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Deciphering the Relationship between the Mass, Size and Engine Properties of Boeing and Airbus Aircraft

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Abstract
In the study, it is aimed to analyze the mass, size, and engine characteristics of different Boeing and Airbus aircraft models, which are the duopoly in air transportation market, and to decipher the correlations between the conceptual design parameters of these aircraft. For this purpose, data on the production year, mass, size, and engine characteristics of 36 Boeing and 20 Airbus aircraft were collected. The fuselage length, cabin width, wingspan and wing area were considered as the size characteristics. In order to compare the mass characteristics of aircraft, the operational empty mass, engine mass and maximum take-off weight (MTOW) were examined. Since commercial jets are important in terms of aerodynamic design, that is, they determine the status of these aircraft models in the matching table, thrust weight and wing loading characteristics are also examined. Th fineness ratios decreased linearly as the wingspan/fuselage length ratios increased. Similarly, as MTOW increases, the operational empty weight/MTOW ratio tends to decrease. Both engine mass and the total thrust of the engines tended to increase linearly with MTOW. The correlations obtained on mass size and engine relations will contribute to the conceptual aircraft design and engine selection.

1. Introduction

The rivalry between Airbus and Boeing has been described as a duopoly in the commercial large-jet market since the 1990s. This duality has become increasingly prominent after a series of mergers in the global aviation industry. Airbus strengthens as a pan-European consortium, while Boeing acquires arch-rival McDonnell Douglas. Other major commercial jet manufacturers, such as Fokker and BAE systems, could not compete with Airbus and Boeing and withdraw from this market. Passenger capacity, range, engine choices, safety and quality, aircraft prices, outsourcing, technology, currency and exchange rates, and production planning are the main components of this competition [1]. Due to Airbus' sales momentum thanks to the A320neo family and Boeing's problems with the Boeing 737 MAX, the A320 family eventually surpassed the Boeing 737 to become the best-selling aircraft [2]. Statistics conducted in 2019 showed that a total of 11394 Boeing aircraft and a total of 10137 Airbus aircraft were in service [3]. The current disputes between Airbus and Boeing are based on the alleged illegal subsidies given by the governments of both countries give to their respective airlines [4]. King [5] states that the long-range Airbus A380 and Boeing 787, have lower fuel costs per passenger, and that these 2 aircraft are not alternatives to each other, but are complementary aircraft. Zeinali and Rutherford [6] suggested that aircraft design parameters (range, payload etc.) changed over time, affecting fuel efficiency, so the CO2 certification requirement had to be adjusted for specific replacement designs. Ariffin et al. [7] studied the relationship between thrust to weight ratio and maximum take-off mass. Results of that study showed that the thrust to weight ratio of narrow-body aircraft was in the range of 0.22-0.32. The claim that the Boeing 747-8I will carry almost as many passengers as Airbus's superjumbo

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(A380) and will be produced for half of Airbus's estimated investment, has triggered a competitive strategy between Boeing and Airbus [8-10]. Onishi [11] studied the preliminary design of a multi-fuselage gigantic flying boat as an alternative to Boeing 747 and A380. Curran et al. [12] applied Value Operations Methodology (VOM) theory to the Airbus A350-900 versus the Boeing 787-9. The results showed that the B787 was superior in terms of cost, while the A350 provided an advantage in terms of passenger satisfaction. Jasmine et al. [13] used seat load factor for payload optimization comparison of Airbus A330 and Boeing 777-300 ER. Raymer [14] proposed an approach to estimate fuselage lengths using maximum take-off gross mass. Raymer found a power correlation between the aircraft mass and fuselage length for different types of aircraft such as sailplanes, homebuilt, general aviation, jets. Bejan et al. [15] suggested that there is a ratio between the wingspan and fuselage length, and between fuel load and aircraft size of aircraft. In that study, the relationship between aircraft was performed on correlations between the mass, speed, engine mass, range etc. Marta [16] performed optimization of small regional jet geometry with parameters of fuselage length, fuselage diameter, wingspan, wing chord using a genetic algorithm. In current study, geometric and size properties (fuselage length, fuselage with, wingspan, aspect ratio), mass properties (OEW, MTOW, engine mass) and aerodynamic characteristics (wing loading, thrust to weight ratio) of 20 Airbus aircraft and 36 Boeing aircraft were compared. As a result of the study, it was aimed to reveal the correlations obtained from the distribution charts for use in the conceptual design of a commercial jet airliners.

