Development of Operating Cost Models for the Preliminary Design Optimization of an Aircraft

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Abstract

The estimation of the operating costs of an aircraft during the design phase is fundamental to direct the project towards a solution that is cost competitive relatively to the aircraft available in the market. Losing track of the operating costs may imply that in the end of the optimization the aircraft, although possibly with major technological advances, is too expensive to operate and no airline is thus willing to buy it. During this thesis, models to determine the operating costs of an aircraft are designed to be used in the preliminary design of the aircraft optimization process. These models are relatively simple and depend primarily on the main physical and performance characteristics of the aircraft. They are designed in such a way that the user can define different mission characteristics, such as the stage lengths or the regions where the aircraft operates, in order to tailor the cost models to individual airline activities. Despite the simplicity of the models, they provide cost per available seat kilometre (CASK) values of the same magnitude of those collected from the financial reports of real airlines. Furthermore, they proved to be useful when determining the differences between the CASK of different routes, identifying which components have a most significant leverage on the final CASK, and when determining the design that is more adequate to one given airline missions profile, through the calculation of the profits generated using fleets composed only of each of the designs being compared.

Keywords: Preliminary Aircraft Design, Cost Models, Direct Operating Costs, Cost Optimization, CASK

1. Introduction

The airlines business is one that requires a high capital investment and delivers a return on the investment lower than most other industries [1]. The competitiveness of the market dictates that the airlines must seek cost saving potentials and efficiency improvements in order to survive.

For this reason, reducing the fuel consumption has been shown to be a critical point in the airlines economics, since today it accounts for roughly 30% of their total costs [2]. Furthermore, as an increasing number of aircraft are in service throughout the world, the emissions and noise will grow accordingly, and measures must be taken to ensure that their levels stay within the demanding environmental requirements that exist today and that the future goals are met [3, 4].

Along with fuel reduction, increased efficiency in other areas must be accomplished. Although oil prices have increased more than three times from the beginning of the century to 2010 (since then they have been slowly decreasing), airlines were able to approximately maintain the cost per revenue passenger kilometre (RPK), due to both fuel savings and reductions on the remaining costs. There are several different measures that can be taken to save fuel, such as estimating more accurately the on board weight or flying at higher altitudes. Besides, modernizing the fleet, by replacing older aircraft with more efficient new ones, with better performance, can lead to significant fuel savings.

Along with the improved fuel burn efficiency, these aircraft also have improved cabin configurations, allowing for more seats relatively to the original ones, which represents even higher savings in the fuel per seat.

Taking all of this into account, and in order to have as many orders as possible, manufacturers are mainly interested in developing aircraft that have the lowest possible operating costs, with a major emphasis on fuel consumption savings, but not forgetting factors such as the airframe and engines maintenance frequency schedules and costs - both in terms of time and spare parts prices.

This thesis is inserted in the project NOVEMOR of the EU 7th Framework Program, of which IST
was the partner leader. The aim of the NOVEMOR research project was to investigate novel air vehicle configurations with new lifting concepts and morphing wing solutions to enable cost-effective air transportation. These solutions were developed from the early stages of the preliminary design in order to lead to innovative designs that can improve aircraft efficiency, through an integrated use of these capabilities. These new designs are expected to increase aerodynamic performance, to reduce structural loads and to yield lighter structures, in order to allow for reduced fuel consumption throughout the aircraft mission and thus improving the green level of the aircraft.

At IST, an MDO framework that includes all aircraft disciplines - such as aerodynamics, structures, propulsion, stability and control - is being developed [5]. Additionally, environmental requirements of noise and emissions as well as operative costs are to be considered in the design optimization of the aircraft, since they are important regulatory limitations and economic factors, respectively, being therefore an active part of the design optimization process. The aim of this work is to develop the Cost Module, in order to primarily estimate as accurately as possible the costs incurred by the conceptual aircraft generated during a mission or a set of missions. The different elements of the direct operative costs will be estimated to make possible the analysis of the different levels of influence that each of the cost elements has on the cost structure. In this way, the choice between different optimization paths taking into account the costs will be easier to make.

2. State-of-the-Art

The Life Cycle of a product begins with the identification of a market need, and the consequent generation of a concept to fulfill that need, ending with its disposal. Asiedu and Gu [6] distinguish between four phases in the product life cycle: design development, production, use and disposal. Figure 1 shows that most of the life cycle costs of a product are incurred in the operational phase, and this is even more significant in the case of aircraft, which have very long life spans. Thus, from the end user point of view, what matters most is how to reduce these operational costs. It is on the early phases of the product design that most of the life cycle costs are defined - at the end of the design process, around 80% of the costs are already defined, regardless of almost everything that comes afterwards. This shows how important it is to design the right aircraft for the right mission, since very few leverage exists for the airline to reduce its operational costs.

