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

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Resumo

Estimar os custos de operação de uma aeronave durante a fase de design é fundamental para direcionar o projecto para uma solução competitiva em termos de custos relativamente aos restantes aviões existentes no mercado. Perder a noção dos custos operativos durante a optimização pode significar que a aeronave, apesar de poder ter avanços tecnológicos significativos, seja tão mais custosa de operar em relação às aeronaves concorrentes que nenhuma companhia aérea deseje comprá-la.

Nesta tese são desenhados modelos para determinar os custos de operação de uma aeronave na fase de design preliminar do processo de optimização, sendo relativamente simples e dependentes principalmente das características físicas e de performance mais importantes do avião. Os modelos são desenhados de forma a que o utilizador possa definir diferentes missões a serem executadas pela aeronave na sua operação, tais como o alcance dos voos ou as regiões de operação, de maneira a adaptá-los à actividade individual de cada companhia aérea.

Apesar da relativa simplicidade dos modelos, os resultados obtidos têm a mesma magnitude dos custos de diferentes companhias aéreas de várias regiões do mundo. Para além disso, os modelos mostraram ser úteis na determinação das diferenças entre os CASK (custo por lugar disponível e quilómetro) de diferentes rotas, através da identificação das componentes do custo com maior impacto no CASK total, e na escolha do design mais adequado ao perfil de missões de uma determinada companhia aérea, através do cálculo dos lucros gerados usando frotas compostas apenas por cada um dos designs em comparação.

Palavras-chave: Design Preliminar de Aeronaves, Modelos de Custos, Custos de Operação, Optimização de Custos, CASK
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
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Nomenclature

Glossary

\( D \) Distance flown

\( D_{p}/Foo \) Mass of pollutant emitted divided by rated output of the engine

\( g \) Gravity Acceleration

\( IR \) Interest rate

\( LA \) Loan amount

\( L/D \) Lift to Drag Ratio

\( LP \) Loan period

\( Me \) Mach number at cruise

\( Ne \) Number of engines on the aircraft

\( p \) Navigation charges weight factor

\( R \) Aircraft Range

\( rc_i \) Individual FIR navigation route charges

\( RC \) Total navigation route charges

\( S \) Number of seats on the aircraft

\( SFC \) Specific Fuel Consumption

\( t_i \) Navigation charges unit rate

\( T_{TOmax} \) Maximum take off thrust for one engine

\( V \) Aircraft Speed
\( W_f \) Aircraft weight at the end of the stage
\( W_i \) Aircraft weight at the beginning of the stage

**Acronyms**

AEA Association of European Airlines
AFW Airframe Weight
ALP Aircraft List Price
AROC Airplane Related Operating Costs
ASK Available Seat Kilometres
ATA Air Transportation Association of America
CAROC Cash Airplane Related Operating Costs
CASK Cost per Available Seat Kilometre
CER Cost Estimating Relationship
CeRAS Central Reference Aircraft data System
CPI Consumer Price Index
CROC Cargo Related Operating Costs
DOC Direct Operating Costs
EASA European Aviation Safety Agency
ECAC European Civil Aviation Conference
EEA European Economic Area
EIA Energy Information Administration
ELP Engine List Price
ERLIG Emission Related Landing Charges Investigation Group
EU European Union
EU-ETS European Union Emissions Trading Scheme
FAA Federal Aviation Administration
FIR Flight Information Region
IATA  International Air Transport Association
ICAO  International Civil Aviation Organization
IOC  Indirect Operating Costs
LCC  Life Cycle Costs
LF  Load Factor
LTO  Landing and Take Off
MDO  Multidisciplinary Design Optimization
MGLW  Maximum Gross Landing Weight
MTOW  Maximum Take Off Weight

NOVEMOR  NOvel Air VEhicle Configurations: From Fluttering Wings to MORphing Flight
OPEC  Organization of the Petroleum Exporting Countries
OWE  Operating Weight Empty
PROC  Passenger Related Operating Costs
R/PK  Revenue per Passenger Kilometre
RDT&E  Research, Development, Testing and Evaluation
RPK  Revenue Passenger Kilometres
SLST  Sea Level Static Thrust
SROC  Systems Related Operating Costs
TOC  Total Operating Costs
US  United States
WER  Weight Estimating Relationship
1 Introduction

Over the last few decades, the world has faced multiple challenging crises, but, nonetheless, air traffic has managed to consistently grow at a long-term steady rate, as shown by both Airbus [1] and Boeing [2] in their market outlook and forecast analyses. For the next two decades, they both predict an annual growth rate in the air traffic measured in terms of Revenue Passenger Kilometres (RPK) of about 5% and in the number of airline passengers of over 4%, primarily as a consequence, as it has been the trend in the recent past, of the accented growth of the emerging economies, where every year the middle classes considerably increase their size, increasing thus the amount of people with capability of flying, for purposes of either leisure or business.

The operation of aircraft, i.e. the airlines business is one that requires a high capital investment and delivers a return on the investment lower than most other industries [3]. The competitiveness of the market dictates that the airlines must seek for 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 [1]. Furthermore, as more and more aircraft are in service throughout the world - Airbus and Boeing predict that the number of aircraft will double from the approximately 20 thousand of today to 40 thousand in 2033 -, the emissions and noise will grow, and measures must be taken to ensure that their levels stay within the demanding environmental requirements that exist today and the goals that have to be accomplished in the future [4, 5].

Along with fuel reduction, increased efficiencies in other areas must be accomplished. Although oil prices have increased more than 3 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 RPK, due to both fuel savings and reductions on the other 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 a more optimal altitude. Besides, modernizing the fleet, by replacing older aircraft with more efficient new ones, which have increased performance, can lead to significant fuel savings. As an example, Airbus new A320neo (New Engine Option) family, which is intended to replace the original A320 family, is predicted to achieve as much as 20% savings in fuel burn [6], which are obtained by more efficient engines - most of the savings are achieved here - and a redesigned wing, with more efficient aerodynamics and a higher quantity of composite materials. Both companies predict that, from the 13000 single-aisle aircraft existent today,
10000 will be replaced in the next 20 years, and a total demand of about 25000 new single-aisle aircraft is expected, showing that airlines are in fact very interested in these more efficient aircraft.

Along with the improved fuel burn efficiencies, these aircraft also have improved cabin configurations, allowing for more seats relatively to the original ones, which represents an even higher economy in the fuel per seat. Throughout the last years, airlines have been improving their load factors as a means to reduce costs, evolving from 70% to about 80% load factors in the last fifteen years alone, according to Airbus [1].

Other operative measures, such as redesigning hubs and flight schedules, and forming alliances with other airlines, have been taken to reduce costs and compensate for the increase in fuel prices.

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 lower possible operating costs, with a major emphasis on the fuel consumption economy, but not forgetting factors such as the airframe and engines maintenance frequency schedules and costs - both in terms of time and spare parts prices.

It is also obvious that, for as low as the operating costs may get, the purchasing price of the aircraft also plays a big role in the airlines decision of acquiring or not that particular aircraft, since it may require such a high investment that the return may not be so easily or rapidly obtained - the ownership costs, related to the depreciation, financing and insurance of the aircraft and which are proportional to its acquisition price represent more or less 30% of the operating costs [7]. This is the reason why new advanced concepts have not yet been explored too deeply for application in commercial civil air transportation, because the technologies and designs involved are in some cases almost completely different from what has been done in the past and the risks undertaken by the manufacturers will most likely lead to very high development costs, which in turn means that the aircraft prices will need to be higher, with no strong guarantee that the operating costs will be that much lower. Thus, there is some fear on the manufacturers side in undertaking such an enterprise which may compromise their future.