2. Material and Method

In the study, data of 20 Airbus and 36 Boeing aircraft including years of first flight, operational empty weight (OEW), maximum take-off gross weight (MTOW), wingspan, fuselage length, cabin widths, wing area, wing aspect ratio, engine mass, and engine thrust are collected from Jane's All the World's Aircraft [17], technical specification data presented in the Rivals in Sky [18], Boeing commercial website [18] and Airbus Family Figures booklet [20]. Details of the studied aircraft models are given in Table 1.

Table 1. List of studied aircraft models including the years of first flight.

#	Model	Year	#	Model	Year	#	Model	Year
1	Airbus A300B4	1972	1	Boeing 707-120B	1957	21	Boeing 777-200	1994
2	Airbus A310-200	1982	2	Boeing 707-320B	1960	22	Boeing 777-200ER	1996
3	Airbus A300-600R	1985	3	Boeing 727-100	1963	23	Boeing 737-600	1997
4	Airbus A310-300	1985	4	Boeing 727-200	1967	24	Boeing 737-700	1997
5	Airbus A320-200	1987	5	Boeing 737-100	1967	25	Boeing 737-800	1997
6	Airbus A321-200	1990	6	Boeing 737-200	1968	26	Boeing 757-300	1998
7	Airbus A340-300	1991	7	Boeing 747-200B	1970	27	Boeing 767-400ER	1999
8	Airbus A330-300	1992	8	Boeing 727-200A	1971	28	Boeing 747-400ER	2001
9	Airbus A340-200	1992	9	Boeing 737-200A	1971	29	Boeing 777-300	2003
10	Airbus A319-100	1995	10	Boeing 747-100B	1979	30	Boeing 777-300ER	2003
11	Airbus A319LR	1995	11	Boeing 767-200	1981	31	Boeing 777-200LR	2005
12	Airbus A330-200	1997	12	Boeing 747-300	1982	32	Boeing 737-700 ER	2006
13	Airbus A340-600	2001	13	Boeing 757-200	1982	33	Boeing 737-900 ER	2006
14	Airbus A318-100	2002	14	Boeing 767-200ER	1983	34	Boeing 787-8	2009
15	Airbus A340-500	2002	15	Boeing 737-300	1984	35	Boeing 747-8I	2010
16	Airbus A380-800	2005	16	Boeing 767-300	1985	36	Boeing 787-9	2013
17	Airbus A350-1000	2014	17	Boeing 767-300ER	1987			
18	Airbus A350-800	2014	18	Boeing 737-400	1988			
19	Airbus A350-900	2014	19	Boeing 747-400	1988			
20	Airbus A350-900R	2014	20	Boeing 737-500	1989			

When scatter plot is created with the values given in Table 1, Fig. 1 is obtained. Boeing entered the commercial passenger aircraft market with its first aircraft, the Boeing 707, in 1957; this was followed by the Boeing 727 and 737 series in 1967. The first Airbus A300B-4 aircraft was produced in 1972, the Airbus A 310 series in 1982, and the Airbus A320 series in 1985. Boeing's first double-decker Boeing 747-200B made its first flight in 1970, while Airbus' first double-decker A380 made its first flight in 2005. Airbus' newly produced Airbus A350 aircraft has been in service since 2014, while Boeing's newly produced Dreamliner 787 has been in service since 2009.

