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The Aircraft Choice Based on the Aircraft Take-Off Runway Length Requirement

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ABSTRACT: The choice of fleet by a given airline must consider different elements associated with both the aircraft and the airports to be operated, making it necessary a method to assist the aircraft choice process. This study assesses the take-off runway distance requirement of different aircraft models and compares the requirement to the take-off runway distance available at a group of airports. Using the Herfindahl–Hirschman index (HHI), the methodology consider the analysis of take-off runway length available on 80 Brazilian airports and compared it to the take-off distance required for 108 combinations of aircraft model, engine model and flight range, considering the take-off performance of the aircraft models with maximum payload weight. In total, 536 routes of four Brazilian airlines has been adopted to simulate the most profitable operating scenario. The result presents the take-off performance of different aircraft models and allows a performance comparison between them. In addition, this research investigates which is the most common flight range in Brazil, and what influence it exerts in the aircraft take-off performance, and contributes to a better match between the aircraft used and the airport operated in fleet optimization.

KEYWORDS: Air transportation; Airline fleet planning; Runway length.

INTRODUCTION

Before an aircraft to take-off, an airline flight dispatcher must assess several parameters regarding the aircraft take-off performance. The same aircraft may require different runway distance to operate depending on its take-off weight, air temperature, altitude, wind and runway declivity. For an aircraft lift off the ground, the wings must produce a lift force greater than the aircraft weight. Four variables are essential to produce such force, and those are airspeed, air density, wing area and coefficient of lift. The last variable is a constant determined by the airfoil design and the angle of attack (Horonjeff *et al.* 2010).

A flight dispatcher cannot change the aircraft wing area and coefficient of lift since these are manufacturing characteristics. In addition, the air density varies significantly according to the altitude, air temperature, and air humidity. Thus, in the lift force equation, the airline employee can only manage the take-off airspeed, but it has a serious limitation. The aircraft cannot keep developing greater speed indefinitely due to the tire speed limitation and, above all, due to the physical length limitation of the take-off runway. Sometimes, this limited available area situation imposes constraints to the aircraft take-off weight. When that happens, the airline dispatcher must decide whether to reduce the payload or the fuel onboard, in order to reduce the aircraft take-off weight. Otherwise, the aircraft will not reach enough speed to produce a lift force greater than its weight within the available runway distance.

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Naturally, a high load factor flight is likely more profitable for airlines than a low load factor flight. Any constraint to the aircraft payload produces a significant downturn into the airline revenue. Therefore, this paper intends to address a method to compare different aircraft models based on their take-off runway distance requirements. In other words, the main objective of this paper is to assess the take-off performance of several aircraft models on a group of preselected airports considering that each one of them has specific characteristics regarding runway distance, reference temperature and airport altitude. From these data, this paper intends to compare the take-off performance between aircraft models and assess which one has better suitability in the respective group of airports.

One of the main contributions of this research is to provide a very useful method for airlines in the process of choosing a new aircraft model to acquire. The airline in question might use the main idea of this paper as an assistant tool to better assess the suitability of each potential aircraft considering the group of airports that the airline operates. On the other hand, one may think this is a useful sale tool for aircraft manufacturers since it might be used to emphasize the great performance of its aircraft towards its competitors.

It is necessary to say that many more other factors are also necessary in the process of choosing a new aircraft model to acquire. The aircraft take-off performance and take-off runway distance requirements are only two points that an airline should consider. Among these, other factors are market demand, number of competitors airlines, number of airports in the network, comfort, fuel consumption and other operating costs and so on (Clark 2007). However, despite the relevance of all these aspects, this paper does not address such features. The reason for that is because many of these factors are highly dependent on aircraft take-off performance. For instance, one aircraft may have lower fuel consumption than its competitors, but this has no use if this same aircraft is unable to take-off with enough payload to break even the flight costs. Similarly, it is not very useful to acquire an aircraft that has several comfortable seats to meet up with the market demand if many of these seats must be empty in order to the aircraft be able to take-off. In other words, there is no use an aircraft that meets all demand requirements and has reasonable operating costs, but lacks the capacity to operate into the group of airports that the airline flies.

Based on these objectives, this paper presents two main objectives. The first regards the take-off runway distance available on each airport, and the second one concerns the take-off runway distance required by each aircraft with a full payload. The combination of both analyses may suggest from and to which airport an aircraft can fly. It is worth to say that there are many other parameters that may influence the aircraft operability at an airport or on a runway and taxiway in general, such as wingspan, which influences ground movements, or the gauge of the landing gear, which may damage the airport pavement (Horonjeff *et al.* 2010). However, this paper does not consider those points and only focuses on the aircraft capability to operate at an airport based on the aircraft capacity to take-off with maximum payload weight within the airport runway distance available.