The discussion in this thesis will focus mainly on the study and prediction of the operating costs of a new aircraft. Predictions for the acquisition cost of such an aircraft, given its importance for the airline, are also discussed.

### 1.1 Context and Motivation

This thesis is inserted in the project NOVEMOR (NOvel Air VEhicle Configurations: From Fluttering Wings to MORphing Flight) of the EU 7th Framework Program, of which Técnico was the leading partner. 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 conceptual design - and not simply as add-ons to later improve some performance characteristics or flight phases - in order to lead to innovative designs that can improve aircraft efficiency, through an integrated use of these capabilities, relatively to the existent conventional tube and wings designs. 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 improve the green level of the aircraft.

At Técnico, a Multidisciplinary Design Optimization (MDO) framework that includes all aircraft disciplines - such as aerodynamics, structures, propulsion, stability and control - is being developed [8]. Additionally, environmental requirements of noise and emissions as well as operating 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.

This tool computes surrogate models of the disciplines using databases to allow for lower computational times, but they can be replaced, if necessary, by higher fidelity computational databases. The MDO architecture has two levels of optimization: the first consists in improving the aircraft performance at a fixed configuration, which means optimizing the morphing strategies for the given flight phases; in the second level an optimization of the aircraft configuration for the best performance based objective function is conducted.

One of the key characteristics of the tool under development is its versatility and modular character - each discipline will have its own module, and can be optimized individually or in group with other disciplines. Additionally, the tool will have a well defined graphical user interface, focused on being user friendly and comprehensive.

The MDO tool already has some modules implemented, such as the aerodynamics or the structural modules, but some others have yet to be developed or are in development. The aim of this thesis is to develop the Cost Module, in order to primarily estimate as accurately as possible the costs incurred by the concept aircraft generated during a mission or a set of missions. The different elements of the direct operating 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. Furthermore, it is intended to establish different types of missions economics-wise, so that a more realistic analysis of the costs incurred can be obtained by capturing as much as possible the particular characteristics of different types of airlines, with the objective of drawing a profile that is adequate to the airline that is to fly the optimized aircraft, taking into consideration aspects such as the location of the airline, its business model, its typical routes or markets served, amongst others.

1.2 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, and ends with its disposal. Asiedu and Gu [9] distinguish between four phases in the product life cycle: design development, production, use and disposal. There are some costs associated with each of these phases and the total Life Cycle Costs (LCC) of a product are shared by the manufacturer, the user and the society. The design development and the production phases bear costs essentially to the manufacturer. In the usage phase, it is the user the one that supports most of the costs, whether it is through the purchase of the product or by the maintenance
and other costs associated with operating the product. Also here the manufacturers or distribution companies support some costs, such as product support, transportation, and other services directly or indirectly related to the product. Finally, the disposal phase is the one where society plays the main role, due to costs associated with waste, pollution and health damages. All these problems borne by society are also present at the production and usage phases, so the costs to society are an important part to consider.

To avoid these impacts on society, governments and other organizations such as the European Union (EU) are imposing increasingly strict regulations and limits on the levels of noise and emissions that aircraft can reach. In its Flightpath 2050 Europe’s Vision for Aviation report [10], the European Commission points to the goals of reducing until 2050 the CO2 emissions per passenger kilometre by 75% and the NOx emissions by 90% relatively to typical new aircraft from the year 2000, through the development of new technologies. The European Union Emissions Trading Scheme (EU-ETS) for aviation [11] pointed to a progressive yearly reduction in the emissions allowances conceded to aircraft operators flying within, from and to the European Economic Area (EEA), but these requirements were suspended for the period 2013-2016, except only for the flights within the EEA [4]. Other major countries have also proposed CO2 emissions reduction goals. In their Aviation Greenhouse Gas Emissions Reduction Action Plans submitted to the ICAO, the US Government has set the goal of achieving carbon-neutral growth for US commercial aviation by the year 2020, using 2005 emissions as a baseline, by improving aircraft and engine technology and operations and by developing new alternative fuels with lower emissions[12], and the Civil Aviation Administration of China expects to reach a reduction of 22% in fuel consumption per Revenue Tonne Kilometre by 2020, with the year 2005 as a baseline, mainly through the optimization of operations at the airports and the optimization of airspace routes [13]. In ICAO 38th Assembly in 2013 [5], ICAO’s member states agreed to deliver a proposal for a global market-based measure scheme to control greenhouse emissions by 2016, to be implemented by 2020. This way, the implementation of a global scheme, rather than various regional ones, will allow an easier integration of the restrictions and a fairer control of the emissions. To achieve these goals, aircraft will also need increased efficiencies so that they can perform the same missions with reduced environmental impacts.

Figure 1.1 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 LCC 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 to the right mission, since very little leverage exists for the airline to reduce its operational costs.

Willcox [7] 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). Figure 1.2 shows the approximate typical relative weights of each of these parts in the total operating costs.

The Airplane Related Operating Costs (AROC) are then further divided into Capital costs, which
comprise roughly 40% of this category, and the remaining 60% are the Cash Airplane Related Operating Costs (CAROC). The former refer to the costs associated with ownership costs, and include costs of financing, insurance and depreciation. The latter is divided into costs associated with the amount of flying hours and flight frequency of a given aircraft, such as the fuel costs, crew wages, maintenance, or even fees. Figure 1.3 shows the typical percentages of each of these components into the CAROC.

It is possible to understand now the influence of each component in the final operating costs of the aircraft. Looking solely on variations of the AROC (this means assuming the Passenger Related Operating Costs (PROC), Cargo Related Operating Costs (CROC) and Systems Related Operating Costs (SROC) to be the same amongst different aircraft), it is possible to understand that if one aircraft is, say, 10% more expensive than a second one (assuming that the aircraft price increase will be reflected in the same way on either the financing, the depreciation and insurance costs), from an airline point of view, buying it is a viable choice only if its CAROC are more or less 7% lower than its competitor. Lower CAROC may be achieved mainly by reducing: the crew cost, either by reducing the number of necessary crew members (which is not very easy to achieve due to regulations and service quality) or the time that they fly for a same flight, which means using faster aircraft in order to reduce block time; fuel costs, by having more efficient engines and aerodynamics; and maintenance costs, which can be achieved by having aircraft with less frequent maintenance schedules and easier and faster maintenance routines. Furthermore, the effect of commonality of fleets also plays a big role on CAROC savings, since the training times and costs of crews and maintenance engineers is lower, and the number of spare parts is also lower, thus reducing the initial investment too.

Achieving these cost saving characteristics is a challenge for the aircraft manufacturer, and the perceived probability of achieving such enhanced performance characteristics comparatively to its competitors or to its previous models dictates how much they are willing to risk in developing new technologies.
or designs. As stated above, an airline is willing to pay more for an aircraft with better performance. There are two ways of looking at 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. The work that has been developed in both these approaches is going to presented in the following two subsections.

1.2.1 Development and Production Costs

According to Asiedu and Gu [9], the development of an aircraft has three phases: the conceptual design, the preliminary design and the detailed design. It begins with the definition of the project, through the recognition of a market need. In the aviation industry, it is not seldom, however, that the airlines first approach the manufacturer with a request for a specific type of aircraft, with characteristics that are suited for their needs. The Boeing 737-MAX family, for example, was designed to meet the airlines requests for an aircraft with increased efficiencies to compete with the A320neo family. In other occasions, although the need was first identified by the manufacturer, the project had to be redesigned in order to take into consideration certain aspects that the airlines thought to be relevant. This was the case of the A350XWB, which at the beginning was simply an A330 with redesigned wings and new engines, but that was later changed to accommodate more seats. This first step kicks off the conceptual design phase, where the main characteristics of the aircraft are defined. Then comes the preliminary design phase, where a more in-depth analysis of the different systems and their interaction is made, along with its optimization. It is in this phase that the planning of the production process also starts, which is of great importance to the efficiency of the production phase. In the last phase, detailed drawings of all the parts of the aircraft and of the production line are made, as well as final corrections and optimizations.