Willcox [8] divides the operating costs into four categories: Airplane Related Operating Costs (AROC), Passenger Related Operating Costs (PROC), Cargo Related Operating Costs (CROC), and Systems Related Operating Costs (SROC). The AROC, which comprise 70% of the operating costs, are the ones that depend mostly on the aircraft physical and performance characteristics, so they are the ones to be optimized during the aircraft design. Within these, 40% corresponds to the ownership costs, which depend on the aircraft price. The remaining 60% (or direct operating costs) are the costs with fuel, cockpit and cabin crews, landing and navigation taxes, noise and emission fees, and maintenance.

2.1. Aircraft Price

There are two ways of looking to how the aircraft price is set: either cost-based pricing, which means that to the manufacturing cost are summed both an assigned part of the development costs and the manufacturer margin to provide a selling price; or a market-based pricing, which means that the price is going to be more a function of the competitors’ prices, and is determined much more by how much the client is willing to pay for that aircraft, given its perception of its characteristics.

Several methods to estimate the price of the aircraft in a cost-based pricing were studied, such as the Rand Corporation DAPCA methods [9, 10] and Roskam’s method [11]. Other methods exist, and are either the ones upon which these methods were drawn, or were drawn upon these methods. There are some problems associated with these methods, namely the fact that they are considerably old, which means that they do not take into account factors such as the new market conditions and the use of new technologies and materials. Furthermore, most of these methods are more suitable to military aircraft programs, which have a very different nature and cost structure than commercial civil aircraft programs. A final problem with this approach is that the aircraft prices are based on the market conditions, i.e. depend on the prices and characteristics of the aircraft from the competing manufac-
With this in mind, the study of the aircraft price was directed to the market-based approach. Here, more recent methods are available, and are all directed to commercial civil aircraft. To estimate the aircraft price, the different methods use a set of variables that reflect more or less directly the economic value of the aircraft, which is what matters most in the end to the airlines. Roskam [11] uses the maximum take off weight (MTOW) as the only variable to calculate the price of the whole aircraft. Although some limitations can be pointed to this approach, such as not accounting for the lower range capacity, which represents a decrease in value for the airlines, when the MTOW increases, good approximations are obtained. Liebeck et al. [12] recognize that aircraft are not sold on a price-per-pound basis and set the airframe price as linear with a variable they call payload-range index, which is the product of the number of seats of the aircraft and its range capacity. Furthermore, they calculate the engine price separately from the airframe, depending on the thrust of the engine and the number of engines of the aircraft. Markish and Wilcox [13], in 2003, present two different equations of the same form to estimate the prices for narrow body aircraft and wide body aircraft, as a function of the seat capacity and the range of the aircraft. In the same year, Isikveren et al. [14] develop a more complex model using as variable the product of the Range and Mach number at long range cruise conditions, cabin volume and number of seats, divided then by the balanced field length. This intends to take into account all those factors that are influenced or influence the weight that Roskam’s relationships could not account for.

2.2. Direct Operating Costs

When it comes to evaluate the value of a given aircraft, airlines are mostly concerned with the economics of flying each possible equipment. The estimation of the Direct Operating Costs (DOC) is an important part of the design process, since it provides a measure of how much it costs to fly an aircraft in a given mission and with a given utilization. These costs are highly dependent on the design of the aircraft, which means that they can be controlled to a great extent by the design engineering team.

Three basic methodologies to estimate DOC of turbine powered aircraft have been designed and served as a basis for the majority of the methods publicly available: the ATA, the NASA and the AEA methods [15]. Liebeck et al. and Roskam also present methods to estimate the DOC based on studies performed by the authors. More recently, Harris [16] has analysed the US Department of Transportation Form 41 data, which contains the actual costs incurred by US airlines separated by each component, and drawn models for calculating each of the components of the DOC. All of these methods reflect the costs incurred by US based airlines, but the CeRAS DOC method [17] is drawn for the European air transportation business.