This study uses information of 80 Brazilian airports and 108 different combinations of aircraft models, engine variants and flight range. It also uses the main idea of Herfindahl–Hirschman index (HHI) to develop an aircraft take-off performance index. The traditional index is chosen as a basis, since it enables to state a nonlinear relation between the aircraft model and the number suitable airports, instead of establishing a simple linear ratio.

TAKE-OFF VARIABLES, AIRCRAFT SIZE DRIVERS AND AIRPORT RUNWAY LENGTH

The air density is a relevant variable in the lift force equation and, therefore, a relevant factor in the take-off procedure. However, the air density is an unmanageable aspect that the airline flight dispatcher cannot control. In fact, the air temperature and altitude pressure have great influence in the air density. As the air temperature increases, the air gets less dense. Similarly, the higher the altitude, the lower the barometric pressure and, consequently, the lower the air density (Horonjeff *et al.* 2010). For those reasons, an airport located at sea level has the air denser than an airport located at a higher altitude, given the same air temperature. Since the lift force is proportional to the air density, an aircraft trying to take-off from an airport with a denser air will need to reach lower speed in order to generate the same lift force than an aircraft trying to take-off at an airport with a less dense air. Therefore, airports located at higher altitude usually have a longer runway than airports located at sea level due mainly to two reasons. The first regards the lift force equation; as mentioned before, less dense air will require a greater take-off speed in order to balance the equation. The second reason is the aircraft engine: a turbofan engine generates less thrust in higher altitude due to the less dense air. This means that, in this situation, the aircraft must accelerate for a longer time in order to reach a certain velocity (Horonjeff *et al*. 2010).

For all those reasons, when engineers are designing an airport runway, they must determine the runway length based on the airport altitude, airport reference temperature and the critical aircraft model that expects to operate there. This kind of planning tries to guarantee the best solution in terms of performance and economics. A too long runway is too expensive to build and to maintain and a too short runway may not be suitable for many aircraft models. Naturally, sometimes the market demand increases and the critical aircraft model changes for a bigger one. If the runway length available is not long enough to allow a take-off operation of this bigger aircraft in its full capacity, it is necessary to constraint the aircraft payload. Whenever this situation becomes a current issue, the best solution is the expansion of the runway. Unfortunately, this is not always possible, either by physical or financial limitations. The only remaining option for the airline, in that case, is to keep the operation with seat-constrained aircraft, or even to change the aircraft model for another one with better take-off performance.

Based on that aircraft size issue, Berster *et al*. (2015) state that airports operating in the limit of runway hourly capacity tend to have an increase in average aircraft size. However, airlines may be creating a second problem when they switch the aircraft model for a bigger one due to the runway hourly capacity. A larger aircraft may even work out for the runway capacity issue by increasing the number of seats available per flight. Although, if the larger aircraft's take-off runway distance requirement is greater than the airport runway length available, the payload capacity is going to be compromised. In this situation, the airline must constrain some of the aircraft's seats in order to reduce the take-off weight, which may cause a severe loss of revenue over time.

Some studies discuss if runway size influences the average aircraft size in the airport. According to Pai (2010), the longer the airport runway, more likely is an increase in flight frequency and aircraft size. This is in accordance with previous explanations since the use of an aircraft with only half load factor is hardly as profitable as a full one, and a large aircraft cannot be used in its full capacity if operating on a short runway, due to the take-off and landing performance restrictions. Pai (2010) investigates the effect of flight distance on the aircraft size and suggests that further destinations lead to bigger aircraft models because of its greater fuel capacity and consequently longer flight range. This is in agreement with the idea of Berster *et al*. (2015), who suggest that the average flight range at a specific airport is one of the most considerable factors which explains average aircraft size. However, Pai (2010) affirms that if the airport is constrained by slots or has adjacent airports, there is a tendency to lower the frequency and to have smaller aircraft models.

Givoni and Rietveld (2009) affirm that air transportation demand is forecasted to keep growing, but aircraft size is not. This is particularly beneficial for airports that already have runway length limitations due to the airport's surroundings. In that case, the airport is not able to expand the runway, but its operations are not likely affected by some potential bigger jet in the future. Nevertheless, the authors bring up the fact that runway capacity determines the airport capacity, in what concern number of aircraft per hour. Therefore, once the runway capacity reaches its maximum, the airline can only use larger aircraft models in order to increase the revenue passengers.

Wei and Hansen (2003), Givoni and Rietveld (2009) and Pai (2010) affirm that some markets, such as the United States of America, prefer smaller aircraft models flying more often than larger aircraft models on fewer frequencies. This is mainly because of business travelers, who may have higher time cost and rather have more time traveling options. Despite that, some authors even discuss that larger aircraft models usually have a less operating cost per seat. Merkert and Hensher (2011), Wei and Hansen (2003), Zuidberg (2014) and Zou *et al*. (2015) counterpoint this benefit by arguing that an increase in aircraft size leads to higher purchasing cost and pilots with a higher salary, not mentioning more expensive airport and air traffic charges.

