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CONCEPTUAL SIZING OF A LONG RANGE TRANSPORT AIRCRAFT

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ABSTRACT

This paper describes a procedure for carrying out conceptual sizing of a long range transport aircraft, using Boeing B787-8 as the baseline. The procedure starts with mission sizing to estimate the empty and fuel weight fractions, leading to the estimate of design gross weight. The drag polar of the aircraft in cruise is estimated using the geometric parameters and mission parameters. The maximum lift coefficient and lift curve slope of the aircraft are also estimated. Wing loading and thrust loading of the aircraft are estimated by carrying out a detailed analysis of the constraints imposed on the aircraft. Weight breakdown for the major assemblies of the aircraft is carried out, and the Payload-Range diagram of the aircraft is drawn. The RDT&E cost and program cost are estimated using the DAPCA-IV model. Finally, the direct operating cost of the aircraft are estimated using the standard AEA-89 method. The results obtained are validated against those reported as a test case by a commercial software. A close agreement is seen for most design parameters, inspiring confidence in the fidelity of the procedure. The procedure is written as a spreadsheet in Microsoft-Excel™ and *Python™, and can be used to carry out conceptual sizing of any long range transport aircraft.*

Keywords: Transport Aircraft Design, Aircraft Conceptual Sizing

1 INTRODUCTION

The first phase in any aircraft design exercise is the conceptual sizing phase in which a layout and configuration of the aircraft is arrived at, such that the user specified and air-worthiness requirements are met. Although standard aircraft textbooks such as [1-6] do describe such methods, it is not easy to implement them straight away for studies related to conceptual design and sizing of a long range transport aircraft. There is also a lack of reliable and detailed data related to a transport aircraft, which can be used for validation of such an exercise.

This paper tries to address this limitation and describes the results of such a study that was carried out, for the latest aircraft from the Boeing's stable, viz., B787-8 *Dreamliner.*

1.1 Brief overview of aircraft design process

An Aircraft design process entails analyses from different disciplines, viz., Aerodynamics, Structures, Controls and Propulsion. A designer must be well versed with all these and the interactions they have with each other. The process of aircraft conceptual design and sizing is an iterative one and involves assumptions, equations, procedures and estimations from various disciplines and different levels of fidelity. The process usually starts after the requirements and mission profiles of the aircraft are finalized through a dialogue with the proposed customers.

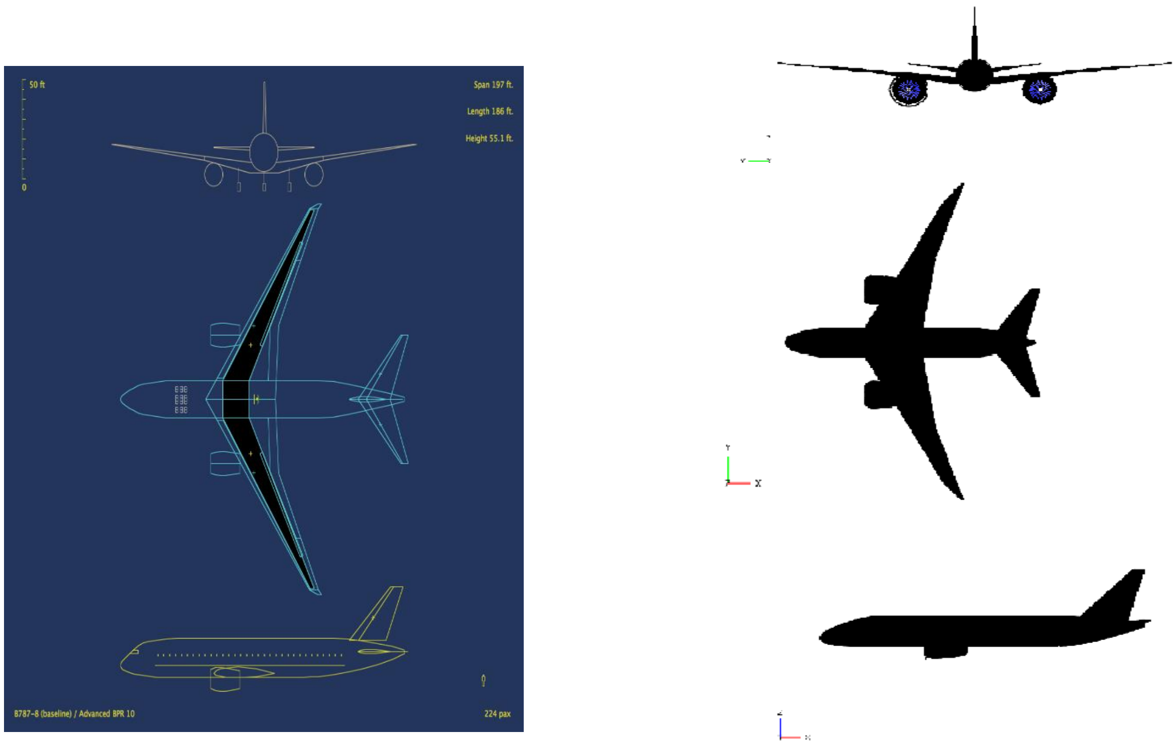
The various constraints imposed by the regulatory bodies have also to be anticipated and taken into account at every step in this process.