Most of these methods rely mainly on the MTOW of the aircraft for calculating the fuel consumptions and costs, the costs with pilots, landing and navigation fees and maintenance costs. The seating capacity is also used for the calculation of the cabin crews costs and the sea-level static thrust is used when calculating the engine maintenance costs. The distances flown in each trip and the number of flight hours are used for the calculation of navigation fees and personnel costs. The flight cycles per year are also an important on the calculation of the maintenance costs, which have a component dependent on the utilization of the aircraft and another one on the cycles performed. The ownership costs, as mentioned earlier, are mostly dependent on the aircraft price, along with assumptions for the rates and periods of the interest, insurance and depreciation costs. None of these methods takes into account, however, the emission and noise taxes. The noise taxes are levied locally by the airports. Some airports, mainly in Europe, also levy emission fees, but European restrictions exist today through the Emissions Trading Scheme (EU-ETS) [3] only for flights within Europe, although the idea is to apply them for every flight to, from and within Europe. The problem with this system is that it consists of allowances bought by the airlines, sometimes at auctions, which means that finding a relationship between the amount paid for the allowances and the distances flown is rather complex.

3. Acquisition Price Models

The acquisition price of the aircraft plays an important role on its direct operating costs, since it defines how much the ownership costs will be. As seen before, the price of a commercial aircraft depends on how much the client is willing to pay for it, i.e. on the value that he/she perceives the aircraft will provide in comparison to the other aircraft available in the market. There are many variables that influence the value perceived by a client of a given aircraft, but it all comes down to having the lower operating costs, often measured in dollars per available seat kilometre (ASK). Three main aircraft characteristics are more closely linked to the perception of aircraft value: the range of the aircraft, since it defines the routes that can be served; the seating capacity, which defines the amount of revenue that can be potentially generated in a given route and, on the costs side, the amount of seats by which the
costs will be divided; and the fuel efficiency, comprising both the engines and the aerodynamic efficiencies, which determines the amount of fuel spent in a given flight mission.

The main physical and performance characteristics of the aircraft and engines being sold today (aircraft from Airbus\textsuperscript{TM}, Boeing\textsuperscript{TM}, Bombardier\textsuperscript{TM} and Embraer\textsuperscript{TM} and engines from CFM\textsuperscript{TM}, General Electrics\textsuperscript{TM}, Pratt and Whitney\textsuperscript{TM} and Rolls Royce\textsuperscript{TM}) were compared against their respective list prices in order to draw relationships to estimate these prices. Models that depended only on one single variable were first tested, and then estimating relationships using more than one variable were designed in order to take into account the main characteristics referred in the previous paragraph. Three different models, with different levels of complexity (or amount of information needed) were designed to be used in different stages of the design process, as more reliable information is available to the optimizer.

It is important to note that, besides the aircraft characteristics, these models depend heavily on the market prices of similar aircraft, since they were designed from their data. If for some reason, for instance, all the aircraft were to cost 10% more of their actual prices or 50 million dollars more, the models devised would no longer be applicable. Thus, from time to time, these models should be reviewed to make sure that their usage still provides good estimates.

3.1. Early Model - MTOW

The first model uses only the MTOW to estimate the aircraft price, since this value, or a good approximation, is available since the earliest stages of the design process. Equation 1 estimates the price for all types of jet aircraft, either narrow body or wide body. The errors are always smaller than 20%, typically decreasing for larger aircraft.

\[
ALP_{\text{Early}} \left[ \text{\$M} \right] = -0.001050 * MTOW^2 + 1.332 * MTOW - 5.656
\]  

3.2. Intermediate Model - Range+Seats

For an intermediate phase of the optimization process, where information about both range and seats is already available, a combination of the Range capability and Seat capacity of the aircraft is used. Equations for each of these variables individually have been designed, and this model presents them together with different weights. Two equations are presented: one for narrow body aircraft, which uses the maximum seating capacity, and one for wide body aircraft, which uses the typical cabin configuration seating capacity.

\[
ALP_{\text{Intermediate}} \left[ \text{\$M} \right] = 0.85 \times [78.182 \times \text{ln}(\text{Seats$_{Max}$}) - 309.62] + 0.15 \times [32.7 \times e^{1.53E-4 \times \text{Range}}]
\]  

\[
ALP_{\text{Intermediate}} \left[ \text{\$M} \right] = 0.85 \times [255.29 \times \text{ln}(\text{Seats$_{Typ}$}) - 1178.1] + 0.15 \times [32.7 \times e^{1.53E-4 \times \text{Range}}]
\]  

The maximum errors of each manufacturer for each category of aircraft (narrow bodies or wide bodies) of the individual range and seats models are lowered with this Intermediate Model for all manufacturers. The same happens with the average errors of each manufacturer. The errors are all smaller than 12.3% except for the Embraer\textsuperscript{TM} aircraft, with some of them almost at 30%. The gains are much more relevant relatively to the range model since the seats model had smaller errors. Nonetheless, apart from the benefit from decreasing the errors, the inclusion of two variables in the model is also important to take into account different characteristics important to the aircraft economics.