Finally, the area available for expansion in the airport's neighborhood, the cost of land and construction cost also determine the length of the runway. Some airports are located where there is no viable option for a runway extension, either due to operational as to financial aspects. Airports like Santos Dumont Airport (SBRJ), at Rio de Janeiro, and Congonhas International Airport (SBSP), at São Paulo, are examples of congested airports, with serious runway length limitations. Because of the dense traffic flow, Congonhas is constrained by slots. Madas and Zografos (2010) investigate which is the best slot allocation strategy for a specific airport and what are the impacts of the slot policy. Similarly, Debbage (2002) proposes that some changes in slot policy should be done in order to make an airport more elastic when managing origin-destination tourist flows.

METHODOLOGY

The Herfindahl–Hirschman index (HHI) is an indicator usually associated with market concentration. The index sums the squares of the market share percentage of each company in the market. The results vary from 0 (highly competitive market) to 1 (market monopoly) (Holloway 2008). However, Zou *et al*. (2015) use the HHI idea for a different purpose. The authors suggest a method to quantify the fleet standardization in any airline by assuming that a fleet composed by a single aircraft model has more concentration in an aircraft model level than a fleet composed by two or more aircraft models. Their study divides fleet standardization into manufacturer, family and model levels and then it uses the HHI index to calculate and classify fleet concentration in each level.

This study also suggests using the original idea of HHI for a different purpose, by creating an index to assess the capacity of different aircraft models to operate in a group of airports. The main idea is to compare the take-off runway distance required by each aircraft model to the runway distance available on each airport. As with the traditional HHI index, the method proposed by this research suggests that the greater the convergence and the greater the concentration of airports in which the aircraft model can operate without restrictions, the greater the result obtained. Therefore, an aircraft model that operates in most airports without weight restriction has a result close to 1; otherwise, the aircraft model has a result close to 0. In other words, the index indicates the suitability of an aircraft model on a group of airports. These results allow comparisons of which aircraft model has the most potential to operate at most of the airports analyzed, without payload restriction.

One of the advantages of using the HHI idea is that it enables to state a nonlinear index instead of a simple linear one, where the result would follow a proportional ration of the number of suitable airports. In other words, the result of this method has very little effect of suitable airports in the beginning. This effect gradually increases to a point where again the result has little effect, as more airports are considered suitable for the aircraft. This implies that the result will be less if there are few suitable airports, gradually increasing until reaching a point where the index will only get higher.

A total of 15 aircraft models were selected from three distinct aircraft families of three different manufacturers. Note that, since most of the aircraft models have more than one engine option, 27 possible aircraft-engine combinations have been found. All aircraft families are currently in operation on at least one of the four major Brazilian airlines during this research: Gol, Latam, Azul and Avianca (domestic flights in Brazil ceased in 2019). Additionally, 80 airports were chosen to provide take-off runway distance data. All airports have the regular operation of at least one of these four airlines. The criteria for the airport selection was that the airport should have regular traffic operation and should authorize flights under visual flight rules (VFR) and instrumental flight rules (IFR). The criteria assume that if the aerodrome already has a regular operation, it indicates an existent demand and, consequently, an economic interest from major airlines. In addition, an airport with IFR operations is more likely to receive larger aircraft models and greater investments over time than an airport with VFR operations only.

To perform the analyses correctly, information regarding the runway length, pavement specifications, altitude and reference temperature of each airport was necessary. Such data was crucial in order to identify which was the performance of each aircraft model at each airport. However, the aircraft manufacturer does not provide on the Airplane Characteristics for Airport Planning (ACAP) document information regarding the aircraft performance on all possibilities concerning altitude and temperature variation. For that reason, this paper applied for every airport the runway length correction method suggested by the International Civil Aviation Organization (ICAO, 2006).

In terms of altitude, the length of the runway available at an airport of 1000 ft and the length of the runway available at an airport of 3000 ft should not be simplistically compared. In other words, one should not compare only the length value itself. This is because high altitude airports have low air density, and therefore the aircraft requires a longer runway distance to take-off. This means that a long runway does not necessarily imply better operating conditions. The ICAO (2006) method counterbalances this air density issue and it allows conversion of the runway distance available to the equivalent distance if air temperature and barometric pressure were equal. Therefore, this paper considers all airports as if their barometric pressure were 1013 hPa (standard barometric pressure at sea level) and had a reference temperature equal to 15 °C (the standard temperature at sea level). This weighing process guarantees a fair comparison of the runway distance of airports that has different atmosphere conditions, including different altitude and the reference temperature. Hence, this paper only considers the equivalent runway distance available obtained from the ICAO method. This process allows a fair comparison of the aircraft models' take-off performance in every selected airport since all aircraft models are under the same evaluation condition. In addition, this process also permits the comparison of the equivalent runway distance available of all selected airports.