1.2 Motivation for the present study

Two popular computer programs, viz., *RDS™* and *AAA™*, are available in the commercial domain for carrying out aircraft design studies, and/or analyses. No procedure or code is available in open literature related to the conceptual sizing phase of the aircraft design process. This gap in the literature was the prime motivation to carry out the present study, in which standard procedures and formulae were coded in *MS-Excel™* and *Python™* for carrying out the following activities related to the aircraft conceptual design phase, including:

- Initial Sizing
- Drag Polar Estimation
- Lift Coefficient
- Weight Breakdown
- Constraint Analysis (Design Point evaluation)
- Range Payload Diagram
- Program Cost Estimation
- Direct Operating Cost

The results obtained using the various equations and methods described using various references were then validated against existing sample analysis in the Aircraft Design software named *PIANO™* [7], developed by Lissys Systems of UK. Figure 1 shows the three-view diagram of Boeing B787-8 aircraft, which was used to extract the geometry for generating the CAD model using *OpenVSP™* [8] software in the present study.



PIANO™ *OpenVSP™*

Figure 1: Three view diagram of B787-8 in *PIANO™* [7] and obtained using *OpenVSP™* [8]

2 METHODOLOGY

Figure 2 is a flow chart of the procedure used for carrying out conceptual sizing of the aircraft in the present study.