3.3. Late Model - Range+Seats+Thrust

Thrust is the last variable added to the price estimating models, since it is available later in the optimization. The reason behind the choice to design a model that uses thrust is that it will allow the optimizer to have an idea of how changes in the engines affect the entire aircraft price.

Although an engine with higher maximum thrust is most likely more expensive, if two aircraft have the same seat capacity and range, the one with higher maximum thrust engines is the cheapest one. As strange as it may sound, it makes sense since an aircraft that needs less thrust is one that will most probably have a higher efficiency, thus consuming less fuel by seat by mile flown. This relation, however, means that if the aircraft are exactly the same (with same aerodynamic efficiency), an engine with higher thrust rate will be priced lower. This way, one is not truly assessing the variations in the engine price but rather the variations in the aircraft efficiency (including the aerodynamic and engine efficiencies) by means of the engine thrust. The aircraft fuel efficiency is a factor much more important to the airlines than the engines thrust, which means that the resulting effect is better than simply capturing the engine price variation.

The incorporation of the thrust variable into the equations (one for narrow bodies and another one for wide bodies) is somewhat complex. Instead of calculating the entire aircraft price, Equations 2 and 3 are now only a part of the entire aircraft price. The other part - representing the engines price - is
given by an additional term, which will be higher if the thrust is lower:

\[ \frac{c}{(\frac{\text{TT}_{\text{omax}} N_e}{S * R})^3} \]

where \( c \) is a coefficient to be determined that is different for narrow bodies and for wide bodies, \( \text{TT}_{\text{omax}} \) is the maximum take off thrust for one engine, \( N_e \) is the number of engines, \( S \) is the number of seats (maximum for narrow bodies and typical for wide bodies), and \( R \) is the range of the aircraft.

To determine the approximate values of the coefficient \( c \), Equation 4 was equalled to the values gathered for the actual engines prices. An average of \( c_{\text{NB}} = 0.0046 \) and \( c_{\text{WB}} = 0.0081 \) was obtained.

The next step is determining how much the engine price amounts in the entire aircraft price. This percentage depends on the aircraft and varies between 20%-35% of the aircraft price - it is generally bigger for smaller aircraft. One possibility was to assume an intermediate value and use it for every aircraft, regardless of their size. This yielded substantially higher errors comparing to the Equations 2 and 3. Alternatively, a relationship between the weight of the engines price on the entire aircraft price and the seats capacity (maximum for narrow bodies and typical for wide bodies), was devised. An exponential curve was fitted to the data points and gave the approximate percentage that the engines price represents on the total aircraft price as a function of the seats capacity (maximum for narrow bodies and typical for wide bodies).

\[ \% \text{Eng.Price} = 2.4876 S^{-0.447} \]

After having the percentage of the engines on the total aircraft price, the following relationships were obtained for narrow bodies and wide bodies, respectively:

\[ \text{ALP}_{\text{LateNB}} \text{[$M]} = (1 - 2.1 * Seats_{\text{Max}}^{0.445}) * \frac{0.0046}{\frac{\text{TT}_{\text{omax}} N_e}{\text{R} \times \text{Seats}_{\text{Max}}}} \] (6)

\[ \text{ALP}_{\text{LateWB}} \text{[$M]} = (1 - 2.1 * Seats_{\text{Typ}}^{0.445}) * \frac{0.0081}{\frac{\text{TT}_{\text{omax}} N_e}{\text{R} \times \text{Seats}_{\text{Typ}}}} \] (7)

Comparing the Late Model with the Intermediate Model, the maximum errors with Bombardier\textsuperscript{TM} and Embraer\textsuperscript{TM} narrow body aircraft decreased from 28.7% to 18.6%, although this decrease has been verified only in the Embraer\textsuperscript{TM} aircraft and an actual increase happened in the errors of Bombardier\textsuperscript{TM} aircraft. Nevertheless, the fact that now no aircraft price is estimated with more than 20% error represents an improvement in the model. With Airbus\textsuperscript{TM} and Boeing\textsuperscript{TM} aircraft, the narrow bodies maximum error decreased from 12.3% to 7.9% and the wide bodies aircraft maximum error decreased just slightly from 10.3% to 9.9%.

Besides the decrease in errors, the fact that the engines and aerodynamic efficiencies are taken into consideration is also an improvement on the previous models. If all the information is available, this is the model that should be used.