Several authors [15–19] refer to these costs as the Research, Development, Testing and Evaluation
(RDT&E) costs. Definitions of the multiple elements of the RDT&E costs vary among the different authors, but they generally include the technology research, design engineering, development support, prototype fabrication, flight and ground testing and evaluations for operational suitability. In some cases it also includes the certification costs of the civil aircraft.

These costs, independently of being named development costs or RDT&E costs, are essentially non recurring costs, which means they are incurred just once and are independent of the number of aircraft produced, excluding the test aircraft.

The production costs are, on the other hand, recurring costs, since they are more or less proportional to the amount of units produced. Also here there are some differences in the way each author defines the constituent elements of these costs, but there is more agreement in the way to divide them: there are the labour and material costs to manufacture the airframe, engines and avionics (or in some cases the costs to buy certain parts); the production tooling costs; and the quality control costs. The overhead and administrative costs are also included in the calculation of the different elements. The production costs are influenced by the learning curve effect, which in the aircraft industry is more or less 75%-80% [15], thus decreasing with the units produced.

It is important to bear in mind that for similar projects, or similar final aircraft, the costs incurred by one manufacturer may differ greatly from the costs incurred by another manufacturer. This is due to their intrinsic differences: different location sites will affect, for instance, the labour rates; different parts providers may charge different prices; different organizational structures will lead to different overhead and administrative costs; different experiences with similar programs will affect the way each manufacturer tackles the problems that will eventually arise; amongst others.

There are essentially three different kinds of cost estimating methods, with different levels of simplicity and applicability: parametric, analogous and detailed [20]. These can be divided into two broader levels: the detailed design level, which requires detailed information about the product, and where the
analogous methods can to a certain degree be included; and the conceptual design level, where the parametric methods, along with methods based on the weight/complexity, are included [21]. Figure 1.4 shows the applicability of each type of methods through the program length.

![Figure 1.4: Estimating Methods vs. Program Phase [21]](image)

Parametric models are simple mathematical equations which use a few physical or performance parameters of the aircraft that are somewhat related to its costs of development and production to estimate the different cost elements or the final acquisition cost. These relationships, often called Cost Estimating Relationships (CERs), are obtained from statistical analyses, so, in order to provide statistically meaningful results, a substantial amount of data is needed. This is one of the major difficulties of these methods, but, once they are available, a quick computation of the costs is possible. They are well suited to compute the expected costs of a program in its initial phase, the conceptual design phase, when little detail is known from the aircraft characteristics. On the other hand, since they are built from previous aircraft programs data, their scope is limited to aircraft within the characteristics range of the data sample, thus not being able to, *per se*, estimate the usage of new technologies. One further difficulty relates to the fact that the best CERs are those developed using more recent aircraft, given the higher probability of similarities in technologies used, but the more recent is the sample, the smaller it will be; thus a compromise must be accomplished.

The analogous models create an estimation of the cost of a new program or product based on the similarity with other programs/products. The critical point in this method is having a good level of judgement of the relevant similarities between the product being developed and the ones with which it is being compared, so the better the judgement, the better the estimates. This method is particularly well suited when the evaluation of the impact of new technologies on the costs is required. The downside is the need for someone that is sufficiently familiar with the product and the program, and this familiarity
also requires the existence of minimally detailed information about the product, thus it is a method that cannot be used in the initial conceptual phase.

The detailed methods can be used only when the design is almost finished. It gives the most accurate estimates for the costs, since it uses the detailed information of the product to calculate the labour rates and hours, the amounts of materials used and their prices. These methods are, however, very time consuming and economically expensive.

Most of the available development and production cost estimating methods in literature are CERs. Three different aircraft design books which present methods for estimating the development and production costs were studied, in order to understand the way these costs are estimated: *Airplane Design* by Jan Roskam [17]; *Aircraft Design: A Conceptual Approach* by Daniel P. Raymer [15]; and *Design of Aircraft* by Thomas C. Corke [16]. These last two are essentially based on CERs presented in reports by the Rand Corporation prepared for the US Air Force in the decades 1970 and 1980: the Development and Procurement Costs of Aircraft models, known as DAPCA-II [18] and DAPCA-IV [19]. Additionally, a method for estimating only the recurring costs - which are roughly the production costs on the other methods - is presented in the Central Reference Aircraft data System (CeRAS) website [22], and is based on the NASA RC Method [23] and on the Engine Price CER by Langhans. Additional methods that were both complete and not an adaptation of the previously stated ones were not publicly available.

Rand Corporation has published four reports from 1966 to 1987 with parametric methods for estimating aircraft airframe costs for the development and production phases. These reports, the so-called DAPCA models, were developed for use in planning and evaluation of military aircraft programs by the US Air Force. DAPCA-II and DAPCA-IV are similar to one another, being the most recent a sort of update of the older ones. They use CERs for estimating the cost of the whole program and of each of the elements into which they divide the program. The relationships are obtained using cost data gathered from airframe manufacturers and from other US Department of Defense references. Since the data is gathered from military programs, the models are more suitable to calculate the cost of military aircraft and not so much for commercial ones. The data is then statistically analysed and exponential regressions are obtained relating a few physical and performance parameters to the costs. None of the reports includes the costs of avionics and engines, but the costs associated to the mounting of the engines are included. Efforts to include a technology index - to take into account the advances in technology with time - and a program variable - to explain differences amongst programs and manufacturers - in the DAPCA-IV report models did not improve the quality of the CERs.

Raymer’s method for estimating the development (RDT&E) and production costs is based on the more recent version of the Rand reports, the DAPCA-IV. Therefore, it is also based on data collected from military aircraft. The same cost elements are present: engineering, tooling, manufacturing and quality control (calculated in hours); and development support, flight-testing and manufacturing material (calculated in dollars). DAPCA-IV assumes the engines cost is known and does not calculate the avionics cost. Raymer provides references to calculate the engines cost and suggests assuming the avionics as 5%-25% of the flyaway costs or as $ 2000 per mass pound in 1986 dollars. These values may seem
very high, but it is noted once again that they correspond to military aircraft, which are equipped with the newest technologies. Furthermore, a list of values for a correction factor for the materials used in the aircraft is presented, since the hours calculated on DAPCA-IV were based on aluminium aircraft. Average 1986 wrap rates, which include not only the direct salaries but also employee benefits, overhead and administrative costs, are listed for each of the cost elements. Finally, Raymer suggests multiplying the calculated total costs of the aircraft by an "investment cost factor", to take into account the cost of money and the manufacturer profit, which is comprised in the interval 1.1-1.2.

Corke presents both the DAPCA-II and the DAPCA-IV equations. The cost elements used are the same and are divided by the RDT&E - which includes also the flight-testing - and production phases. Estimations of the engines costs are included. Corke makes the conversion of the costs from the reports' year to the present using the Consumer Price Index (CPI). Hourly rates - which include salaries, overhead, benefits, administrative expenses and other direct charges - are converted for each of the cost elements assuming a linear variation along the years. A 10% profit is assumed for the whole program. Finally, the unit acquisition price of the aircraft is given as a function of the amortization period: one price is set for the aircraft built until the amortization number has been reached, and another price is set for the aircraft built from then on.

