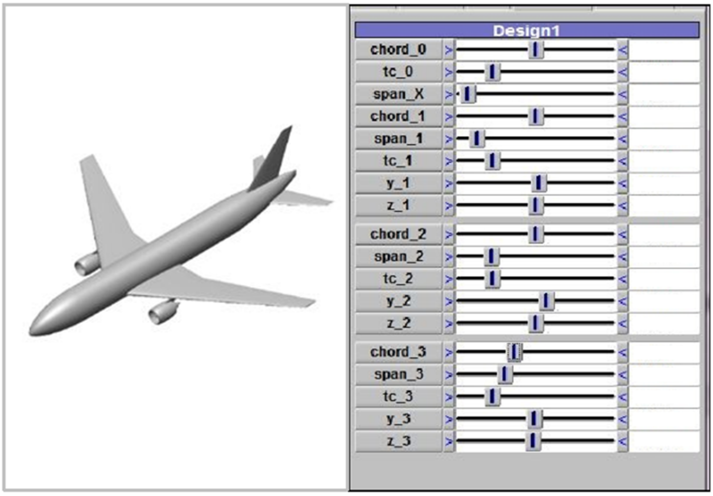


Fig. 5. Weight evaluation software interface

6 Comprehensive Assessment of Comfort and Economic Indicators

After formulating the scoring rules for the comfort and economic indicators respectively, the evaluation matrix for the comfort indicators is listed in Table 2:

Table 2. The evaluation matrix for the assessment

Comfort indicator factors	weights	Comfort Rating Points	Fuel Consumption Rating Points
Seat comfort level	m1	a1	_
Cabin overcrowding level	m2	a2	_
Cabin noise level	m3	a3	_

Pressure altitude level	m4	a4	_
Total comfort points		$\sum_{k=1}^{n} m_k a_k$	
Total economic performance points			b
Total points			$\sum_{k=1}^{n} m_k a_k + b$

7 Example Analysis

In this paper, a twin-aisle airliner with a conventional configuration is selected as the base case, while different fuselage widths, cabin noise levels and cockpit pressure heights are selected for the variation of the airliner widths, and the individual model scenarios are substituted into the estimation model shown in Fig. 5 for the weight calculations and the fuel consumption level assessments. The constructed aircraft model is showed in Fig.6. While 27 sets of metrics combinations were constructed for the three dimensions of comfort metrics, as showed in Fig.7.

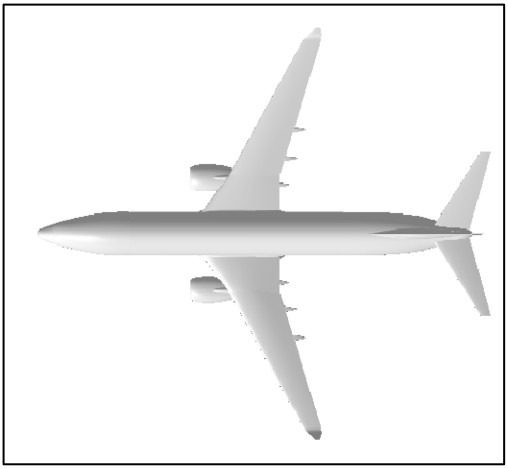


Fig. 6. Constructed aircraft model

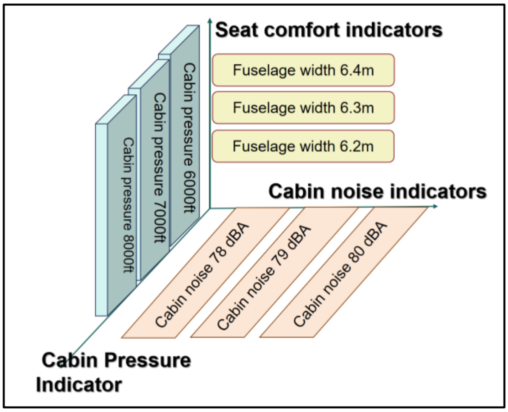


Fig. 7. 27 sets of metrics combinations

The fit of the seat and armrests was evaluated in terms of hip width and shoulder width dimensions based on the predicted 2030 North American male mannequins from a computer-aided human numerical system for occupant simulation, mostly used for vehicle ergonomics analysis, which provides a wealth of mannequins and predictive data. Based on the predicted 2030 North American male human body model, different fuselage width indicators can be evaluated and scored for comfort. At the same time, a cabin model was constructed to carry out cabin noise assessment as showed in Fig 8; and a fuselage weight assessment model was constructed and brought into the software shown in Fig 5 for calculation.