In order to keep the analyses more realistic, this paper also considers the average flight range of the airlines and its effect on the aircraft take-off performance. As previously explained, a long flight requires more fuel, and this consequently increases the take-off weight. This paper divides the flight range into four groups: flight range up to 500 nm, from 501 to 1000 nm, from 1001 to 1500 nm, and from 1501 up to 2000 nm. Table 1 presents information on average flight range in Brazil.

Table 1. Average flight range in Brazil.

Flight range up to	Routes		Number of scheduled flights daily		Weekly flight frequencies	
	Quantity	% Share	Quantity	% Share	Quantity	% Share
500 nm	290	54.10	2365	67.48	10884	66.53
1000 nm	165	30.78	780	22.25	3617	22.11
1500 nm	79	14.74	352	10.04	1830	11.19
2000 nm	2	0.37	8	0.23	28	0.17
Total	536	100	3505	100	16359	100

According to Table 1, from all 536 routes regularly operated by Brazilian airlines, more than a half corresponds to flights up to 500 nm. This distance is equivalent to a one-hour flight from Brasília to Rio de Janeiro. Besides the flight range of each route, this paper also considers two other factors, such as the number of scheduled flights daily (time options) and the weekly flight frequencies. In other words, it is possible to precise the number of flights that occurs in each flight range group. Only 28 flights per week have a flight range longer than 1501 nm, which is equivalent to a four hours flight from São Paulo to Manaus. Therefore, aircraft models with such flight range are not so desirable in this market.

As explained before, the aircraft take-off weight (TOW) is a fundamental variable to calculate the runway distance required for a safe take-off operation. This variable is equivalent to the sum of the aircraft operational empty weight (OEW), the payload weight (PW) and the fuel weight (FW) of the flight. Clearly, all aircraft have a maximum payload weight (MPW) and a maximum fuel weight (MFW) due to physical and structural limitations. However, the maximum take-off weight (MTOW) is usually lower than the sum of OEW, MPW and MFW. This implies that an aircraft cannot take-off with both MPW and MFW. This situation usually demands a tradeoff of one for another. In other words, the airline has to choose between taking off with maximum payload or maximum fuel. Since a high load factor flight is much more profitable and desirable than a low load factor flight, this paper assumes that the airline rather has an MPW than an MFW. Therefore, the required take-off distance considers the aircraft TOW as the sum of the aircraft OEW, MPW, and FW required for the flight.

Once the air temperature, airport altitude and aircraft TOW are known parameters, the required take-off runway distance for each aircraft model can be determined according to its respective ACAP document. Equation 1, therefore, compares whether the Airport *i*, with a runway distance available (Rwa) supports the operation of aircraft *j*, with MPW and take-off distance required (To), loaded with enough fuel to fly the range *k*.

$$A_i o = \frac{Rwa_i}{To_{jk}} \tag{1}$$

where $A_i o$ stands for the operability of airport *i*, Rwa_i is the equivalent runway distance available at the airport *i* and To_{jk} is the take-off runway distance required by the aircraft *j* for the Flight Range *k*.

If the result of Eq. 1 is equal to 1 or more, the runway distance available at the airport is clearly longer than the take-off runway distance required for the aircraft, which indicates that the airport *i* supports the operation of aircraft *j* fueled for flight range *k*.

Otherwise, the runway available is not long enough and the aircraft j cannot operate in the airport i under these conditions. The results of all airport/aircraft/flight range combinations may be applied to Eq. 2 and 3.

$$ToPerf_{HHI_{jk}} = \left(\frac{\sum A_{jk}}{\sum A} \right)^2 \tag{2}$$

$$ToPerfMkt_{HHI_j} = \sum_{k=1}^{n} Fr_k \left(\frac{\sum A_{jk}}{\sum A} \right)^2 \tag{3}$$

where A_{jk} is the number of airports that supports operation of aircraft j for flight range k, A is the total number of airports and Fr_k is flight range k.

Equation 2 presents the take-off performance (ToPerf) of each aircraft model j for the respective flight range (Fr) k. These equations allow a direct comparison between aircraft models and their capacity to operate without payload weight restrictions. However, Eq. 2 allows only a comparison of aircraft suitability on-air markets (ToPerfMkt) that has no predominance of flight range. In the case of Brazil, most part of the flights occurs within 500 nm. This means Eq. 3 is more suitable to analyze the problem since it considers the share of each flight range as a weighing factor. In other words, both equations can be used to evaluate the potential of each aircraft model regarding the aircraft suitability on a group of airports, but only Eq. 3 considers the specific share of each flight range. Table 2 shows an example of the derivation process for a fictional aircraft of Eq. 2 and 3.

