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Influences of Figure of Merit in Aircraft Design

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Abstract

In aircraft conceptual design process, the figure of merit is used as the criterion for indicating a better design; therefore, it has a significant impact on the aircraft configuration. This paper presents the influences of the three chosen figures of merit –the operational empty mass, fuel mass and takeoff mass– on the designed aircraft. The design of a medium haul transport aircraft with various mission performances is used for the comparative study. More insight into the multidisciplinary interaction in the aircraft design process is obtained. The results explicitly show the impact of the selected figure of merit on the aircraft configuration, mass and direct operating cost.

Keywords: Figure of merit, Aircraft design

1. Introduction

Aircraft conceptual design and optimization is the process of searching for an optimum design satisfying predefined requirements and constraints. The process involves identifying a set of design variables, which describe the aircraft, to be altered during the optimization process; the figure of merit or the objective function to be optimized; and constraints to be satisfied. The figure of merit is used as the criterion for indicating a better design; therefore, it has a significant impact on the designed aircraft. At present, the cost and aircraft mass are normally used as the figure of merit to be minimized. The direct operating cost (DOC) is usually used for civil transport aircraft, whereas, the total life cycle cost (LCC) is used for military aircraft. Although the cost is a very important parameter, unfortunately so many non-technical issues are involved such as operators, economics and politics which are difficult to be predicted. The aircraft mass (or weight) is also often employed as the figure of merit. This is mainly because it is directly related to the aircraft performance and, hence, cost, and because it can be estimated more accurately.

This paper investigates the influences of the figure of merit on the design of civil transport aircraft. The aircraft operational empty mass implying an efficient airframe, the required fuel mass indicating aerodynamic efficiency, and the take-off mass compromising overall performance are chosen as the figures of merit to be minimized. The direct operating cost of each optimized design is also evaluated. The results are then compared to provide more insight into the design of transport aircraft.

2. Methodology and Case Study

To completely understand the interaction of various disciplines in the aircraft design process, a simple aircraft sizing and optimization program (ANSI C code) for civil transport aircraft has been developed and employed for this study. The sizing part (or aircraft synthesis) is mainly based on the empirical formula given in Howe [1], and LSGRG2C optimization program [2] is integrated as the optimizer. The direct operating cost (DOC) is estimated using the method given in Jenkinson et al [3].

The aircraft take-off mass M_{TO} is defined as

$$M_{TO} = OEM + PAYL + FUEL \qquad (1)$$

where *OEM* is the operational empty mass consisting of mass of the airframe, engines and operational items, *PAY*L is the mass of payload i.e. passengers and their belongings, and *FUEL* is the total fuel mass required to perform the specified flight mission.

In this study, three figures of merit were chosen to be minimized: the aircraft operational empty mass *(OEM)*, fuel mass *(FUEL)* and take-off mass (M_{TO}), in order to investigate the effects that the figures of merit have on the aircraft configuration. The medium haul transport aircraft having the specified mission as shown in Table 1 was used for this study. The combination of the number of passengers, mission ranges and chosen figures of merit formed totally 45 study cases to be evaluated.

Table 1 Mission requirements

Items	Requirements
No. of passengers	120, 135, 150, 165 and 180
Range (km)	4000, 5000 and 6000
Takeoff field length (m)	≤ 2200, ISA sea level
Landing field length (m)	≤ 2200, ISA sea level
Approach speed	≤ 70 m/s
Cruise Mach number	0.82
Cruise Altitude (km)	11
Cargo	LD3
Propulsion	2 engines, T/W_{eng} = 6 Bypass ratio = 5.5

As a typical design of transport aircraft, the fuselage dimension is mainly determined by the volume required to accommodate passengers; therefore, it is left constant during the optimization process. Accordingly, it may be stated generally that the main design process is to size and optimize the wing and engines under constraints to meet the specified requirements. The chosen design variables are shown in Table 2, and the design constraints are listed in Table 3.

3. Results and Discussions

An example of aircraft characteristics optimized to the chosen figures of merit with 150 passengers (pax) and the cruise range of 5000 km is shown in Table 4. It can be seen that the minimized *OEM*, provides the smallest aircraft. The aircraft was optimized by decreasing the wing area and aspect ratio resulting in a lighter airframe weight and, hence, more efficient airframe. As would be expected, the minimized *FUEL* gave the smallest fuel consumption. The fuel mass was minimized mainly by extensive increase in wing aspect ratio to reduce the aircraft drag resulting in a higher lift-to-drag ratio (C_L/C_D) which, in turn, lead to the lower fuel consumption. The aircraft is more aerodynamically efficient. As a result of substantial increase in aspect ratio and wing area, the wing mass, accounting for eighty percent of the lifting surface mass, was increased significantly leading to the largest takeoff mass. The minimized M_{TO} was optimized by compromising both the airframe mass and fuel mass to achieve the minimum takeoff mass. The aircraft is slightly larger than that of the minimized OEM.