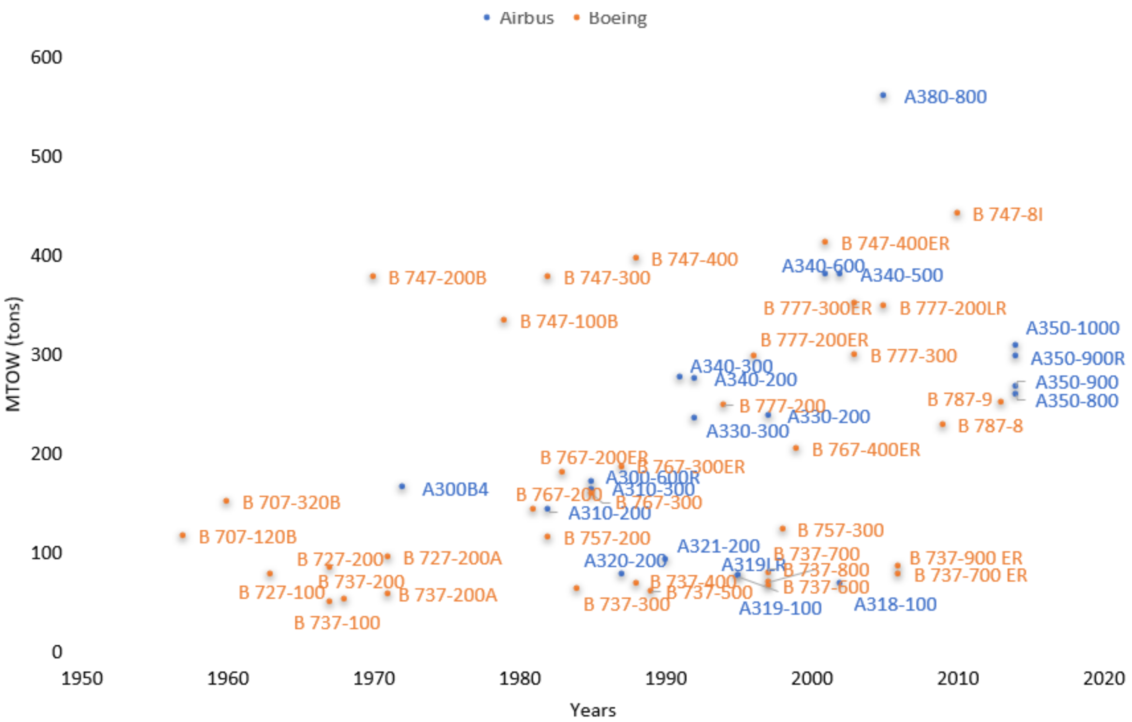


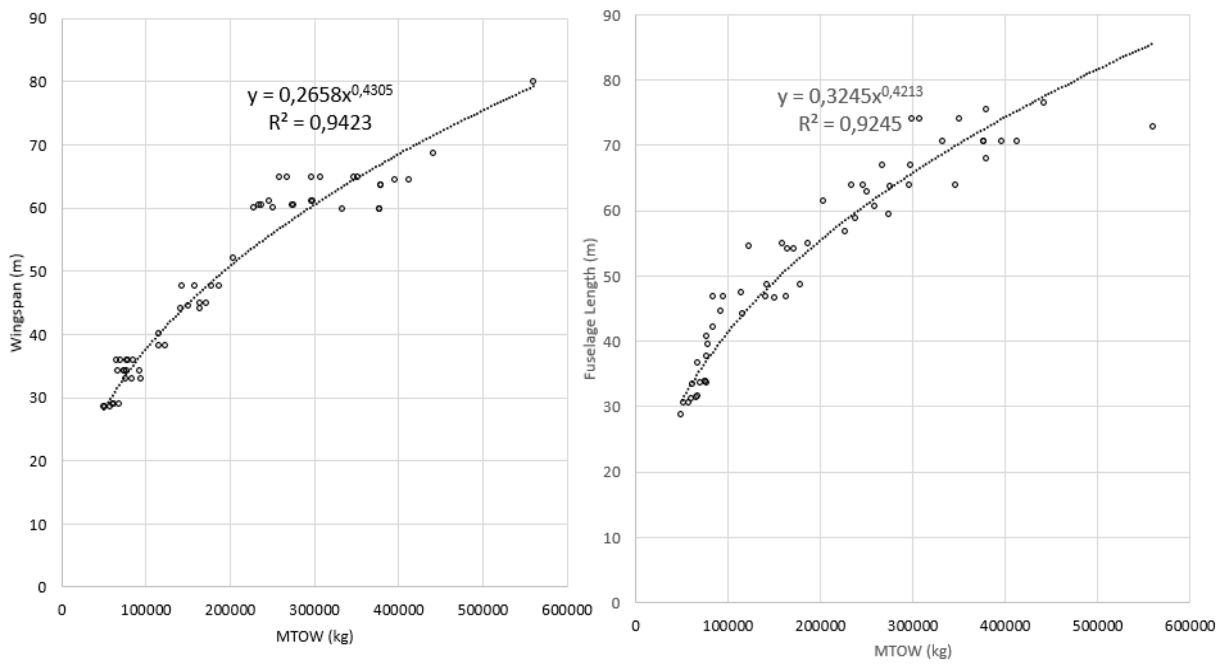
Figure 1. Distribution of MTOW data for the year of production of Airbus and Boeing aircraft