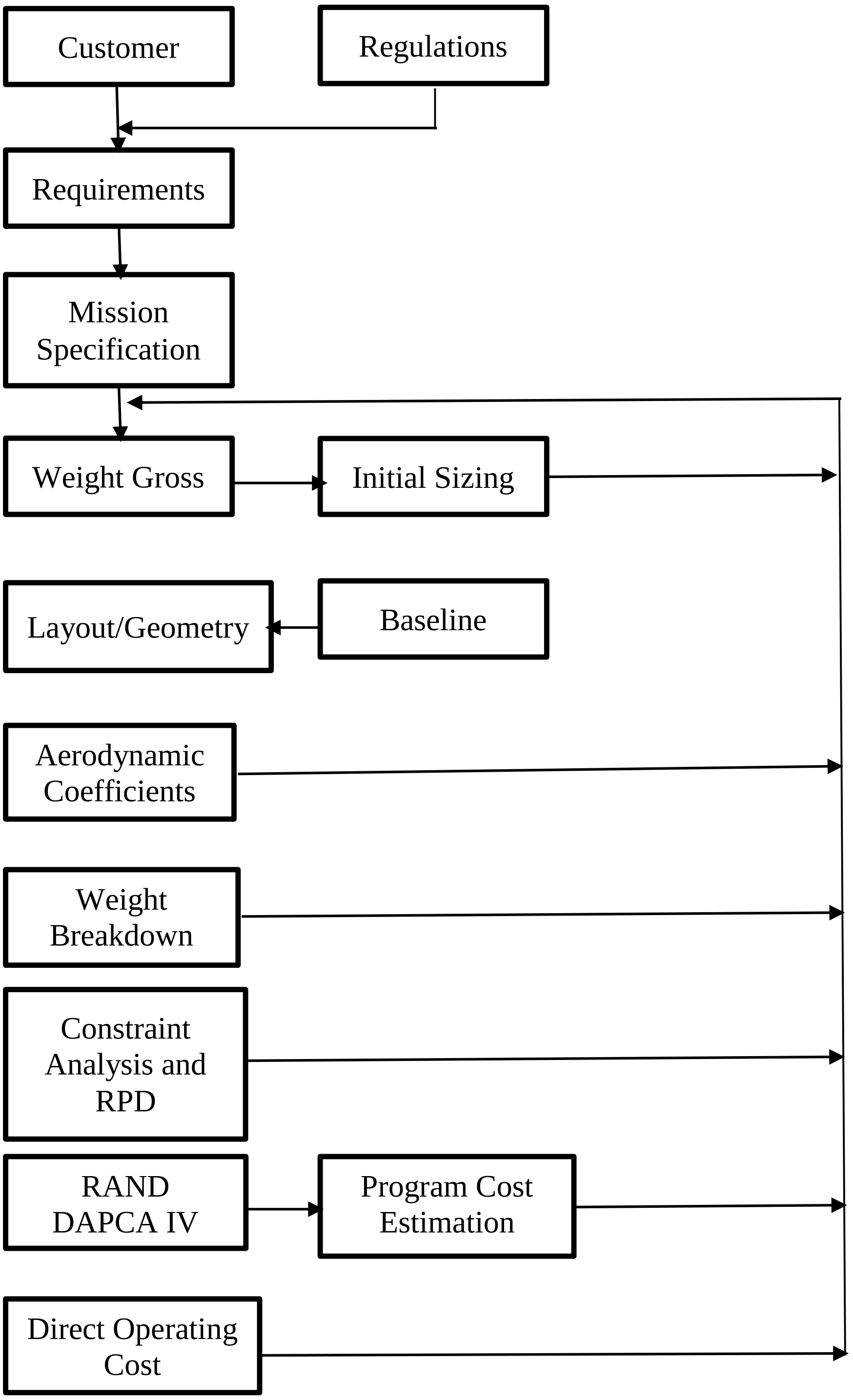


Figure 2: Schematic of the present methodology

3 BACKGROUND THEORY

The formulae and procedures used for calculating the values in the various modules of this methodology were extracted from various sources, such as [1-6]. Due to brevity, the details of these formulae and procedures are not being reproduced here; since they are listed in [9]. In the subsections that follow, a comparison of the results obtained for the various modules by the methodology are compared with those quoted in the PIANO output [7].

4 ANALYSIS OF RESULTS

4.1 Initial Sizing

In aircraft design parlance, *initial sizing* refers to estimate of design gross weight of aircraft for carrying out the specified mission profile. In the present study, the procedure and formulae for the initial sizing described by Raymer [1] were followed.

Figure 3 shows a comparison between the values of fuel consumed in each segment estimated in the current methodology (blue) with those quoted for the same mission in *PIANO*™ (black).

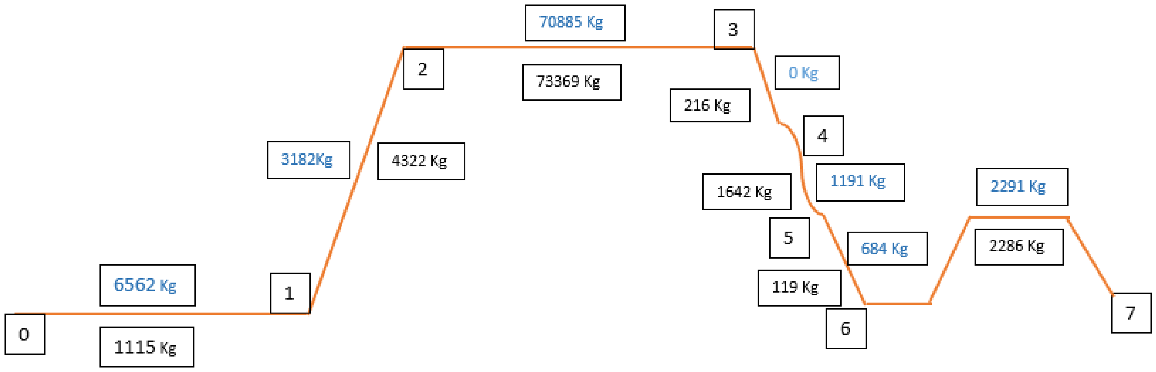


Figure 3: Mission profile, and estimated and quoted values for Mission Segment Fuel

A close match in the estimated and quoted values of mission segment fuel consumption is seen, except for the first (i.e., Warm-up, Taxi-out & Take-off), Descent and Reserve Fuel. However, the values of Total Fuel and Design Gross Weight were seen to match very well.