Unlike Raymer and Corke, Roskam presents his own method for estimating RDT&E and Production costs. This method can be used both for the estimation of a military aircraft program or a civil aircraft one. For the RDT&E phase, the total cost is divided into the following elements: Airframe Engineering and Design, Development Support and Testing Cost, Flight Test Airplanes, Flight Test Operations, Test and Simulation Facilities, Profit and Cost to Finance the RDT&E phase. In general, these elements correspond more or less to the elements present in the DAPCA reports, although the flight testing phase is more detailed. The Flight Test Airplanes cost component includes the cost of engineering and avionics for the test aircraft, and the manufacturing labour, manufacturing material, tooling and quality control costs. Test and Simulation Facilities costs take into account the need or not for new facilities, and are measured as a fraction of the total RDT&E costs. The cost equations for each of the parts of the cost elements are exponential equations, where the main variables used are AMPR weight (lbs) and maximum speed (kt). Here, the AMPR weight can be calculated in detail using an equation provided with the different weight elements - that can be estimated using Part V of the book series - or, when the knowledge of the different weight elements is limited, using an approximation related to the take off weight. Other variables also appear in these expressions: number of aircraft built in the RDT&E phase, a judgement factor which accounts for project difficulty, a judgement factor which accounts for the integration of CAD drawings in the design, the rate of production for the RDT&E phase and a factor to take into account the use of materials different than aluminium. When calculated in hours, the costs are multiplied by the appropriate hourly rate. The other costs are multiplied by a Cost Escalation Factor to account for the year at which the costs are being calculated. Regarding the production phase, its costs are divided into: Airframe Engineering and Design, Airplane Production, Production Flight Test Operations and Financing. The equations are, as the previous ones, exponentials and use essentially the same variables. The number of aircraft produced in the RDT&E phase is substituted by the number
of aircraft produced in the production phase. The Airplane Program Production element comprises the costs of engines and avionics, the cost of the interiors, and the manufacturing labour, manufacturing materials, tooling and quality control costs. Summing the RDT&E and the Production costs and dividing by the number of aircraft already produced yields the aircraft price. The calculated aircraft price declines with the number of aircraft manufactured, due to the learning curve effect and also to the decrease in the contribution of the RDT&E costs. With this method, it is also possible to capture the differences in aircraft price with variations in take-off weight, maximum speed and production rate. All three of them are more noticeable when few aircraft have been produced, with the price being more sensitive to maximum speed and less sensitive to production rate.

CeRAS is a database with design data of commercial aircraft. It is aimed to help research projects dealing with preliminary and conceptual aircraft design studies. In the CeRAS website [22] is presented a model for calculating the recurring costs of an aircraft based on a parametric study for NASA [23] and an engine cost estimation relationship developed by Langhans. The NASA RC Method calculates the aircraft production cost through the usage of CERs for several aircraft systems as a function of each of those systems' weights. These CERs are very suited for use in the preliminary design phases. Apart from the CERs, this report also developed Weight Estimating Relationships (WERs), which can be used when there is a lack of information on some systems' weight. These CERs and WERs were derived from a sample of 26 transport aircraft, 17 of which were commercial aircraft and the other 9 military ones, unlike DAPCA reports, which use only military aircraft and with various mission types. Despite the use of a sample of commercial and military aircraft, the results seemed to provide good quality on the estimation of either type of aircraft. Since for transport aircraft the speeds do not differ very much from one aircraft to another, this was not considered, contrary to the Rand reports and Roskam's method. Furthermore, this method captures with much more detail changes in different parts of the aircraft, such as the wings or the landing gear, for instance. The previous mentioned models were divided into cost elements that had not to do with any specific part of the airframe, thus this kind of insight was not possible using them. On the other hand, although the authors have validated the method regarding the total cost estimate, compensatory effects between system costs may exist, so caution must be taken when using the CERs provided to ensure that the data used is adequate to the relationship itself. Moreover, when some dramatic technological breakthrough happens or when the aircraft program is focused on weight reduction these CERs are likely to be invalid, since for each of the aforementioned cases the costs are almost certainly higher. When using composite materials, the authors believe that the higher cost of these materials can be compensated by the decrease in weight provided by them, thus maintaining more or less the same cost per pound. Additional characteristics of this method are the inclusion of a 10% profit on the final cost, the inclusion of the learning curve effects and the provision of a table with, although subjective, confidence measures for each CER, which may be of some help when analysing the results of each system's contribution to the total cost. Finally, the major drawback of this method is the non-inclusion of the Non Recurring costs. Nonetheless, for the cases tested, the CERs presented are a good comparison point.

One of the most obvious characteristics of these methods is that they are all very old. The most
recent method non heavily based on another one is that presented by Roskam, which is 25 years old now. This is a major drawback when thinking of using them for the aircraft developments of today. Several new technologies, materials and production techniques have emerged, and those that were new at the time these methods were developed are now in a much more mature state, which implies that their costs are lower now. Furthermore, if even at the time of their development the use of these cost estimating relationships were not recommended when analysing the costs of aircraft with a high degree of dissimilarities, it is obvious that that recommendation is even more pertinent if today these CERs were to be used on novel configurations, such as the joined wing concept. On the other hand, the fact that either the Rand methods or the NASA RC Method have been much more recently used in Corke (2002) and integrated in the CeRAS project (2010), respectively, indicates that they are at least useful for comparison up to an acceptable degree of accuracy. The second characteristic of these CERs that is of little use for the project developed in this thesis is the fact that, except for the NASA RC Method, they are developed for use in military aircraft, which have different cost characteristics, since the nature of the programs is inherently different - use of more advanced technology, for instance - and the parts of the aircraft, namely the fighters and bombers, are much more costly due to their high performance characteristics requirements.

It is thus concluded that the least inadequate method for the evaluation of the aircraft costs in this thesis scope is the NASA RC Method, although, as mentioned above, its validity today would have to be checked beforehand.

1.2.2 Acquisition Prices

As stated previously, the acquisition price of the aircraft plays a significant role in the operating costs of a company, since the cost incurred in its purchase will directly influence the costs of ownership (depreciation, insurance and interests). For this reason, being able to estimate this value is of great importance for the calculation of the airline economics.

There are two ways the aircraft selling price can be set: either cost-driven or market-driven. In the first approach, the aim is to gradually recover the development investment with every unit sold, thus the money spent on this phase must be divided by a given number of aircraft, according to the manufacturer expected sales. The production costs must then be summed to that value. This will yield the cost of the aircraft, at least for the units that are still to support the RDT&E costs. Adding a profit margin for the manufacturer company finally leads to the aircraft selling price. However, the purchase price of a certain aircraft is more a function of the market trends and even the relationship between the manufacturer and the airline than a function of the costs incurred in its development and production - this is particularly true when talking about commercial civil air transportation - , and is, not accounting for inflation, almost always constant through time [20, 23]. The Lockheed L-1011 Tristar, for instance, which entered service in 1972, was sold from 1975 to the end of the program for a price lower than the costs, leading to overall program losses of more than $1 billion [21].