3. Results and Discussion

Various scatter plots related to the size, geometric, mass, and aerodynamic characteristics of the aircraft have been created from the compiled data. Some power and linear correlations with a high value of R-Squared (R^2, coefficient of determination) value were obtained from the distribution charts for use in the conceptual design of commercial passenger jets. In this section, first, geometric and dimensional characteristics, then mass characteristics and finally aerodynamic characteristics of Airbus and Boeing aircraft were compared, and correlations were revealed. It is known in the literature that the wingspan and fuselage length are functions of maximum take of weight (MTOW); in this study, it is explained what kind of correlation occurs with the equations obtained from the charts. Fig. 2 shows the power correlation between the fuselage length and MTOW, as well as power correlation between the wingspan and MTOW. Eq. 1 gives the correlation between fuselage length and MTOW, where length is in meters and MTOW is in kilogram. Eq. 2 gives the correlation between the wingspan and MTOW, where the length is in meters and MTOW is in kg. There is a power relationship between MTOW and length.

$$\text{Wingspan} \cong 0.26\ \text{MTOW}^{(0.43)} \tag{1}$$

$$\text{Fuselage length} \cong 0.32\ \text{MTOW}^{(0.42)} \tag{2}$$



(a) (b)

Figure 2. (a) The power correlation between the wingspan and MTOW (b) The power correlation between the fuselage length and MTOW

Fineness ratio is the ratio of the fuselage length of to its maximum width X, which is a leading parameter in parasite drag of an aircraft. Fig. 3 shows the linear relationship between fineness ratios in Airbus and Boeing aircraft according to wingspan/fuselage length ratios. Airbus' fineness ratio (fuselage length/cabin width ratio) ranges from 8.3 (A310-300) to 14.1 (A340-600), while Boeing's fineness ratio ranges from 8.2 (Boeing 737-100) to 15.7 (Boeing 757-300). Since cabin widths range from 3.5 m (Boeing 727) to 6.5 m (A380) and fuselage lengths range from 31.4 m (Airbus A318-100) to 76.3 m (Boeing 747-8I), it is the fuselage lengths that determine the fineness ratio rather than the cabin width. The wingspan varies from 34.1 m (A318, A321) to 79.8 m (A380) in Airbus, and from 28.4 m (Boeing 737) to 68.5 m (Boeing 747-8I) in Boeing. The wingspan-to-fuselage-length ratio in Airbus ranges from 0.76 (A321-200) to 1.1 (A380). The wingspan-to-fuselage-length ratio in Boeing ranges from 0.69 (Boeing 757 300) to 1.14 (Boeing 737-600). The ratio of wingspan to fuselage length in Boeing varies between 0.69 (Boeing 757-300) and 1.14 (Boeing 737-600). The deviation in Airbus's slope in Fig.3 is due to the Airbus A380 aircraft.