4.2 Aerodynamic Analysis

Aerodynamic analysis involves estimation of the value of zero lift drag coefficient (C_{D0}), profile drag coefficient (k) and maximum Lift coefficient ($C_{L,\ max}$) for the aircraft. In the present study formulae from [1] & [2] were used, as applicable. The estimation of zero lift drag coefficient (C_{D0}) and the profile drag coefficient (C_{Di}) was carried out using component build-up method described by Brandt et al. [2]. As can be seen in Table 1, the estimated drag coefficients of each component, and C_{Di} are seen to be within ~ ± 6% with the values quoted in [7]. The total drag coefficient (C_D) for the quoted cruise C_L value is also seen to match very well with the values reported in [7].

Component	PIANO™ [7]	Calculated	% Error
Wing	4.73E-03	4.98E-03	+5.2
Winglets	3.70E-05	3.78E-05	+2.3
H-Stabilizer	1.05E-03	1.08E-03	+2.7
V-Stabilizer	7.69E-04	7.54E-04	-1.9
Fuselage	5.00E-03	4.88E-03	-2.4
Nacelle	1.19E-03	1.14E-03	-3.9
Total C_{D0}	1.28E-02	1.29E-02	+0.7
C_{Di}	1.02E-02	1.08E-02	+6.1
C_D for C_L = 0.508	2.30E-02	2.37E-02	+3.1

Table 1: Results of component built-up method for drag breakdown estimation

Using the formula provided by Raymer [1], the maximum Lift coefficient ($C_{L,\,max}$) and the lift curve slope (a) for the un-flapped wing is estimated to be 1.7246 and 0.3241 per degree, respectively.

4.3 Weight Breakdown

The component weight breakdown is carried out based on the procedure given by Kundu [6]. Figure 4 shows the breakdown of maximum takeoff weight (MTOW) of the aircraft.

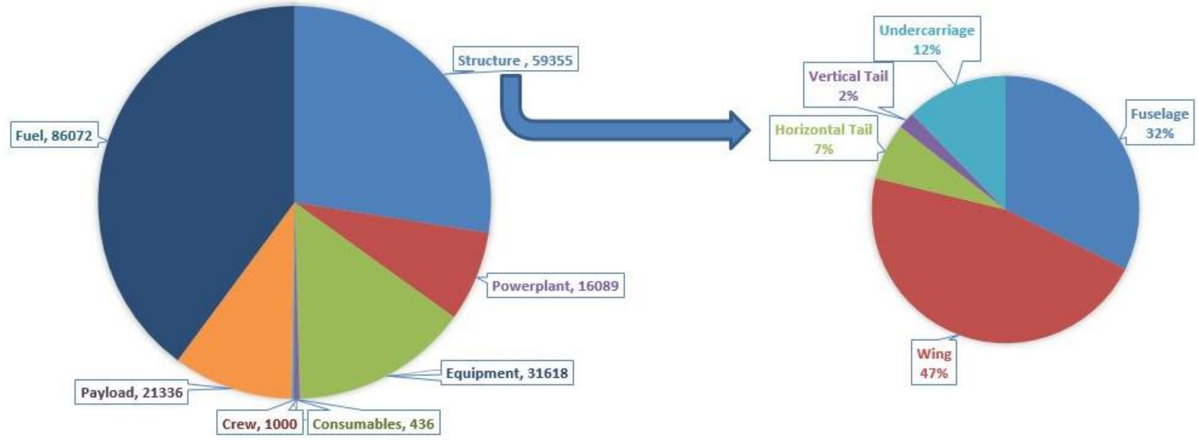


Figure 4: Component Weight Breakdown

The estimated weight for most structural components matches quite well with the values quoted in [7], except for two components, viz., Vertical Tail and Horizontal Tail. It is seen that the formulae for these components give much higher weight than the actual weight for other aircraft also. Nevertheless, the error in the predicted structural weight and operating empty mass is seen to be ~ 8.6 % and ~13.5%, respectively, which is acceptable for a conceptual design exercise.

4.4 Constraint Analysis

The most important task in aircraft conceptual design is to estimate the values of two key sizing parameters, viz., Wing Loading (W/S) and Thrust Loading (T/W) that meet all the requirements specified by the user, as well as the regulatory bodies. This exercise is termed as the *Constraint Analysis*. In the present study, the list of requirements and constraints is listed in Table 2.