4. Operating Cost Models

4.1. Flight Costs

Today, the most significant part of the operative costs are the fuel expenses due to the steep rise of the crude oil prices in the last decade. Although the calculation of the fuel costs is as simple as multiplying the fuel price by the fuel consumption, which should be provided by the propulsion module, the problem lies on the estimation of the fuel price on the long run, which is known to be very volatile, and the choice of slightly different values may yield distinct optimal designs. Data about the present jet fuel prices can be seen in the IATA website, and it shows the differences amongst the different regions of the world, which is useful to use with airlines based on different parts of the world. Since the fuel prices can change drastically in short periods of time, depending on countless factors, it is impossible to devise a relationship that could forecast the fuel prices. Several projections are available, ranging from very optimistic ones to the most pessimistic. It is advised the consultation of these projections (for instance the ones from the US Energy Information Administration or from the Organisation of the Petroleum Exporting Countries - OPEC) in order to come up with an estimation of an average fuel price, which will depend on the time span of the operation life and in great part on the opinion that the user has about the future prices.

Expenses with cockpit crews are a rather complicated task to model. These include the expenses with the captain and first officer and with any extra crew members that may be needed for long-haul flights. Furthermore, the expenses with cockpit crew members include not only their salary, but also other benefits (such as retirement plans, health care, among others), bonuses for international flights, overtime, and extra expenses with hotels and per diems. These benefits and other expenses can be very different from one airline to another, depending on their policy, and even more from one region of the world to another, which makes the task of building a general model more complicated. Cockpit crews salaries are based on the hours flown. This means that waiting times on airports and prior preparation for the flights are
that the increase in hourly costs is equal for all destinations, i.e. $b$ is always the same and equal to 2.2. The only parameter that changes with the destination is $a$. The different destinations are considered to be short-haul (up to 6 hours), medium to long-haul (between 6 and 8 hours) and very long-haul destinations (more than 8 hours), where in three crew members are needed. These relationships are assumed to stand for the rest of the world, since no information for other regions could be found, either to create new relationships or to adapt these ones.

The flight hour costs with cabin crews, unlike those with cockpit crews, depend solely on the number of members that are on board and not on the aircraft MTOW. However, different airlines may choose to use, in the very same aircraft type, different numbers of cabin crew members. The minimum required by American and European airworthiness authorities is one flight attendant per 50 seats or part thereof. In spite of this, due to different levels of service provided, airlines may choose to have more flight attendants on board. Data from the same source used for the cockpit crews expenses was gathered for cabin crews and the hourly cabin crews expenses by member is given by an equation of the form $a \times \exp(b \times \frac{Pax}{FA})$. In this equation, $a$ changes according to the destination, with short-haul flights (up to 6 hours) having $a = 40.413$ and longer flights $a = 44.454$. The parameter $b$ is set to be equal to 0.0239 regardless of the flight duration and $\frac{Pax}{FA}$ is the passenger to flight attendant ratio, which must be equal or lower than 50. The values obtained must then be multiplied by the number of flight attendants on each flight to yield the costs with cabin crews for each flight hour.

Landing fees are charges paid by the airlines to the airports for each landing that an aircraft performs there. The primary reason for their existence is to support the costs of maintaining the airport facilities and operations and to improve the quality of the airport services. Although this is not the only fee with this purpose, it is the only one considered in these models since, for a given airport, it depends solely on the aircraft characteristics, namely its weight. Since the landing fees are charged by the airports, their amounts can vary quite significantly from one airport to another, depending on the demand for that airport, on the existing neighbour airports and their fees and on the airports management entities. For this reason, the world was divided into the following regions, which have similarities in the fees applied: Europe, North America, Latin America, Africa, Middle East and Asia/Oceania. In a second level, North America was further divided into first tier cities, where the main airports are, and second tier cities and Asia/Oceania was also divided into airports in developed countries and those in developing countries.

For all the regions, the landing fees are applied using a formula of the form $a \times MTOW^2$, where $a$ differs between regions. However, in US airports, MGLW (maximum gross landing weight) should be used instead of MTOW.

Navigation fees, according to ICAO, should be levied to support the costs of providing air navigation services (operation, management, administration, maintenance and also costs of capital and depreciation). These charges should be user supported, i.e. following the user pays principle, non-discriminatory relatively to the origin of the user, charged, as far as possible, one single time per flight, and based on the distance flown and less than proportionally on the aircraft weight. As with the landing charges, the world was divided into those exact same different regions, except that now North America is divided only into US and Canada and the Asia/Oceania region is no longer divided. The navigation fees are of the form $a + b \times D \times MTOW^2$, where $D$ is the distance flown in each airspace and the exponents and coefficients vary from one region to another.