Narrow-body aircraft have a cabin width of less than 4 meters and a single aisle. The cabin width of wide-body aircraft is more than 5 meters; exceptionally, the Boeing 767 is a wide-body aircraft with a width of 4.72 meters. Airbus's A310 and A320 series are narrow-body aircraft (3.7 m), while the A330, A340, A350 and A380 series are wide-body aircraft. Boeing's 707, 727, 737 and 757 series are narrow-body aircraft (3.5 m), while the 747, 767, 777 and 787 series are wide-body aircraft. In different types of the same models, the aspect ratio and wing area are generally same, and in general, aspect ratios are between 8-10. Airbus's wing aspect ratios range from 7.5 (A380) to 10.1 (A340), while Boeing's wing aspect ratios range from 7 (Boeing 747) to 11.1 (Boeing 787). As extreme examples, the Boeing 737-400 has a wing area of 91 m^2, the Boeing 747-8I has 554 m^2, the Airbus A-320 has 123 m^2, and the A380 has 845 m^2.

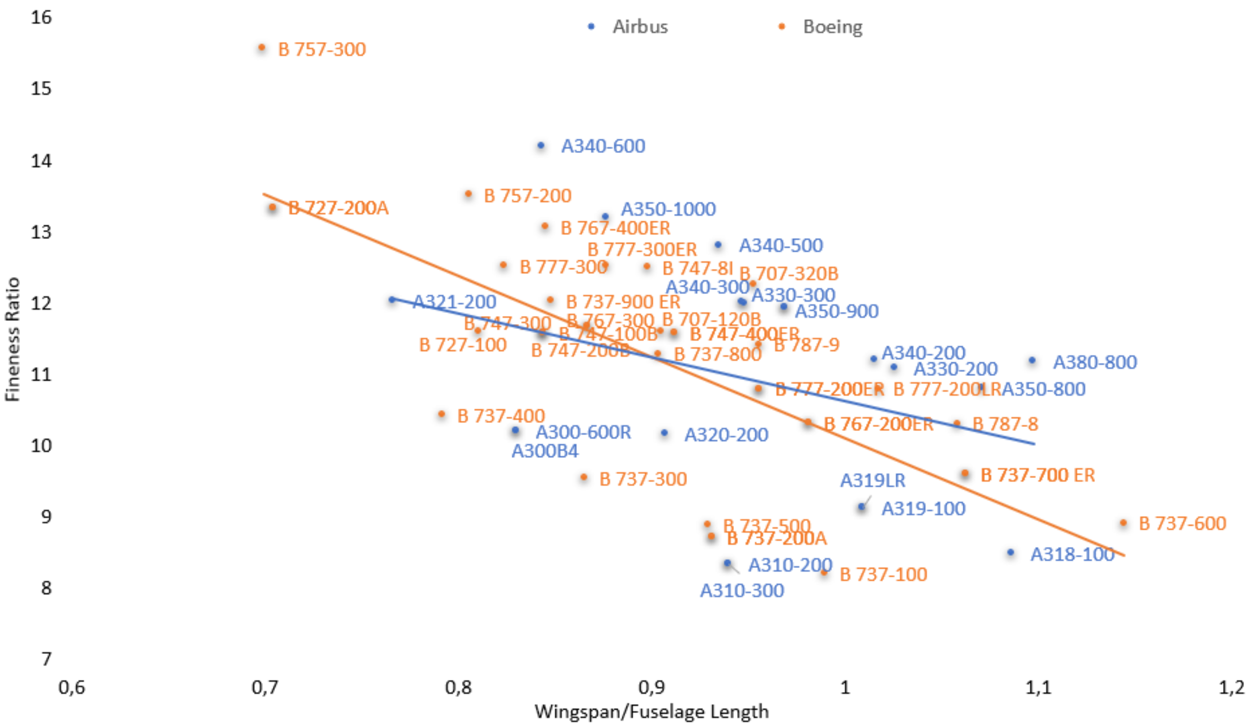


Figure 3. Distribution of fineness ratios in Airbus and Boeing aircraft according to wingspan/fuselage length ratios