Table 2. Derivation process for fictional aircraft model.

Fictional aircraft model	Flight range			
	500 nm	1000 nm	1500 nm	2000 nm
Take-off distance required	1300 m	1500 m	1700 m	1800 m
Number of suitable airports	79	69	54	46
ToPerf (Equation 2)	0.975	0.744	0.456	0.331
Share of weekly flight frequencies	66.53%	22.11%	11.19%	0.17%
ToPerfMkt (Equation 3)	0.865			

Table 2 presents the derivation process of a fictional aircraft model. This aircraft has a range of more than 2000 nm. As the flight range increases, the take-off distance required increases as well. For a flight range of 500 nm, the aircraft requires at least 1300 m to take-off and for a flight range of 2000 nm, the aircraft requires at least 1800 m to take-off. Naturally, there are less suitable airports as the flight range increases. ToPerf assesses the performance of the fictional aircraft on the group of airports per flight range. ToPerfMkt assesses the performance of the fictional aircraft on the group of airports and weighs the share of weekly flight frequencies.

RESULTS

The take-off runway distance required by an aircraft and the runway distance available at an airport are fundamental elements for Eq. 1, and consequently, for Eq. 2 and 3. On the other hand, the take-off runway distance required by an aircraft depends on the aircraft's take-off weight, the air density and aircraft's take-off performance. Table 3 presents the real runway length and the equivalent runway length of the 80 airports considered in this study. The same table also shows the take-off runway distance required by the aircraft models (aircraft/engine combination) per flight range.

As Table 3 presents, most airports (36.3%) has a real runway length between 2000 and 2499 m. However, there is almost a 10% reduction in the number of runways within that same distance when considering the equivalent runway length. On the equivalent runway distance column (more restricted conditions), most runways (40%) categorize into the 1500–1999 m group. Few airports have a real runway length with 3000 m or more and there are fewer when considering the equivalent runway length. As Table 3 shows, this aspect is not an issue to the aircraft models analyzed, since none of them require a take-off runway distance of 3000 m or more. In fact, for a flight range up to 500 nm, which is the most common range in Brazil, more than a half of the aircraft models only need a runway with 1499 m or less, and none requires a runway with more than 2000 m. As expected, the take-off runway distance required increases as flight range increases. Although, in all four flight range categories the runway distance most required is 1999 m or less, which is also the most common equivalent runway distance available in the 80 airports.

Table 3. Runway distance available and take-off runway distance required.

Runway length category (m)	Runway distance available				Take-off runway distance required per flight range							
	Real runway length		Equivalent runway length*		500 nm		1000 nm		1500 nm		2000 nm	
	Airports	%	Airports	%	Acft's	%	Acft's	%	Acft's	%	Acft's	%
1000–1499	2	2.5	11	13.8	16	59.3	10	37.0	5	18.5	2	7.4
1500–1999	24	30.0	32	40.0	11	40.7	15	55.6	16	59.3	11	40.7
2000–2499	29	36.3	22	27.5	0	0.0	2	7.4	5	18.5	9	33.3
2500–2999	16	20.0	13	16.3	0	0.0	0	0.0	1	3.7	5	18.5
3000–3499	7	8.8	1	1.3	0	0.0	0	0.0	0	0.0	0	0.0
3500–3999	1	1.3	0	0.0	0	0.0	0	0.0	0	0.0	0	0.0
4000–4499	1	1.3	1	1.3	0	0.0	0	0.0	0	0.0	0	0.0
Total	80	100	80	100	27	100	27	100	27	100	27	100

Acft's: Aircraft models. *The equivalent runway length runway equals to the real runway length, but considering the barometric pressure and reference altitude balance of ICAO (2006), as mentioned in previous sections.

Table 4 presents the main results of the ToPerf and ToPerfMkt equations individually for each aircraft model/engine variant. Some aircraft models have been removed from the Table 4 to make it better viewable. For a fair comparison between aircraft models, it is necessary to also consider the aircraft size. The number of seats available on each model works as a proxy for the aircraft size. As expected, if one considers the ToPerf individually for each aircraft model/engine variant, there is a decrease in suitability as flight range increases. This means that as greater the aircraft take-off weight, lower is the number of operational airports and, consequently, lower is the number of suitable airports for the aircraft model/engine variant. The ToPerf equation allows a direct comparison between different aircraft models. For that, one may compare the average performance of the aircraft models or even compare a specific flight range category.