From all the regions analysed, it was only in Europe that most airports had noise charges or surcharges. It was thus assumed that only in European airports these charges are levied. These noise charges are generally calculated through the classification of the aircraft into noise categories, which are in most of the times drawn based on the noise certification of aircraft by ICAO standards present in Annex 16, Volume 1, Chapters 2, 3 and 4. For these categories there are three different measurement points, each one with its limits for each category. Aircraft compliant only with Chapter 2 are not allowed to land in most European main airports, except in emergency cases. Chapter 3 aircraft are further divided into 3 categories, high, base and low, according to the cumulative margin, which is the sum of the differences between the measured noise at the three points and the limits at those points. The noise charges do not stand alone, but are rather dependent on the landing charges. The way they are calculated is through the multiplication of the landing charges by a coefficient according to the noise category of the aircraft, as shown...
Table 1: Noise level categories and coefficients.

<table>
<thead>
<tr>
<th>Category</th>
<th>Cum. Margin in [EPNdB]</th>
<th>Coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>&lt;0</td>
<td>2.5</td>
</tr>
<tr>
<td>B</td>
<td>0-5</td>
<td>1.5</td>
</tr>
<tr>
<td>C</td>
<td>5-10</td>
<td>1.25</td>
</tr>
<tr>
<td>D</td>
<td>10-15</td>
<td>1.0</td>
</tr>
<tr>
<td>E</td>
<td>15-20</td>
<td>0.9</td>
</tr>
<tr>
<td>F</td>
<td>&gt;20</td>
<td>0.8</td>
</tr>
</tbody>
</table>

As in the case of noise charges, the emission-related charges are only levied on European airports. However, the application of these charges is more restrict, being applied in fewer airports than the noise-related charges. Only airports with a large amount of traffic or located within considerably populated areas are eligible to apply this charge, as advised by ICAO Document 9082. The airports found to levy these charges are located in London, in Germany, Denmark and Switzerland. Apart from the charges levied by the airports, as mentioned previously, there is in Europe the EU-ETS, which, for now, is only applicable to flights within Europe. The problem with this scheme is that it works through the purchase of allowances, rather than a direct cost on the emissions of a given flight. Furthermore, these allowances can be bought at different prices, depending on various factors such as the airline need for allowances, their overall availability, amongst others. For all these reasons, it is very difficult to allocate a cost to an emission value, and thus this system is not going to be considered.

Contrary to what happens with the noise charges, the emission charges are independent of other fees and are based on the absolute emissions (hydrocarbons and oxides of nitrogen) of an aircraft and vary linearly with them. The emission charges are calculated multiplying a charge factor that varies from one airport to another and the emission value calculated using a formula based on the European Civil Aviation Conference recommendation 27-4, developed from the work done by the ERLIG group.

4.2. Maintenance Costs

Regarding the maintenance costs, sufficient information could not be found to draw models from scratch, since the maintenance is a complex task, which depends not only on the hours flown, but also on the cycles performed by the aircraft. Additionally, it is not homogeneous through time, i.e. there are peaks of maintenance costs at different times due to the different levels of maintenance that either the airframe or the engines require during their life span. Furthermore, the maintenance can be done in-house or be outsourced, with each of these options having different costs. Lacking the data needed to draw a model, the remaining option was to adapt one existing model. The choice fell on the CeRAS maintenance model because it more recent than the other models available, which means that it represents better the maintenance practices of today, such as the progressively less frequent maintenance checks and the more expensive materials spendings due to the increased use of advanced materials, namely the composites. Despite being more recent, the CeRAS models were still updated to 2014 costs using labour costs indexes and materials costs indexes. There are two airframe maintenance cost equations, one for the labour and the other one for the materials, and only one for the engines, which includes both the labour and materials.

4.3. Ownership Costs

Concerning the ownership costs, the methods reviewed were studied to understand how the depreciation, insurance and interest costs were taken into account. It was chosen to assume that the aircraft is fully owned by the airline and not leased, since this was the practice most used in the aforementioned methods. The depreciation takes into account both the aircraft as bought and its airframe and engine spares. The airframe spares are considered to amount to 10% of the airframe price and the engines spares 15% of the engines price. The aircraft is assumed to depreciate evenly through 20 years until 10% of its initial value. Regarding the insurance, it is assumed that it has an annual cost of 1.5% of the aircraft price, excluding spares. The interest costs were also assumed to be equal every year, during 15 years, assuming an equal principal payment plan, with a rate of 5%, and are charged upon the aircraft price plus spares. These values can, however, be changed to be adapted to one given airline situation when performing an optimization.