From the trendline equations presented in Fig. 4, it can be said that there is a power correlation between the wing area (S_{wing}) and MTOW in commercial aircraft with a high R^2 value. Although Airbus and Boeing have similar curves in terms of wing area, it can be said that Airbus aircraft have a slightly larger wing area than Boeing aircraft. Eq. 3 and Eq. 4 gives the correlations between the MTOW and wing area where wing area is in m^2 and MTOW is in kg. Although Durmus [21] proposed a power law of 2/3(0.66) in subsonic aircraft, in this study, the power relationship between wing area and mass in large commercial aircraft was approximately 0.84 and 0.9. It can be said that the power relations obtained in Eq. 3 and Eq.4 are proportional to the square of the relations obtained in Eq. 1.

$$S_{wing,\ Airbus} \cong 0.0044\ MTOW^{(0.91)} \qquad (3)$$

$$S_{wing,\ Boeing} \cong 0.0101\ MTOW^{(0.84)} \qquad (4)$$

The ratio of operational empty weight (OEW) to MTOW is an important parameter in the payload analysis of commercial aircraft. Fig. 5 shows the distribution of the operational empty weight of the aircraft according to the MTOW ratios. OEW/MTOW ratios in Boeing aircraft range from 0.42 (Boeing 777 200 LR) to 0.61 (Boeing 737-200). The OEW/MTOW ratios in Airbus aircraft range from 0.42 dec A350-900R) to 0.58 (A318-100). Generally, the frequency range of the OEW/MTOW ratio is between 0.45 and 0.55. In general, it can be said that the OEW/MTOW ratio decreases as the aircraft mass increases according to linear relationship. Exceptionally, it can be stated that the slope of the double-decker aircraft, namely the Boeing 747 and the Airbus A380, is inconsistent with the general curve slope.

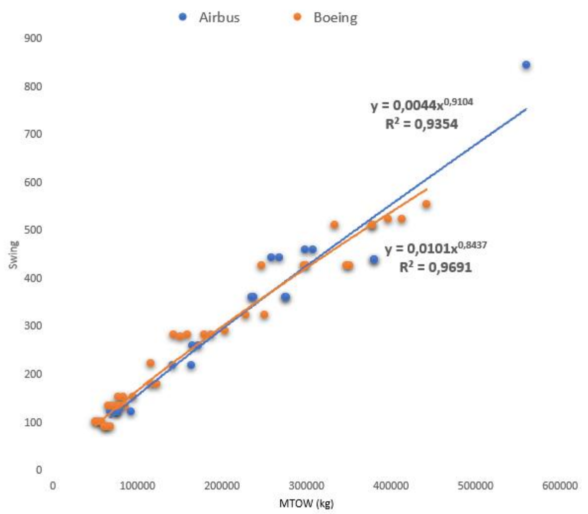


Figure 4. The correlation between wing area and MTOW in Airbus and Boeing aircraft