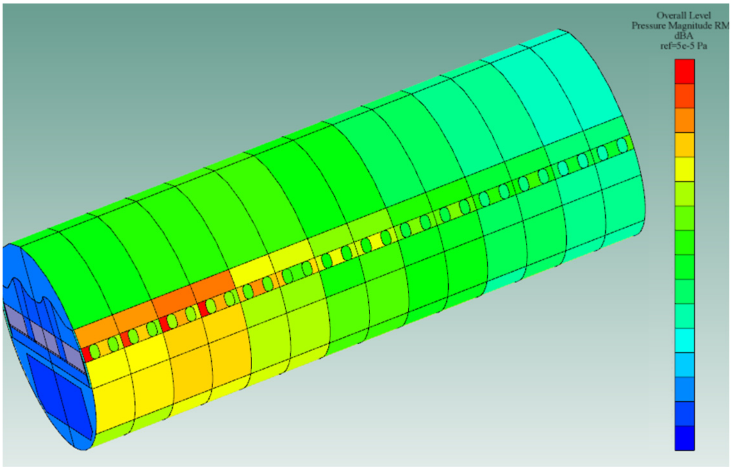


Fig. 8. Fuselage SEA model.

The calculated maximum take-off weight distribution is showed in Fig 9.

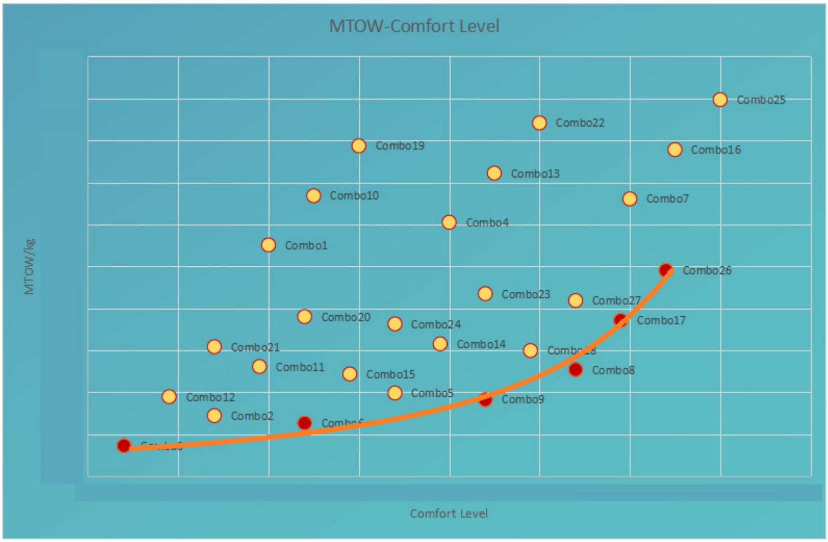


Fig. 9. The calculation results for the 27sets data

From the figure, it can be seen that there exist seven sets of Pareto optimal solutions, seven sets of data, all of which are listed in Table 3. Based on the comfort indicator scoring system constructed within the project, as well as the economy indicator scoring system, the final seven sets of indicators obtained were scored, and the final analysis yielded the highest score for combination 9.

Combination 9 has the highest comfort level for the noise level, while the fuselage width and cabin pressure are both the lowest comfort indicators, and the economy level decreases less, and it can be found that the cabin comfort level can be significantly improved after reducing the cabin noise through the appropriate weight cost and ensuring that the aircraft still has good economy, which allows the aircraft design to get the highest score.

Table 3. The evaluation matrix for the assessment

Comfort Indicators Combination	**Fuselage Width/m**	**Cabin Noise/dBA**	**Cabin Pressure/ft**	**MTOW/kg**	**Economic performance score**	**Comfort Rating score**	**Total score**
Combination3	6.2	80	8000	STD	16	3.84	19.84
Combination6	6.2	79	8000	+897	15.75	4.04	19.79
Combination9	**6.2**	**78**	**8000**	**+1177**	**15.65**	**4.24**	**19.90**
Combination8	6.3	78	8000	+1536	15.55	4.34	19.89
Combination17	6.3	78	7000	+2122	15.3	4.39	19.69
Combination26	6.3	78	6000	+2717	15.1	4.44	19.54
Combination25	6.4	78	6000	+3753	14.5	4.5	19

8 Conclusion

The results of this study show that achieving the optimal balance point of fuselage structural weight on comfort and economy is a challenging task. When weighing comfort and economy, designers need to consider the combined effects of several factors, including structural weight, fuel efficiency, and passenger comfort. This trade-off requires a comprehensive consideration of the advantages and disadvantages of different design alternatives in order to find the optimal solution.

Through the explorations in this study, we have come up with some insights for future aircraft design. Future aircraft design should focus on the balance between structural lightweight and comfort optimization, and adopt advanced materials and design techniques to achieve higher levels of comfort and economy. At the same time, the overall optimization of aircraft systems should be enhanced to achieve better combined comfort and economy performance.

The analyses in this study were limited by some modelling assumptions. For example, the definition of comfort metrics may be oversimplified and does not take into account individual passenger differences and the subjective nature of comfort experience. In addition, there may be some subjectivity and uncertainty in the development of economy indicators. Future research will further refine the model to consider the influence of more factors.

Through the above research, we believe that the analysis of comfort and economic trade-offs will continually be an important research direction in the field of aircraft design in the future, providing aviation engineers with more scientific and reasonable design solutions and promoting the sustainable development of the aviation industry.

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