This section will review the literature for methods on the estimation of aircraft acquisition prices taking into consideration the market-driven approach. The methods consist mainly in simple relationships
that estimate the aircraft price as a function of a few performance and physical characteristics. Since the price is set by the market conditions, these characteristics have to be meaningful to the customer operational-wise, for it is his perception of the value of the aircraft - or, from another perspective, the aircraft operational gains or savings - that will ultimately determine how much he is willing to pay for it. Examples of meaningful performance and physical characteristics are the fuel consumption, the number of seats, the maximum range or the size - width or length - and weight of the aircraft. No single aircraft has exactly the same characteristics as another one, nor it is developed to emulate the characteristics of its competitors, but rather to have some performance upgrade in a single or in multiple key aspects. However, it can be fit into a certain segment, which comprises precisely the other aircraft that are its competitors. In the same way the range or the speed or any other performance characteristic are close to the competitors values, the selling prices will most likely also be of the same magnitude. It can even be considered as a characteristic of that aircraft: some will have it a bit higher, some will have it a bit lower, depending on all the other characteristics compared to the competition. As an example, both the A320-200 and B737-800 are priced at roughly $93 millions [24, 25], as of 2014. They have similar operational characteristics, such as a maximum take-off weight of 78-79 tonnes, a cruise speed of 0.78-0.785 Mach, a range of 3060-3300 NM (with the highest corresponding to the A320-200) and seating capacities of 150-160 for a 2-class typical configuration or 180-189 with a 1-class dense configuration (with the highest value corresponding to the B737-800). The advantage of the seating capacity for the Boeing aircraft may be compensated for some airlines by the advantage in range capacity of the Airbus aircraft, thus leading to a similar selling price. If an aircraft, however, has a significantly higher performance characteristic which can yield lower operating costs, the customer is willing to pay more, and its price will be higher than that of its competitors. This is the example of the newly developed A320 and B737 families, respectively the A320neo and the B737-MAX families. These new families have a high commonality with the previous families, but redesigned wings, the introduction of new materials, such as composites, and mainly the new more efficient engines provide savings on fuel costs and total operating costs of approximately 15% and 8%, respectively, apart from reductions in emissions and noise [26, 27]. Furthermore, these new families have also an increased seating capacity, leading to a more efficient use of the aircraft, and a larger range. The operating costs savings of these new aircraft lead to an increase in their prices - although the development effort was not the same as the one required to build a completely new aircraft - , with the A320neo being priced at $102.8 millions and the B737-8 at $106.9 millions [24, 25]. The difference in prices may be due to claims from Boeing that its family will be more efficient in operating cost per seat relatively to its Airbus counterpart [27].

One point that is of great importance to discuss is the discounts that aircraft manufacturers offer to their customers. It is known, much as in any other business, that aircraft manufacturers offer discounts that can vary from few percentage points to more than 50% of the list prices [28]. As a general rule, the higher is the number of aircraft ordered by a client, the higher are discounts he gets. However, discounts magnitudes vary from one client to another: those who have a stronger bond to the manufacturer are able to get higher discounts, while those who have not so much experience in buying aircraft usually have lower discounts. The discounts also vary from manufacturer to manufacturer and from one aircraft
family to another: it all comes down to how many aircraft are going to be produced and sold. Airbus and Boeing are usually able to lower the prices of their aircraft by as much as 50% relatively to the list prices, sometimes even more than 60%. Since they produce enormous quantities of aircraft, chiefly the single-aisle families, they are able to allocate a smaller amount of the development costs to each aircraft. On the other hand, companies like Bombardier and Embraer, which are now trying to compete in the 125-150 seats market with their CSeries and EJet-E2, respectively, that have increased efficiencies against the Airbus A319 and the Boeing 737-800NG [29, 30], are not able to offer aircraft with such discounts, since the return on investment is divided by a much smaller number of aircraft. Even with lower list prices, and increased efficiencies, most airlines still prefer the Airbus and Boeing aircraft, since they perceive commonality with the rest of their fleet as a sufficiently strong cost saving factor.

The main difficulty with discounts is not so much the differences between those got by different airlines or given by different manufacturers, but rather the fact that they are publicly unknown. This creates a problem of whether one should assume the list prices as the comparison term with the estimation methods’ prices, even though they are recognizably different from the actual prices, or use instead assumed discount rates for different aircraft, adjusting the prices aircraft by aircraft and then comparing these adjusted prices with the estimation methods. As one last note on this topic, aircraft manufacturers have been regularly raising their list prices for the last two decades, along with the discount percentages, which were of just a few percent in the mid 1990’s [28]. This means that actual prices may have not changed that much. This creates another problem since the aircraft acquisition price estimation methods studied range from as early as 1989 to 2003, and escalation factors based on consumer price indexes are used to transform the then-dollars to today-dollars, thus introducing a price raising factor that may not be proportional to the increase in prices of the aircraft along the last few decades, which makes the task of evaluating and comparing these methods even harder.

Roskam [17] presents a series of relationships for different aircraft types, such as Business Jets, Turboprop Commuters and Commercial Jets. The relationships were derived from prices of aircraft around the late 1980s. The estimated price is log-linear with take-off weight. The fact that the estimation is based solely on variations of the take-off weight is a major limitation of these relationships. Changes in speed or fuel efficiency, for instance, do not influence the estimated price, which is not true in reality. Furthermore, an increase in weight may decrease the range of the aircraft, which would be seen as a poorer characteristic to the customer, but at the same time it can allow for more seats, which may be seen as a good characteristic to enhance operations efficiency. It is not possible to capture these effects with a dependency exclusively on weight.

Liebeck et al. [31] made in 1995 a report for NASA with design and economic studies for subsonic aircraft. The study was divided into four classes of aircraft: short-range with 150 passengers (SR-150), medium-range with 225 passengers (MR-225), medium-range with 275 passengers (MR-275), and long-range with 600 passengers (LR-600). As part of the determination of the costs of ownership, parametric relationships were developed for estimating the airframe price and the engines price. In the engines price only the bare engines are included, since the rest of the propulsion system (e.g., nacelles, thrust
reverser) are assumed to be part of the airframe. Liebeck recognizes that aircraft are not sold on a price-per-pound basis, but its price is rather marked-based. This is applicable not only to the airframe but also to the engines. The primary independent variable for calculating airframe price was payload-range index (PRI) - dimensioned in (seats.NM)/1000. Three linear equations, of the form \( a + b \cdot PRI \), were developed - one for SR-150, one for MR-225, and a last one for both MR-275 and LR-600. In addition, a secondary variable, the Airframe Weight (AFW) in pounds, was used in a power curve \( a \cdot (AFW/1000)^b \) relationship to assess the impact of airframe downsizing afforded by technological advances. In this case, only two equations were developed, one for the SR-150 aircraft and the second one for all other aircraft. Regarding the engine price, its value is a function of the engine thrust, and the relationships have a log-linear form: \( a \cdot thrust^b \). For each of the aircraft classes, Liebeck obtains data from engine manufacturers on the price and thrust of an engine at the time (1995) and their predictions for an advanced-technology engine for the year 2005. The coefficients \( a \) and \( b \) are then obtained using engine manufacturer's data and calibrating the curve to the values of price and thrust provided by each of the engine manufacturers. Prices for both 1995 technology and 2005 at-the-time predicted technology are obtained for the SR-150 aircraft, for MR-225 and one for both MR-275 and LR-600. The total aircraft price is obtained summing the estimated airframe and the engines prices.

Markish and Willcox [32] present two different relationships for estimating the aircraft price: one for narrow-body aircraft and another for wide-body aircraft. These relationships were derived from 11 narrow-bodies and 12 wide-bodies existing at the time (2003). The estimated price is a function of the seat capacity and the design range, both as a fraction of a reference seat capacity and a reference range. No significant relationship was found between the price and speed of the aircraft. An additional term is then subtracted to account for the additional cost the operator incurs if the aircraft’s CAROC are greater than the industry average CAROC for an aircraft of the same approximate size. This means that if the expected operating costs (excluding ownership costs) are higher, the market price will be lower, as a reflection of the lower attractiveness of the aircraft for the airline companies. These costs are, however, difficult to predict in a preliminary design phase, and thus this last term may not be of great help for this phase.