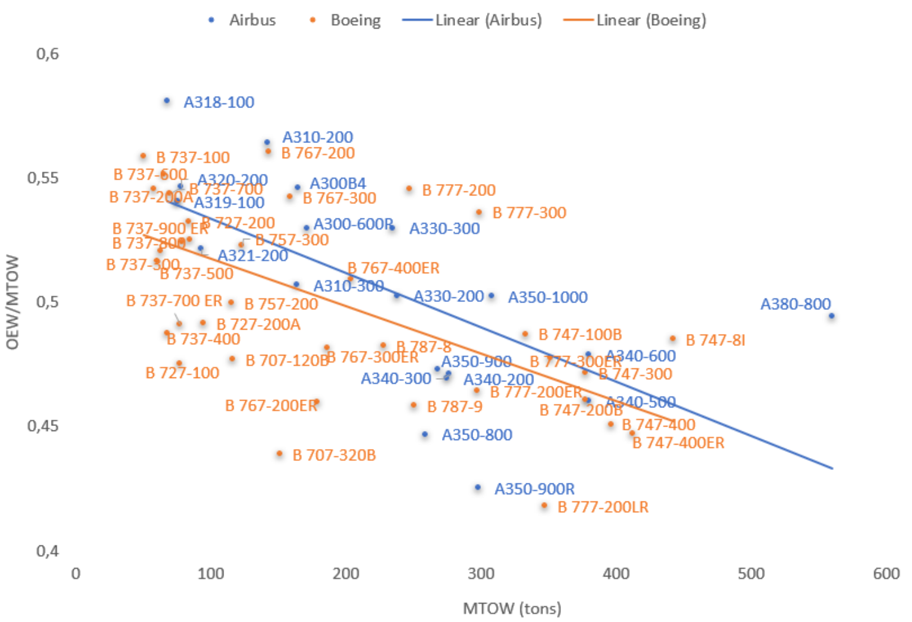


Figure 5. OEW/MTOW distribution chart with MTOW on Airbus and Boeing aircraft

Based on the results presented in Fig. 6(a) and 6(b), it can be said that there is a linear relationship between MTOW with both the engine mass and total engine thrust. On the other hand, the same engine (GE CF6-80C2) can be used in aircraft types belonging to the same series (such as Boeing 767-200, 767-300, 767 400 ER) despite their different MTOWS. Since the level of technology affects the correlations of aircraft parameters, some correlations have obtained for before and after based on the year 1990, which is the year composite materials began to be used in aircraft. The correlation results indicate that, the engine weight increases as the bypass ratio increases. Eq. 5 and Eq. 6 gives the correlations between the engine mass and MTOW, where both are in tons.

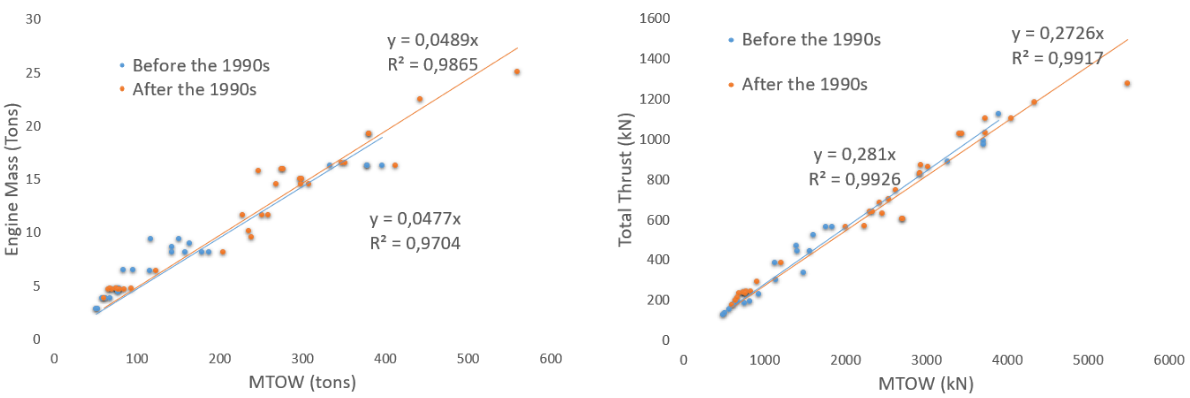
$$\text{Engine mass}_{\text{After the 1990s}}=0.0489\ \text{MTOW} \tag{5}$$

$$\text{Engine mass}_{\text{Before the 1990s}}=0.0477\ \text{MTOW} \tag{6}$$

A linear relationship was found between the total engine thrust and MTOW with a the R^2 is 0.99. Eq. 7 and Eq. 8 gives such correlation considering the year of first flight.

$$\text{Total Engine Thrust}_{\text{ After the 1990s}}=0.273\text{MTOW} \tag{7}$$

$$\text{Total Engine Thrust}_{\text{ Before the 1990s}}=0.281\text{MTOW} \tag{8}$$



(a) (b)

Figure 6. (a) Correlation between engine mass with MTOW considering the year of first flight (b) Correlation between total engine thrust and MTOW considering the year of first flight.

The thrust-to-weight ratio (T/W) is a ratio that describes an aircraft's thrust relative to its weight. Thrust-to-weight ratios of Airbus and Boeing aircraft are given in Fig. 7. The T/W ratio is a dimensionless parameter. In general, an accumulation occurs in the range of 0.25-0.35 in medium-weight aircraft (MTOW<200 tons), while an accumulation is observed in the range of 0.25-0.30 in heavy-weight aircraft (MTOW> 200 tons).