Table 2 Design variables

	Design variables
1.	Aspect ratio
2.	Quarter-chord sweep, $\Lambda_{1/4}$ (deg)
3.	Thickness-chord ratio, t/c
4.	Taper ratio
5.	Fuel mass fraction
6.	Takeoff thrust-weight ratio, T/W
7.	Takeoff wing loading, W/S (N/m^2)
8.	Thrust at sea level per engine (N)

Table 3 Design constraints

	Design constraints	Value
1.	Fuel volume remaining (m^3)	= 0
2.	Takeoff field length (m)	≤ 2200
3.	2nd segment climb gradient (%)	≥ 2.4
4.	Initial cruise rate of climb (m/s)	≥ 1.5
5.	Cruise CL buffet	$\leq 0.65 \cos \Lambda_{1/4}$
6.	Approach speed (m/s)	≤ 70
7.	Landing field length (m)	≤ 2200
8.	Sensitivity to turbulence	≥ 0
9.	Maximum wing span (m)	≤ 80
10.	SEP at diving speed (m/s)	≥ 0

Table 4 Optimized aircraft characteristics

Minimized Figures of Merit	M_{TO}	OEM	FUEL		M_{TO}	OEM	FUEL
A/C Dimensions:				OEM fraction	0.52	0.52	0.55
Wing				ZFM fraction	0.76	0.76	0.79
Aspect ratio	9.60	9.23	15.78	Fuel mass fraction	0.24	0.24	0.21
1/4c sweep (deg)	27.28	26.59	32.53				
t/c ratio	0.13	0.13	0.13	**Performance:**			
Taper ratio	0.25	0.25	0.25	No. of passengers (pax)	150	150	150
Wing area (m^2)	101.81	101.48	111.95	Takeoff field length (m)	2200.00	2153.48	2200.00
Wing span (m)	31.27	30.61	42.03	2nd climb gradient (%)	2.48	2.40	5.36
Fuselage				Initial cruise RoC	2.81	2.90	4.83
Fuselage width (m)	4.07	4.07	4.07	Initial cruise CL/CD	17.08	16.79	19.92
height (m)	4.20	4.20	4.20	Initial cruise CL	0.52	0.52	0.49
length (m)	38.15	38.15	38.15	Cruise CL buffet	0.58	0.58	0.55
				Cruise Mach number	0.82	0.82	0.82
Mass Group (kg):				Cruise altitude (km)	11.00	11.00	11.00
Fuselage mass	8116.49	8116.49	8116.49	Range (km)	5000	5000	5000
Operational mass	2330.00	2330.00	2330.00	Approach speed (m/s)	70.00	70.00	70.00
Payload mass	14550.00	14550.00	14550.00	Landing field length (m)	1579.28	1579.28	1579.28
Lifting surface	6905.73	6751.56	9701.58	Sensitivity to turbulence	2586.35	2601.23	2489.17
Propulsion	4111.22	4203.23	4288.00	SEP at Vd	0.00	0.00	2.51
System & Equip.	6509.31	6527.68	6789.20	Thrust per engine (kN)	84.58	86.47	88.22
Landing gear	2633.31	2640.74	2746.54	CLmax clean wing	1.50	1.50	1.50
FUEL mass	14019.46	14222.83	13198.20	CLmax takeoff	2.31	2.33	2.19
Empty mass	28276.06	28239.70	31641.81	CLmax landing	2.89	2.91	2.74
OEM	30606.06	30569.70	33971.81				
Zero fuel mass	45156.06	45119.70	48521.81	T/W (takeoff)	0.29	0.30	0.29
MTO	59175.52	59342.53	61720.01	W/S (N/m^2)	5699.93	5734.45	5406.80

The impacts of the figures of merit on the wing aspect ratio and wing area are shown in Figures 1 and 2 respectively. The results clearly demonstrate consistency of the impacts as mention earlier. The larger aspect ratio and wing area are required for the aircraft with more payload and also range regardless of the choice of the figure of merit.