Isikveren et al. [33] take the so-called "Productivity Index" developed by AlliedSignal Aerospace to evaluate business aircraft and adapt it for commercial aircraft, calling it "Productivity Index for Commercial Aircraft" (PIC). It is the product of the Range and Mach number at long range cruise conditions, Cabin Volume and Number of Seats. This is then divided by the Balanced Field Length. This relationship is able to account for all those factors that are influenced or influence the weight that Roskam’s relationships could not account for: changes in the maximum take-off weight are reflected on the possibility of adding more seats to the aircraft, but at the same time might mean that the range is lower and that the required field length is longer. On the other hand, the fact that there are no weighting coefficients to each of the variables means that an increase of 10% in the seat capacity would influence the price as much as an increase of 10% in the range. This is evidently not necessarily true. Moreover, these relationships were derived for regional aircraft, and the author does no more than assuming that they may be applicable to all commercial aircraft.
After gathering performance and physical characteristics from Boeing, Airbus, Embraer and Bombardier aircraft, the methods from Roskam, Liebeck et al. and Marksih and Willcox were compared against these manufacturers' list prices and against each other.

Figure 1.5: Estimated-to-List Price Ratio vs. List Price (2014) for Airbus, Boeing, Embraer and Bombardier aircraft for typical seating configurations.

The ratio between the prices estimated by each of the methods and the 2014 list prices can be seen from Figure 1.5. The methods from Markish and Willcox and from Liebeck et al., which use seating capacity as a variable, accounted to the typical seating capacity of the aircraft rather than the maximum seating capacity. Furthermore, Markish and Willcox method should take into consideration a decrement on the price that is used to account for a higher CAROC relatively to other aircraft, and it was not considered in this estimation. Additionally, the Liebeck et al. method should also take into account the engine prices, and they were not included here either. The engines typically account for 15-30% of the whole aircraft price, thus the estimations from Liebeck et al. should be closer to the 80% mark.

Finally, Roskam's method is applied to every aircraft, while Markish and Wilcox divide the set of aircraft into narrow body (or single-aisle aircraft) and wide body aircraft, and Liebeck et al. divide further into Long Range aircraft (in which are included all the Airbus and Boeing wide body aircraft), Medium Range aircraft (which was not used due to the unlikely outcomes), and Short Range aircraft, with the remaining Airbus and Boeing aircraft and all the Embraer and Bombardier aircraft going into this category. It is arguable whether A320 and B737 families should be inserted in the Short Range category. The categorization done by Liebeck is somewhat subjective, since it considers only a reference aircraft with 150 seats and 2500 NM of range. While these aircraft have ranges that go from about 3000 NM to as much as 4200 NM (close to the 4500 NM Medium Range category mark), most of them are under 185 seats (only the new A320neo and A321neo have higher seating capacities). After testing for both cases - placing these families on the Short Range category and on the Medium Range category -, it was chosen to consider them as Short Range aircraft since the results were much more consistent. This leaves a gap in the range spectrum, since there are no aircraft in the Medium Range category. This category is for a reference aircraft with 4500 NM of range and a 225 seating capacity. After placing the A320
and B737 families in the short range, there were no aircraft left that could be placed in this category in a way that made sense. The Long Range category is in fact made of a Long Range reference aircraft with 7500 NM of range and 600 seats and a Medium Range reference aircraft with a range of 6000 NM and 275 seats, and they both use the same relationship. This category is referred here simply as Long Range for the sake of simplicity. That is the reason why all the other aircraft that could be considered as medium range aircraft are placed under the Long Range category.

It is important now to note how the price data was gathered. Both Airbus and Boeing have their list prices available on their websites, so the prices obtained are the true list prices. Regarding Embraer and Bombardier, they do not make their list prices explicitly available. The data was gathered from press releases describing deals with customers for both manufacturers. These values may contain errors since the press releases do not state the price of each aircraft but rather the value of the deal, which is often rounded. The values obtained from several press releases for the same aircraft and the same year were averaged to provide an estimation of the actual price. Moreover, some of the aircraft prices could not be obtained from press releases from 2014, but only from previous years. The previous years prices were updated to 2014 prices using the average of the percentage of price raises for all the other aircraft from that given manufacturer between those years and 2014. While for Boeing and Airbus price raises are more or less of the same percentage across all aircraft models and families, it could not be assured that the same happens with Embraer and Bombardier, so the calculated list prices may come with a slight error. It is not easy to quantify this error, but it is believed, since prices do not increase, in general, more than 5% each year (the most common value is around 3%), that the error would be smaller than 5%.

Proceeding to the analysis of Figure 1.5, it is possible to distinguish two different zones: one with aircraft price lower than 150 million dollars and another one from then to more than 400 million dollars. The first zone comprises single-aisle aircraft, such as the A320 family, Boeing 737 family and all the Embraer and Bombardier aircraft. In the second zone are the wide body aircraft from Airbus and Boeing. The estimated prices in the latter zone are more or less the same relatively to the actual prices amongst the different methods, at around 60% of today list prices - it is noted that the prices are updated from the year the formulas were devised to 2014 dollars using a consumer price index. In this zone, almost every estimation is within the range 50-70% of the list prices and they seem to be constant with aircraft list price. Since these methods were made from 1989 to 2003, the discounts at the time were not as high as they are today - list prices were closer to the actual prices -, and the difference may be due to that increase in list prices that is not that much verified in the aircraft actual prices. At the time these relationships were devised, they may have provided results much closer to the at-the-time list prices.

In the lower prices zone, a very different scenario can be seen: prices estimates are much more scattered, and Liebeck et al. and Markish and Willcox estimates - both using seating capacity and range as their variables - give now estimates with significant differences, differently from the similar estimates for the wide body aircraft. Roskam estimates are somewhat similar to Liebeck et al. estimates, both in value and in the trends they show as a function of list price. On the right-hand side of the vertical black line (A320 and B737 families), the estimates are still around 60% of the list prices. Markish and Willcox estimates are in line with the estimates for wide body aircraft, just below the 60% line, with a few points
above that line. On the other hand, Liebeck et al. and Roskam estimates are well between the 60-80% ratios.

On the left-hand side of the black vertical line, where there are only Embraer and Bombardier aircraft, Markish estimates diverge from the other two. Although not being explicitly stated, Markish narrow body aircraft price estimating relationship was devised using only Boeing and Airbus aircraft data, so it is understandable why this relationship estimates these manufacturer’s aircraft prices consistently with the wide body category but differently from Embraer and Bombardier aircraft. The higher estimated prices by Roskam and Liebeck et al. are harder to explain. There are two factors which can contribute to this, either alone or together: a) both estimating relationships do it due to aircraft characteristics which either justify the higher prices or are off the acceptable range for use in the relationships; or b) the aircraft list prices are closer to their real value, mainly because these manufacturers do not provide discounts as high as the other two, so their aircraft list prices may not be that much inflated. Analysing the domain of application of the relationships - factor a) -, it is found that all these aircraft are within the acceptable range defined by Roskam. Regarding Liebeck et al. method, the case is a bit more complicated. His relationships, as mentioned previously, are divided into Long Range, Medium Range and Short Range aircraft. He does not state what are the range intervals for each of the categories, so it is much of a subjective choice. Furthermore, in the Short Range category, where Embraer and Bombardier are undoubtedly inserted, Liebeck et al. use as reference an aircraft with 150 passengers capacity. Once again, there is no defined passenger capacity range for which it is acceptable to use the relationship. In this case, the database used has aircraft with a range from 66 to 130 typical seat capacity. It is not possible to say whether it is or it is not acceptable to use the Short Range relationship with these aircraft. Comparing to the Roskam’s estimates, they are sufficiently close to be possible to conclude that they provide approximately the same results - they may be, however, both well estimated or both poorly estimated. Due to the consistency shown between the Airbus and Boeing narrow body estimates and the wide body estimates, it is believed that Roskam and Liebeck estimates for Embraer and Bombardier aircraft are acceptable and thus reason b) is probably what drives the most the results obtained.