Thrust to weight (T/W)-wing loading (WL) charts are knowns as matching charts to optimize an aircraft's aerodynamical design point by flight phases such as cruise, take-off, and landing. Low T/W and low WL limits the take-off and cruise flight phases, while high WL and high T/W limit the landing (approach) flight phase. The matching chart given in Fig. 8 indicates an idea of the design point of commercial passenger aircraft. While maximum cruise speed and gust stability increase with increasing wing loading, while short take-off landing (STOL) capability of aircraft increases with decreasing wing loading.

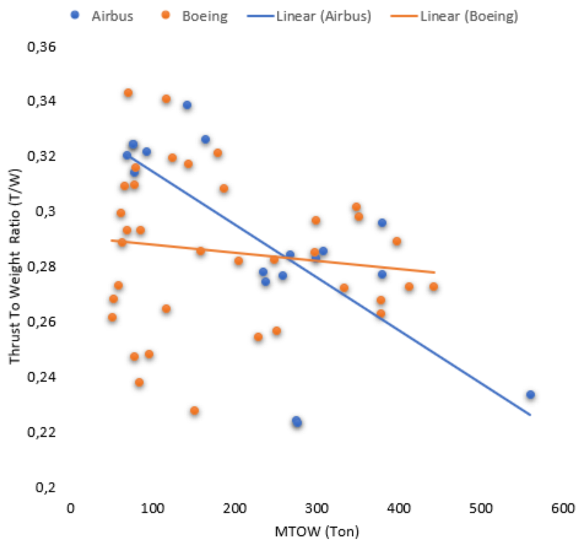


Figure 7. Correlations between thrust to weight ratio (T/W) and MTOW

Figure 8. Aerodynamic design point of Boeing and Airbus aircraft

4. Conclusion and Suggestions

In this study, the geometric, mass, and aerodynamic characteristics of 20 Airbus and 36 Boeing aircraft were compared. A power relationship between fuselage length and MTOW, wingspan and MTOW has been deciphered. In general, fineness ratio ranges from 8.3-14.1 in Airbus, and 8.2-15.7 in Boeing. The cabin width of the narrow-body Airbus is about 3.7 m and that of Boeing is about 3.5 m. Cabin width of wide-body Airbus is 5.3-6.5 meters and that of Boeing is 5.5-6.1 meters and exceptionally, the Boeing 767 is a wide-body aircraft with a width of 4.72 meters. The length of fuselage varies between 31.4-75.3 m in Airbus and varies between 30.5-76.3 m in Boeing. The wingspan ranges from 34.1-79.8 m in Airbus, that of Boeing ranges from 28.4-68.5 m. in Airbus, the wingspan/fuselage length ratio ranges from 0.76 to 1.1 and that of ranges from 0.69 to 1.14 in Boeing. Wing area ranges from 123-845 m^2 in Airbus and 91-554 m^2 in Boeing. In general, aspect ratio values are accumulated between 8-10, although Airbus's wing aspect ratios range from 7.5 to 10.1and Boeing's wing aspect ratios range from 7 to 11.1. In general, accumulation range of OEW/MTOW ratio is from 0.45 to 0.55. OEW/MTOW ratios range from 0.42 to 0.61 in Boeing and that of range from 0.42 to 0.58 in Airbus. Engine mass is between 4.0-7.0% compared to total aircraft mass in Airbus and that of between 3.94-8.06% in Boeing. Thrust to weight (T/W) ratios of accumulated in the range of 0.25-0.35 in medium weight aircraft (MTOW<200 tons), and that of in the range of 0.25-0.30 in heavy weight aircraft (MTOW>200 tons). There is a linear relationship between wing area-MTOW and total engine thrust-MTOW with a high R-squared. Fineness ratios decreased linearly as wingspan/fuselage length ratios increased and as the MTOW increases, the operational empty weight/MTOW ratio tends to decrease. Engine mass and the total thrust of the engines have tended to increase linearly with increasing MTOW.

Statement of Research and Publication Ethics

The study is complied with research and publication ethics.

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