Parameter	**Value**	**Units**	**Operating Condition**
Design Cruise Mach No	0.9		@ H = 37000 ft, ISA
Landing Stalling Speed	102	kt EAS	@ W = 365000 lb, SL ISA
Landing Ground Roll	2037	ft	@ W = 365000 lb, SL ISA
Take-off Stalling Speed	138	kt EAS	@W = 476000 lb, SL ISA+15
2nd Stage Climb Gradient	3.49	%	@ W = 476000 lb, SL ISA+15
Balanced Field Length	9255	ft	@ W = 476000 lb, SL ISA+15
Missed Approach Gradient	2.1	%	@ W = 365000 lb, SL ISA

Table 2: User Requirements and Constraints for Boeing B787-8 aircraft

The final constraint diagram, obtained using the formulae and procedures defined by Brandt et al. [2] is shown in Figure 5. The design point obtained in the present study is T/W = 0.33 and W/S = 310 kg/m^2.

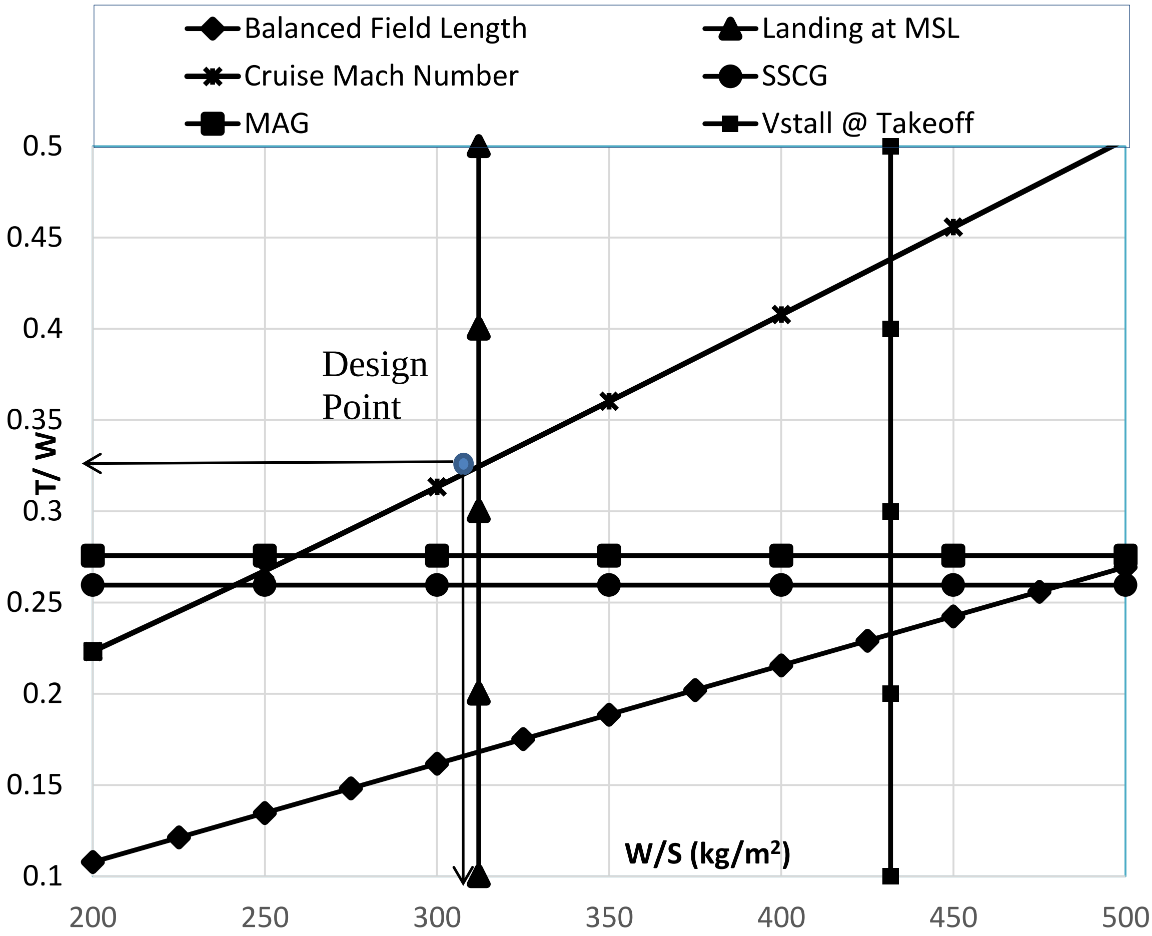


Figure 5: Constraint Diagram

4.5 Range Payload Diagram (RPD)

The Range Payload diagram (RPD) helps illustrate the trade-off between the two contrasting terms of relevance to an airline operator, viz., the Range and the Payload that can be carried over that Range. The estimated RPD for this aircraft is as shown in Fig. 6.