1.2.3 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. 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. The DOC, along with the Indirect Operating Costs (IOC), form the Total Operating Costs (TOC) of an airline or a particular aircraft. The DOC elements are connected to the act of flying an aircraft, such as the fuel spent on a trip, the costs with crews, or the maintenance associated with the trip flown. 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. On the other hand, IOC are the costs related to the management strategies and level of service of the airline, and include items such as the costs of sales and marketing, general and administrative costs, the costs of handling and meals, or the costs of maintenance and depreciation of the ground equipment and facilities [17].
Although it is not possible to ignore these costs from the point of view of the airline, since they account to between 15% to 50% of the TOC [34], the aircraft design team has very few or no influence over them.

In the scope of an aircraft design optimization, it only makes sense thus studying the influence of the design parameters in the DOC part of the airline costs. 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 [35]. In 1944, the Air Transportation Association of America (ATA) developed the first method to estimate the direct operating costs. This method has since been updated several times until its final version published in 1967. In this method, the items considered to be part of the DOC were the costs with flight crews, maintenance (of both the airframe and the engines), fuel, depreciation (of both the aircraft and its spare parts), and insurance. Liebeck et al. [31], in a study for NASA, with data on the costs of McDonnell Douglas aircraft in commercial service up to 1993, later developed a method based on the ATA method, named DOC+I method, where the "+I" denotes the addition of the interest costs associated with the financing for the acquisition of the aircraft. Furthermore, while in the ATA method costs with cabin crew, landing fees and navigation fees were considered as part of the IOC, Liebeck incorporated them in the DOC. Liebeck's method has the advantage of being a much more recent method than the ATA method, which is of particular importance since it already reflects airline costs in a US deregulated environment. In 1989, the Association of European Airlines (AEA) has also drawn a methodology for calculating the DOC that is similar in structure to that later developed by Liebeck et al. (with the addition of the ground handling fees), but which reflects the reality of the cost structure of European airlines. The parameters associated with the aircraft design (opposing to those associated with the routes flown) used by these methods are more or less similar among them. The cost of acquisition of the aircraft (and airframe and engines separately) is used to compute the costs of depreciation, insurance and interest, and to compute also the costs of maintenance. The engines thrust (and in the case of AEA the engines by-pass ratio also) is also considered in the calculation of the engine maintenance costs and the mass of the airframe is a parameter to compute the airframe maintenance costs. The take off weight is used to compute the cockpit crew costs (since their salaries usually increase with the size of the aircraft) and the landing and navigation fees. The seat capacity of the aircraft is used to determine how many flight attendants are needed. The mass of fuel spent is the main parameter in determining the fuel costs. Oil costs are also computed by ATA, but are neglected by the other two, due to their minor effect on costs relatively to fuel.

It should be noted that these three methods, and the methods that will be later mentioned, are to be used only for comparison between different designs, and not to calculate the actual absolute DOC of a given aircraft. The main purpose is to give a reliable comparison between the costs incurred in each of the DOC elements or in the DOC as a whole. Even if they do not yield accurate results, it is of extreme importance that changes in the aircraft design can be captured in the same way amongst the different methods. This applies both to the whole DOC and to its different elements.

The DOC can be divided into three main areas: the ownership costs, where most authors include the costs of depreciation, insurance and interest; the flight costs - those associated with each trip -, which include the costs of fuel, cockpit and cabin crew and navigation and landing taxes; and the maintenance
costs, both for the airframe and engines, which take into account the labour costs, the costs of materials and in most methods the overhead burden costs. Following, a review of how more recent methods approach these different DOC elements is made in order to understand all the variables that influence them.

Ownership Costs

a) Depreciation

The definition of depreciation costs is very similar from one author to another. The price of the aircraft airframe and engines and its spare parts must be known. The spare parts for the airframe and the engines can be taken into account together or, as most usual, separately. Typically, airframe spare parts are valued at around 10% of the airframe cost and engine spare parts are worth around 25% of the engines cost [31, 34]. The depreciation periods may also vary between the airframe and engines. When considering an uniform depreciation for the whole aircraft, values are typically around the 15 year mark [31, 36, 37], but longer periods can also be found [34, 38], either because the author considers the technologies are in a more mature phase, or due to economical conditions. Roskam suggests a depreciation period of 7 years for the engines and of 10 years for the airframe. Although being considerably lower than the depreciation periods suggested by the other authors, it gives the idea that the depreciation of the engines should be quicker relatively to the airframe. Regarding the residual value, most of these authors consider a value of 15% of the original cost, but lower values or no residual value at all can also be found. Finally, depreciation may be allocated in a per trip basis or per block hour basis, depending on how the DOC will be presented. For both, annual utilization must be calculated. Roskam suggests gathering actual data on the utilization of the aircraft. When this is not possible, he presents an equation that is a function of block time, similarly to the ATA and AEA methods. Most methods provide reference utilization values for different types of aircraft ranges. CeRAS DOC method [37] calculates the yearly utilization based on the average flight time of each trip, an additional time that accounts for turnaround times, and the downtime due to maintenance checks and night curfew.

b) Insurance

Airlines carry insurances for four main reasons [17]: i) ground or flight risk of airframe damage or total loss; ii) passengers liability in case of injury or death; iii) third party liability in case of injury or death; and iv) cargo damage risk. Only the first point is of importance for the calculation of the DOC. The other points should be treated in the scope of the IOC. Although the most common practice is to pay insurance to insurance companies, the airline may also choose to carry a part of the insurance on its own, through the creation of a fund. The funding of this reserve must be, however, attributed to the operation of each of the aircraft of the airline, so it may be treated the same way [17]. When the aircraft are not owned by the airline but rather rented or leased, the insurance may already be included in the leasing/renting contract. Anyhow, the payment of insurance will be considered in this thesis. The premiums that the airline must pay are proportional to the aircraft price and are calculated in an annual basis. This means that the higher the aircraft utilization, the lower are the insurance costs per trip. Furthermore, insurance premiums are also dependent on the risk associated to that aircraft perceived
by the insurance company. Since safety standards have to be observed by airworthiness authorities for an aircraft to fly, the risk associated with that particular aircraft is well defined. However, there is also the risk associated with the airline that is operating the aircraft, or the non-technical risk. This risk depends on the nature of the operation - for example, its geographic location - and with the airline security level. Prior to 9/11, the insurance premiums used to be below 1% of the aircraft price, but this value has increased in the following years [39], which shows how the world social and economic conditions may also have a determinant role in the insurance costs. Still, most authors suggest values for insurance premiums to be between 0.5 and 3% [17, 31, 34, 37, 38].