According to Table 4, on average, the Airbus' models show better results if compared to similar Boeing's aircraft models. The Airbus A318 presents a result of 0.784 and 0.609 depending on the engine variant, while the same size Boeing 737-300 presents a result of 0.285 and 0.484. Clearly, there is a great difference between the results of both manufacturers' aircraft models. This emphasizes the relevance of the take-off performance comparison since the airline operating result might vary significantly depending on the fleet choice. Despite the lower performance, it must be noted that the Boeing 737-300 entered in service almost 20 years before the A318. This means that the Airbus' model has much more improvements in fuel efficiency and engine thrust than Boeing's model. As an example of this effect, the same A318 has a much closer result with the Next Generation B737-600, which has the same size and has a result of 0.589 and 0.858, depending on the engine variant. Since the Boeing's aircraft entered in service only a few years earlier, it presents a much more competitive result and may provide better operating performance for the airline, depending on the aircraft's engines.

Table 4. Aircraft take-off HHI performance.

Aircraft Characteristics				$ToPerf_{HHIjk}$						$ToPerfMkt_{HHIj}$	
Manufacturer	Model	Seats (single-class)	Engine model (Takeoff thrust)	HHI_ 500 nm	HHI_ 1000 nm	HHI_ 1500 nm	HHI_ 2000 nm	Model average	Manufacturer average	HHI_j	Manufacturer average
Airbus	A318-100	132	CFM56 Series (24500 to 32900 lb)	1.000	0.810	0.744	0.581	0.784		0.928	
Airbus	A318-100	132	PW6000 (22000 to 24000 lb)	0.810	0.744	0.581	0.303	0.609		0.769	
Airbus	A319-100	156	IAE V2500 Series (23000 to 26600 lb)	1.000	1.000	0.975	0.810	0.946	0.618	0.997	0.761
Airbus	A320-200	180	CFM56 Series (27980 to 30000 lb)	0.788	0.581	0.345	0.263	0.494		0.692	
Airbus	A321-100/200	220	IAE V2500 Series (30400 to 32000 lb)	0.581	0.375	0.263	0.106	0.331		0.499	
Boeing	B737-300	134	CFM56-3B1 (20,000 lb)	0.581	0.375	0.150	0.035*	0.285		0.487	
Boeing	B737-300	134	CFM56-3B2 (22,000 lb)	0.810	0.581	0.331	0.214*	0.484		0.705	
Boeing	B737-400	159	CFM56-3B2 (22,000 lb)	0.544	0.331	0.150	0.045*	0.267		0.452	
Boeing	B737-500	122	CFM56-3B1 (20,000 lb)	0.810	0.620	0.375	0.150*	0.489		0.718	
Boeing	B737-600	130	CFM56-7B18/-7B20 (20,000 lb)	0.975	0.744	0.375	0.263*	0.589		0.856	
Boeing	B737-600	130	CFM56-7B22 (22,000 lb)	1.000	1.000	0.810	0.620*	0.858		0.978	
Boeing	B737-700/W	148	CFM56-7B26 (26,000 lb)	0.810	0.788	0.766	0.701	0.766	0.425	0.800	0.594
Boeing	B737-700ER/EWR/C/CW	148	CFM56-7B20/-7B22/-7B24 (20,000 lb)	0.456	0.263	0.083	0.008	0.202		0.370	
Boeing	B737-700ER/EWR/C/CW	148	CFM56-7B26/-7B27 (26,000 lb)	0.879	0.810	0.744	0.581	0.754		0.848	
Boeing	B737-800	184	CFM56-7B24/-7B26/-7B27 (26,000 lb)	0.581	0.331	0.250	0.150	0.328		0.488	
Boeing	B737-900/W	189	CFM56-7B24/-7B26 (24,000 lb)	0.263	0.150	0.035	0.008	0.114		0.212	
Boeing	B737-900ER	189	CFM56-7B26/-7B27 (26,000 lb)	0.263	0.150	0.106	0.035**	0.138		0.220	

continue...

Table 4. Continuation.

<table>
<tr><th colspan="4">Aircraft Characteristics</th><th colspan="6">$ToPerf_{HHIjk}$</th><th colspan="2">$ToPerfMkt_{HHIj}$</th></tr>
<tr><th>Manufacturer</th><th>Model</th><th>Seats (single-class)</th><th>Engine model (Takeoff thrust)</th><th>HHI_ 500 nm</th><th>HHI_ 1000 nm</th><th>HHI_ 1500 nm</th><th>HHI_ 2000 nm</th><th>Model average</th><th>Manufacturer average</th><th>HHI_j</th><th>Manufacturer average</th></tr>
<tr><td>Embraer</td><td>E170STD</td><td>78</td><td>CF34-8E5 (14500 lb)</td><td>1.000</td><td>1.000</td><td>0.879**</td><td>0.744**</td><td>0.906</td><td rowspan="4">0.749</td><td>0.986</td><td rowspan="4">0.930</td></tr>
<tr><td>Embraer</td><td>E175STD</td><td>86</td><td>CF34-8E5 (14500 lb)</td><td>1.000</td><td>0.810*</td><td>0.601**</td><td>0.106**</td><td>0.629</td><td>0.912</td></tr>
<tr><td>Embraer</td><td>E190STD</td><td>106</td><td>CF34-10E5 / −10E6 (20360 lb)</td><td>1.000</td><td>0.810</td><td>0.744**</td><td>0.544**</td><td>0.774</td><td>0.929</td></tr>
<tr><td>Embraer</td><td>E195STD</td><td>118</td><td>CF34-10E5A1 / −10E6A1 / −10E7 (20360 lb)</td><td>0.975</td><td>0.810*</td><td>0.581**</td><td>0.375**</td><td>0.685</td><td>0.894</td></tr>
</table>