5. Results

In order to test the relationships developed, a preliminary design of an aircraft optimized in the context of the NOVEMOR project was used. This aircraft has characteristics similar to those of the Embraer™190: it is a narrow body aircraft, with maximum seating capacity of 113, a range of 4387 km, two engines with a maximum take off thrust of 93.45 kN each, an MTOW of 58 t, an MGLW of 53 t, an operative weight empty (OWE) of 34 t and a Payload of 14 t. It was also assumed that the Chapter 3 cumulative margin was equal to 10 EPNdB and that the aircraft performed its missions at 85% of the payload capacity. Three test cases were performed, one where the cost per ASK (CASK) for
Different missions are compared using this aircraft, another one where one stretched and one shrunken version of the aircraft are designed and their CASK are compared, and one where the mission profiles of two real airlines are taken into account to assess the profitability of the choice between an all base version fleet and an all stretched version fleet. Finally, the CASK’s obtained are benchmarked against the CASK of real airlines.

5.1. Test 1 - Different Missions

Different missions, in different regions and different airports, were considered. Firstly, two missions with a range close to the range capacity of the aircraft were tested: one in the US from New York City (a major city) to Portland (a second tier city), with a distance of 3935 km and a utilization of 10 hours per day (referred to as US1-US2 Long); and another one in Europe, from Lisbon to Moscow - two airports without emission charges -, with a distance of 3914 km and a utilization per day of 10 hours too (referred to as EU0-EU0 Long). Then, the airlines with most Embraer 190 and 195 jets in their fleets were studied and the routes that they most often do with these aircraft were recorded. A representative set of 7 different missions were studied, from which were selected two missions: one in Europe with a length of 690 km and a 11 h/day utilization, between an airport that does not levy emission fees and another one that does (referred to as EU-EU3.3 Short); and another one in Australia, with a length of 713 km and a 8 h/day utilization (referred to as Asia-Dvdp Short).

The CASK obtained for the first two missions are very similar in all the components except for the Navigation fees costs, which are considerably higher in Europe, being responsible alone for the 9% higher total CASK. Then, comparing EU0-EU0 Long with EU0-EU3.3 Short, all cost elements are higher in the latter mission, except for Navigation fees because they are linear with the distances flown. The greater increase is seen in the Maintenance Costs (more than three times higher), which depend strongly on the flight cycles. Overall, the CASK for the short European mission is almost double the CASK for the long mission. As a final note on these routes, the emission fees costs are very low compared with the remaining costs. The use of the EU-ETS could provide increased costs in this component, but, as mentioned before, it is very difficult to model a relationship between the fuel consumed and the costs associated with this emissions scheme. Finally, a comparison between two missions with similar distances but different utilizations shows that the Ownership costs increase 50% with a utilization around 30% smaller. Figure 5.1 shows the typical proportions of each of the cost components, as obtained for the EU0-EU3.3 Short mission.

5.2. Test 2 - Different Aircraft Versions

Next, two versions of the aircraft were roughly designed to provide the main parameters needed to use the cost models. This design was done by analysing existing families with a base aircraft and stretched and shrunken versions, where the main difference is the fuselage length and the remaining structures are kept mainly unchanged. Variations of the price, MTOW, sea-level static thrust (SLST) and range with the number of seats were obtained with the relationships presented next derived from fitting curves to the data points of the families referred:

\[
\frac{Price}{Price_{base}} = 0.7427 * \frac{Seats}{Seats_{base}} + 0.2604 \tag{8}
\]

\[
\frac{MTOW}{MTOW_{base}} = 0.4950 * \frac{Seats}{Seats_{base}} + 0.5099 \tag{9}
\]

\[
\frac{SLST}{SLST_{base}} = 0.3986 * \frac{Seats}{Seats_{base}} + 0.5963 \tag{10}
\]

\[
\frac{Range}{Range_{base}} = 1.0074 - 0.352 * ln\left(\frac{Seats}{Seats_{base}}\right) \tag{11}
\]

On an absolute basis, the total CASK is higher for the smaller version of the family and lower for the longer version. For the nine missions studied previously, the shrunken version has a total CASK between 6.0% and 7.4% higher than the base version and the stretched version has a total CASK between 6.3% and 7.5% lower than the base version. The flight costs are the source for most of the differences, since they amount to around 50% of the total CASK and the changes are of around 10% higher and lower CASK for the shrunken and stretched versions, respectively. However, the biggest relative differences are on the maintenance costs, with around 14% increases in CASK for the shrunken version and around
10% decreases in CASK for the stretched version. The ownership costs suffer almost no change.