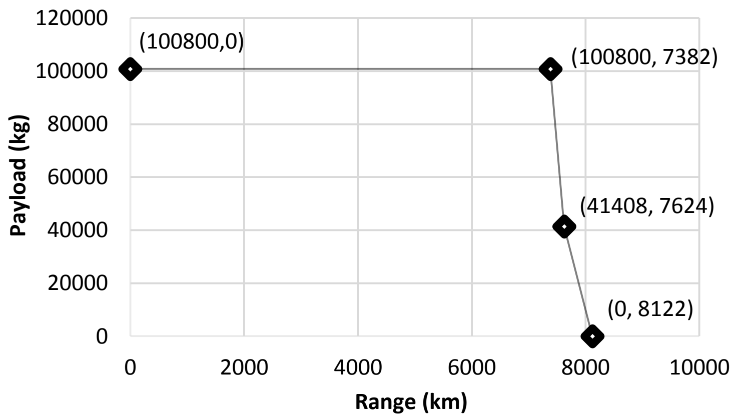


Figure 6 : Estimated Range Payload Diagram for B787-8

4.6 Program Cost Estimation

The Rand DAPCA IV (Development and Procurement Cost of Aircraft) IV model described by Raymer [1] was used to estimate the cost to be incurred in the Research Development Testing and Engineering (RDT&E) phase. Fig. 7 shows the breakup of the various components of the RDT&E cost, which was estimated as $10.23 billion. Using the same model, the program cost for a production run of 1100 aircraft was estimated to be $116.17 billion.

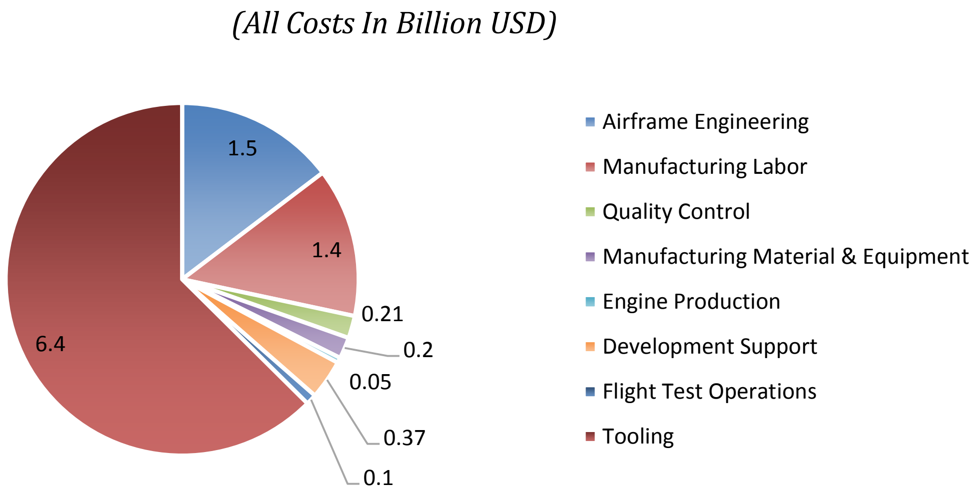


Figure 7: Breakup of RDT&E Cost for Boeing B787-8

4.7 Direct Operating Costs

The direct operating cost of an aircraft comprises various elements, including, but not limited to, loan payment, insurance, maintenance cost, fuel and oil cost, as outlined in [9]. Table 3 lists the values of DOC estimated in the present study.

DOC Term	Value (USD)
DOC/hour	18223
DOC/trip	315551
DOC/km	28.38
DOC/pax/km	0.13

Table 3: Direct Cost Estimation

5 CONCLUDING REMARKS

The present study shows that it is possible to use the procedures described in standard textbooks for aircraft conceptual design [1-6] to obtain reasonable estimates for the gross weight, aerodynamic coefficients, and weight breakdown of a long range transport aircraft. The methodology described in this paper can permit carrying out constraint analysis, as well as obtaining the Range-Payload diagram of the aircraft. The results obtained by the methodology compare well with those obtained using a commercial aircraft conceptual design and sizing code (i.e., *PIANO*™ [7]), which illustrates its efficacy.

6 ACKNOWLEDGEMENTS AND REFERENCES

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