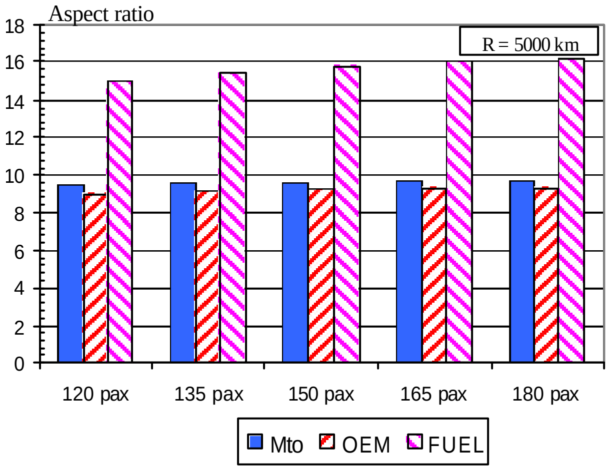

Figure 1 Effect of the figures of merit on aspect ratio

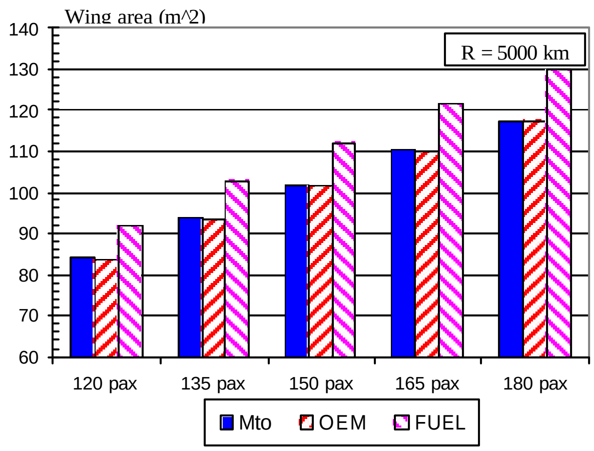

Figure 2 Effect of the figures of merit on wing area

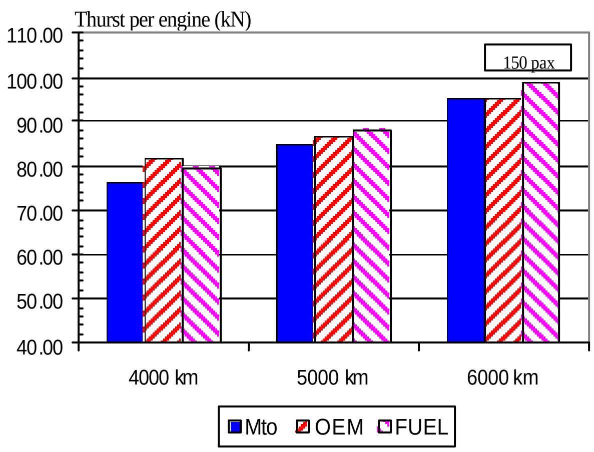

Figure 3 Effect of the figures of merit on engine size

The influence of the figure of merit on the engine size is shown in Figure 3. To minimize the fuel mass, the engine size (or the required thrust) would generally be decreased as shown for the case of 4000 km range. However, for the greater required range, the engine was sized based on the constraint on the same takeoff length, and the greater total weight due to the required range. This resulted in the larger engine than would it be if the takeoff length was extended.

The variation of the minimized takeoff mass M_{TO} with the design payloads and ranges is shown Figure 4. The results show the linear relationship of the variation. Furthermore, the results show the significant impact of the payload on the takeoff mass; for example, by adding 15 more passengers weighted about 1455 kg, the aircraft takeoff mass increases 5910 kg, or with the mass ratio of about 4 to 1.