If there are no structural nor aerodynamic problems, the stretched version is the cheaper to operate in an ASK basis. In the same basis, the shrunk version is the most expensive since its structures and aerodynamic surfaces are over dimensioned.

5.3. Test 3 - Profitability

The choice of an aircraft is not dependent solely on the CASK, but it has to be taken into account which one of them better suits the missions to be performed. Although the CASK is lower, the total operating cost is higher for the stretched version, and if an airline cannot have a sufficient number of passengers flying the stretched version, the choice of the base or shrunk versions may be more profitable. With this in mind, a comparison between two airlines mission profiles using the base and the stretched versions tested was made. The missions performed by Air Canada™ and KLM™ City Hopper with their short haul fleet (Embraer™190, A320 family aircraft and Fokker 70) were recorded by length of missions. Figure 5.3 shows the distribution of missions for both of these airlines as a percentage of their total amount of short haul flights by distance intervals (from 0 to 200 km, from 200 to 400 km, and so on). It can be seen that the KLM™ City Hopper missions are more concentrated on the very short flights, while Air Canada™ has more longer missions. For each of these missions and for each of the airlines, the CASK was calculated, as well as the total cost per trip. Then, the total yearly costs for all the missions in their respective proportions and the global CASK (total costs divided by the total amount of ASK) were calculated. In general, the costs for the European airline are larger than those for the Canadian one.

\[
\frac{LF_{\text{stretch}}}{LF_{\text{base}}} = \left( \frac{R/PK_{\text{base}}}{R/PK_{\text{stretch}}} \right)^{2.5}
\]

The total profit for Air Canada™ decreased slightly from 3.05 to 3.04 US$ millions when changing from an all base version to an all stretched version fleet, while for KLM™ City Hopper the total profit increased more than 10% from 1.26 to 1.42 US$ millions. These results show that the models designed can identify the best of two aircraft versions for different airlines. However, they depend on the assumptions made for the margin between the R/PK and CASK and for the exponent in Eq. 12. Varying the values of the margin from -50% to +50% of the value used showed that the there is no significant gain or loss for Air Canada™ using the stretched version, but that KLM™ City Hopper always benefits with this choice. However, increasing the exponent of Eq. 12 shows that both companies gain with the stretched version but that this gain is more relevant for KLM™ City Hopper, while decreasing its value shows that both airlines lose with using the stretched version but that this loss is lower for Air Canada™. These results point to the need of an accurate definition of the price-demand elasticity behaviour of the passengers for each airline when optimizing the choice of different aircraft designs.

Finally, a benchmark of the results obtained was performed. Using a mission of 1200 km in the US with both the base and stretched versions, the CASK obtained with 2014 fuel prices was 8.80 and 8.17 US$ cents respectively. Comparing with the overall company CASKs for Southwest™ airlines, American Airlines™, JetBlue™ and Air Canada™, these results are between 15-40% higher. Comparing solely the fuel CASK, the results obtained with the models are less than 15% higher. Comparing now the CASK obtained for both versions in a 700 km mission in Europe, it was obtained a CASK of 11.83 and 10.98 US$ cents for the base and stretched ver-
ions, respectively. These results are between the overall company CASKs of British AirwaysTM and KLMTM. Ideally, the breakdown of the CASK by cost component for these airlines would allow a better comparison and a clear identification of the sources for the differences obtained. However, this information is not available. Nonetheless, given the results are in line for the European case and have the same magnitude for the North American case, the models seem to provide estimates coherent with the real costs of airlines.

6. Conclusions

The estimation of the operating costs of an aircraft during the design phase is fundamental to direct the project towards a solution that is cost competitive relatively to the aircraft available in the market. Losing track of the operating costs may imply that in the end of the optimization the aircraft, although possibly with major technological advances, is too expensive to operate and no airline is thus willing to buy it.

The work developed in this thesis consisted of building cost models to estimate the direct operating costs of different designs under consideration during the design optimization process. Besides providing final CASK values of the same magnitude of those of real airlines, the models proved to be useful when determining the differences in the CASK between different routes, identifying which components have a most significant leverage on the final CASK, and when determining the design that is more adequate to one given airline missions profile.

References