*For this flight range, this aircraft model requires a tradeoff between payload (decrease) and fuel (increase) to augment the flight range in less than 250 nm. **For this flight range, this aircraft model requires a tradeoff between payload (decrease) and fuel (increase) to augment the flight range in more than 250 nm.

The Boeing 737-300 is one of the oldest Boeing's aircraft model considered in this paper, but it does not present the worst performance, which was the result of 0.114 of the B737-900/W with a 24,000 lb-engine. The most probable reason for that is related to the aircraft size and not so much with the age of the project, since this aircraft belongs to a relatively new generation. The same situation occurs among Airbus' and Embraer's aircraft models. The bigger jet from each one has the worst performance in its respective manufacturer group (A321 with IAE V2500 Series and E195 with a 20,360-lb-engine, respectively).

Those results agree with Pai (2010), who affirms that airports with longer runway tend to have an increase in aircraft size since bigger aircraft models need more take-off runway distance to operate. In addition, since the Embraer's aircraft models have lower seat capacity (118 seats) than Boeing and Airbus, it has a greater average among all aircraft manufacturers (0.749). However, since Embraer's aircraft are not designed to fly long distances, all aircraft models have to tradeoff payload for fuel in order to be able to fly 1500 and 2000 nm without exceeding the aircraft maximum take-off weight. Pai (2010) and Berster *et al.* (2015) address this issue and associate flight distance to aircraft size, due to the fuel capacity issue. The Airbus average is 0.618, while its rival Boeing presents a result of 0.425. Unfortunately, the Airbus' documents used to verify each aircraft performance does not specify the engine takeoff thrust as Boeing's and Embraer's documents do. For that reason, some bias may be inferred due to this data limitation.

As discussed, the air transport market in Brazil has a tendency for flights up to 500 nm. Since the ToPerfMkt equation considers the probable use of the aircraft in the market, all aircraft models present a better performance in this index. Those results are highly influenced by the Brazilian market characteristics since short ranges require less fuel, which leads to a lighter aircraft, and, therefore, the aircraft needs a shorter distance to take-off. In other words, in Brazil, the aircraft models are more commonly required to fly distances that are shorter than 500 nm, which decreases the need for long runways and increases the number of airports capable to receive the aircraft with maximum payload. Some aircraft models, such as A318, A319, B737-600, E170, E175, and E190 even present results greater than 0.900, which is a result that only two aircraft models achieved in the ToPerf model. The manufacturer average also presents an increase in its results of 0.143 for Airbus, 0.168 for Boeing and 0.181 for Embraer. The results of all aircraft models and aircraft manufacturers indicate that the combination between aircraft model and flight range weighting factor generates a better performance result than when not considering the latter one.

Another interesting aspect is the effect caused by the variation of the engine type over the results of the same aircraft model. Since many aircraft models have more than one option for engine model, the aircraft operator may usually choose freely among the options available. Clearly, an engine model with lower take-off thrust will require a long take-off runway due to its limited thrust capacity. Since the thrust capacity changes the aircraft take-off performance, the results also vary according to the aircraft motorization. For instance, a B737-300 equipped with a CFM56-3B1 at 20,000 lb has a result for ToPerf of 0.285 and 0.487 for ToPerfMkt, while the same B737-300 equipped with a CFM56-3B2 at 22,000 lb has a result of 0.484 and 0.705, respectively. This situation occurs in all engine variation within the same aircraft model. Therefore, such characteristics must be carefully considered when comparing the aircraft models.

CONCLUSION

The method proposed in this paper intends to provide a simple, but a still efficient method to compare the performance of different aircraft models. The equations assess the potential of each aircraft to operate in a group of airports by comparing the take-off runway distance required by each aircraft and the take-off runway distance available at each airport. This comparison has great utility for airlines in fleet and network planning areas. Clearly, during the process of aircraft model selection, an airline analyzes several parameters besides the aircraft take-off performance, such as purchasing or leasing price, maintenance costs, training costs, fuel efficiency, flight range, comfort, aircraft size, cargo capacity, passenger demand, and others. Therefore, this method does not have the pretension to inform which is the best aircraft model for an airline. Instead, this paper intends to work as a decision tool, which can assist in the decision-making process.