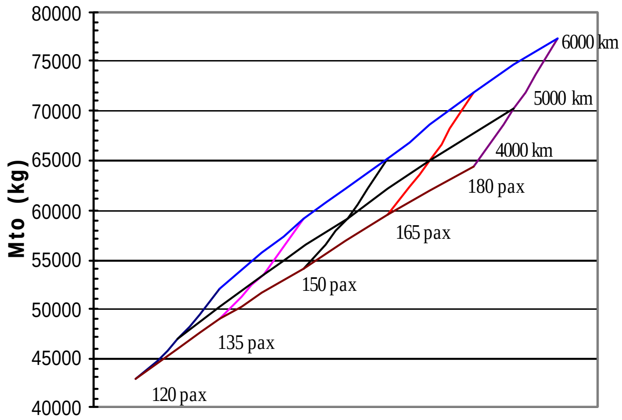

Figure 4 Variation of the minimized takeoff mass

The mass penalties associated with the designs to each figure of merit as a percentage of the optimum value are evaluated and shown in Table 5. The average off-design penalties for all 45 study cases are illustrated in Figure 5. The results show that the minimized *FUEL* imposed the greatest mass penalty on its design, whereas the least penalty was on the design of minimized M_{TO}. In addition, all penalties are more pronounced with the increase of the payload (passengers). Note that, for a higher range, the difference between penalty on the minimized *OEM* and that on the minimized M_{TO} is less. This indicates that the aircraft optimized to the *OEM* is almost identical to that optimized to the M_{TO}.

Table 5 Off-design penalties

Case:	**Off-design penalty (%)**		
150 pax , R =5000 km	$\boldsymbol{M_{TO}}$	***OEM***	***FUEL***
Takeoff mass	0.00	0.28	4.30
Operational empty mass	0.12	0.00	11.13
Fuel	6.22	7.76	0.00
Total	6.34	8.05	14.39
Average penalty	***2.11***	***2.68***	***4.80***

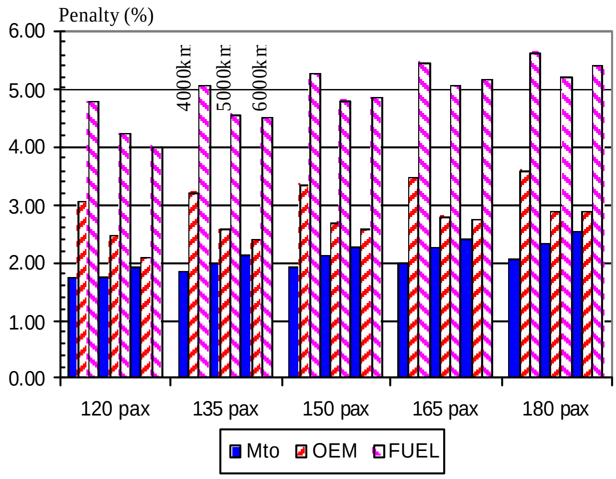

Figure 5 Average off-design penalties

The direct operating cost per hour in 1995 US$ [3] associated with each design was estimated and presented in Figure 6. It can be seen that the minimized M_{TO} design results in the minimum direct operating cost. The largest direct operating cost was on the minimized fuel design due to the higher airframe price associated with the larger weight. It can also be seen that the direct operating cost per hour decreases as the mission range increases.

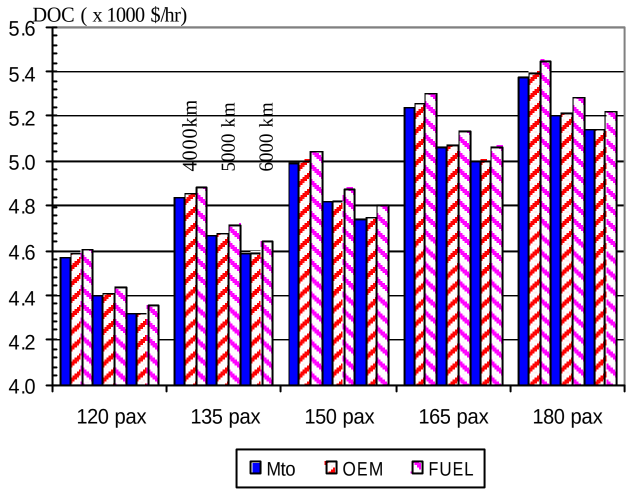

Figure 6 Estimated direct operating cost per hour

4. Conclusions

A design and optimization code was developed to study the influences of the figure of merit on the design of civil transport aircraft. Three figures of merit –the aircraft operational empty mass, the fuel mass, and the takeoff mass– were investigated. The study provides more insight into the multidisciplinary interaction in the aircraft design process, and the results show the followings:

- The design optimized to the minimum takeoff mass imposes the least penalty on off-design figures of merit.
- The minimized fuel mass provides the most efficient aerodynamic design, but with the greatest mass penalty and the largest design.
- The smallest design is obtained when optimized to the minimum operational empty mass.
- The design optimized to the minimum takeoff mass leads to the minimum direct operating cost, and the largest direct operating cost is on the design optimized to the minimum fuel.

5. References

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