This method also carries some limitations that must be considered. For instance, the methodology based on the HHI does not consider the importance that each airport has for the airline's network. All airports have an equal impact in the proposed index, making it not possible to identify whether the aircraft has the capacity to operate at airports that are more strategic for the airline. Also, the runway length available at the airports does not consider the presence of a stopway or a clearway, which has a huge influence on the aircraft take-off weight and performance. More than that, due to data limitations, all calculus regarding the aircraft performance is based on the Aircraft Characteristics for Airport Planning (ACAP) document, which only provides some general information regarding the real aircraft performance. This aspect does not exert any influence on the validity of the method, but it produces bias on the results, making it harder to interpret due to the inaccurate input data. Furthermore, the same aircraft model may be certified with different take-off weight, depending on the airline needs and requirements, such as internal layout, extra fuel tanks, flight system entertainment and so on.

An interesting aspect of the method is the possibility to compare the aircraft models considering the flight range. The results of this procedure are much like market demand. Perhaps the fact that three out of four major Brazilian airlines operates aircraft models from the A320 family instead of Boeing's aircraft is one of the possible explanations why the Airbus' models present better performance results than its rival. Although, it must be considered that Gol, which is the only one that operates the Boeing 737, has in most of its fleet the short field performance package. Boeing developed this feature under the request of the airline, which at that time was considering the purchasing of several B737-800. This package allows the aircraft to operate in the most profitable route in the country without severe payload restrictions: São Paulo–Rio de Janeiro. In order to present this package, Boeing executed some technical variations in the aircraft and certified the aircraft operation on relatively short runways. Once more, the data information available did not present the specific performance of the aircraft model with the short field performance package installed. This lack of information may have been decisive for the better performance results obtained by the Airbus aircraft models.

This paper provides an assistance tool to assess the suitability of each aircraft model to operate in a group of airports. The method is very useful for airlines in the network planning and fleet selection process. Also, aircraft manufacturers can use the main idea of the paper to emphasize the great take-off performance of its aircraft. Finally, future researches may include in analyses some other relevant variables for a fleet choice, such as aircraft purchasing or leasing price, maintenance costs, training costs, fuel efficiency, aircraft size, and cargo capacity.

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REFERENCES

[ICAO] International Civil Aviation Organization (2006). ICAO 9157 PART 1: Aerodrome Design Manual Part 1 Runways. Montreal: ICAO. [accessed Sep 15 2018]. https://standards.globalspec.com/std/10188115/icao-9157-part-1

Berster P, Gelhausen MC, Wilken D (2015) Is increasing aircraft size common practice of airlines at congested airports? J Air Transp Manag 46:40-48. https://doi.org/10.1016/j.jairtraman.2015.03.012

Clark P (2007) Buying the big jets: fleet planning for airlines. 2nd ed. Abingdon: Routledge.

Debbage KG (2002) Airport runway slots: limits to growth. Ann Tour Res 29(4):933-951. https://doi.org/10.1016/S0160-7383(02)00004-X

Givoni M, Rietveld P (2009) Airline's choice of aircraft size – Explanations and implications. Transp Res Part A Policy Pract 43(5):500-510. https://doi.org/10.1016/j.tra.2009.01.001

Holloway S (2008) Straight and level: practical airline economics. 3rd ed. Abingdon: Routledge. Chapter 5, Unit Cost.

Horonjeff R, McKelvey FX, Sproule WJ, Young SB (2010) Planning and design of airports. 5th ed. New York: McGraw-Hill.

Madas MA, Zografos KG (2010) Airport slot allocation: a time for change? Transp Policy 17(4):274-285. https://doi.org/10.1016/j.tranpol.2010.02.002

Merkert R, Hensher DA (2011) The impact of strategic management and fleet planning on airline efficiency – A random effects Tobit model based on DEA efficiency scores. Transp Res Part A Policy Pract 45(7):686-695. https://doi.org/10.1016/j.tra.2011.04.015

Pai V (2010) On the factors that affect airline flight frequency and aircraft size. J Air Transp Manag 16(4):169-177. https://doi.org/10.1016/j.jairtraman.2009.08.001

Wei W, Hansen M (2003) Cost economics of aircraft size. J Transp Econ Policy 37(2):279-296.

Zou L, Yu C, Dresner M (2015). Fleet standardisation and airline performance. J Transp Econ Policy 49(1):149-166.

Zuidberg J (2014) Identifying airline cost economies: An econometric analysis of the factors affecting aircraft operating costs. J Air Transp Manag 40:86-95. https://doi.org/10.1016/j.jairtraman.2014.06.007