**c) Interest**

Aircraft are either owned by the airline or rented/leased from an aircraft leasing company. Authors are more or less evenly divided on how to approach this component of costs, and the fact that around half of the aircraft operated by US airlines are leased [38] only supports this division. Leases have the benefit of being less capital intensive and of avoiding the risk associated with the loss of the residual value of the aircraft, but may come with higher yearly payments and do not allow the benefit of write-offs, since they can only be treated as expenses. Swan and Adler [39] defend the usage of a monthly dry leasing rate of 0.9% and 0.8% over the price paid by the leasing company for short-haul and long-haul aircraft, respectively. Harris [38], regarding the renting option, suggests an annual rental expense of 8.35% of the capital invested by the renting company. When it comes to the airline getting financing to buy the aircraft, the interest rates depend greatly on the worldwide financial climate, on the banks or governmental institutions that offer the financing and on the airline financial condition. The interest rates suggested are mostly in the range 5-8% of the aircraft plus spare parts cost [31, 35]. Liebeck et al. note that actual interest costs for a given aircraft decline over the years as the down payment increases, but for purposes of simplicity these values are assumed to be constant until the final payment.

**Flight Costs**

**a) Fuel and Oil**

The expenses with fuel are one of the most simple to calculate. There are only two components in the fuel cost calculation: the fuel consumed in the entire flight, and the price of the fuel. The latter component is actually the most difficult to estimate in the long term because fuel prices vary quite significantly over the course of 20 years, more or less the life span of an aircraft. This means that the relative weight of fuel expenses can vary in such a way that a given design optimized for the today conditions may be much more expensive to operate in some years relatively to its today competitors. Predictions for long term fuel prices are difficult to make, and often vary a lot from year to year and between the predictor institution. As an example, the predictions for 2035 crude oil prices (which form the basis for jet fuel prices) from the US EIA in their Annual Energy Outlook reports of 2012, 2013 and 2014, were compared with those from the OPEC in their annual World Oil Outlook reports of 2011, 2012 and 2013 (the time data on these three reports correspond to that of the three from EIA). The comparison is illustrated in Table 1.1. It can be seen that not only a great discrepancy between the estimated prices in each year exists, but they also have opposite trends in the three analysed years. This means that various sources
should be sought to try and make a series of different fuel price scenarios, since they are such a relevant component of the DOC.

Table 1.1: Comparison between the 2011, 2012 and 2013 estimates for the 2035 crude oil price per barrel (nominal prices) by EIA and OPEC

<table>
<thead>
<tr>
<th>Year</th>
<th>EIA [$/barrel]</th>
<th>OPEC [$/barrel]</th>
</tr>
</thead>
<tbody>
<tr>
<td>2011</td>
<td>230</td>
<td>133</td>
</tr>
<tr>
<td>2012</td>
<td>220</td>
<td>155</td>
</tr>
<tr>
<td>2013</td>
<td>193</td>
<td>160</td>
</tr>
</tbody>
</table>

The other component of fuel expense, fuel consumption, is approximately linear with the distance flown (in the cruise case) and almost linear with the weight of the aircraft. If no actual data on the fuel consumed during a flight is known, there are several methods to estimate it with different degrees of complexity.

One of the simplest is the Breguet Range equation (Eq. 1.1):

\[
\text{Range} = \frac{V}{g \cdot \text{SFC}} \times \frac{L}{D} \times \ln \left( \frac{W_i}{W_f} \right),
\]

where \( V \) is the speed of the aircraft, \( g \) is the gravity acceleration, \( \text{SFC} \) is the specific fuel consumption of the engines, \( L/D \) is the lift over drag ratio and \( W_i \) and \( W_f \) are the initial and final weights of the aircraft.

Assuming the general characteristics of the aircraft are known, this equation needs only the definition of the mission, \( i.e. \) the range, to estimate an approximate weight of fuel consumed during cruise. The fuel consumed in ground operations and in climb and descent is not covered by this equation, since the speed, the drag to lift ratio and the efficiency of the engines have to be constant for this equation to be used. A factor can be used to account for the spendings on these phases, but it varies with stage length.

A much more complex method has been developed by Scholz \[36\]. In this method, the impact of each aircraft system on the fuel consumed during the flight is measured, and all these contributions are then summed to yield the final fuel consumption, which is measured for seven different stages of the flight: engine start; taxi; take off; climb; cruise; descent; landing, taxi and engine shut down. Furthermore, the method divides the fuel consumption into six different causes: the fuel costs due to carry a fixed mass; due to carry a variable mass; due to mechanical power off-takes from the engines; due to additional drag caused by antennas, drain masts, etc.; due to bleed air off-takes; and due to ram air off-takes.

One of the advantages of this method is that it allows an effective identification of the potential savings in fuel consumed by system. However, a great amount of detail on the flight conditions and aircraft characteristics is required (such as rates of climb and descent, flight path angles, flight stage times, drag coefficients and areas from the antennas and other systems external to the fuselage and wings), which may not be easily available during the optimization. If all of these data were known throughout the course of the entire flight, then the fuel consumed would most likely also be known, and then the computation of the fuel expenses would be trivial.

Finally, the oil and lubricant expenses are neglected by most authors, since they are much lower than those with fuel. Roskam \[17\] suggests an equation which depends on the number of engines and on the
block hours for turbine engines, but a value of 5% of the total fuel expenses is also suggested to simplify calculations.

b) Cockpit Crews

Cockpit crews expenses may seem easy to calculate but this is not exactly the case. There are several factors upon which these costs depend. A basic approach is to multiply the labour rate of a cockpit crew member by the number of cockpit crew members and the block hours to obtain the expenses for a given trip. In fact, these costs are linear with block hours, but there are other factors involved. Typically, the higher the aircraft take off weight and the more senior are the cockpit crew members the higher are their salaries [17, 31, 38]. Furthermore, the flight crews contracts generally vary depending on the airline company, on the union contracts and even on the country where they are based [38, 39]. Coefficients to account for these differences can be employed, but in certain cases, such as in the airline influence case [38], the determination of such a coefficient is a subjective task. Regarding the union contracts factor, since there is one union that has monopolized the workforce in the US, the contracts terms are very uniform in this country, but there is more variation in the rest of the world [39]. Further factors that influence the real expenses with crews and that are difficult to model exist, such as the overhead costs, or the costs associated with waiting to fly times, or stop-overs on other countries or cities, or even trainings, which are of particular importance when a new aircraft is being used. These expenses can be considered to be general operating costs and thus part of the IOC [34].

Apart from the difficulty to determine the wage of the cockpit crew members, there is also the difficulty of determining the number of pilots and co-pilots that have to board the aircraft for different flight missions. Roskam suggests doubling the cockpit crew members from two to four for flights longer than ten hours. Swan and Adler consider that up to eight hours of flight one should use two cockpit crew members, three for flights between eight and twelve hours, and four for longer than twelve hours flights. Flight time limitations for flight crew members are stated, for operations in the US, in FAR part 121 subparts Q, R and S. From 18 February 2016, Comission Regulation (EU) 83/2014, which dictates new rules for the flight time limitations, is to be applied in the EU. It is important to note that these regulations do not state how many flight crew members should fly a certain flight with a given length, but they rather state the flight hours limitations of the pilots in given periods of time. The choice of how many pilots should be used depends ultimately on the airline operations management team. That is why recommendations on the number of crew members used vary among the different methods.

c) Cabin Crews

The cabin crews expenses, as the cockpit crews expenses, are linear with the block hours flown and depend on the number of flight attendants per flight, which depend on the aircraft seat count. The minimum number cabin staff members is set by Federal Aviation Administration (FAA) requirements for US operations (FAR part 121 subpart M) and by European Aviation Safety Agency (EASA) for European operations (Commission Regulation (EU) No 965/2012 Part-ORO) and is equal to one flight attendant per each 50 or fraction of 50 seats available. However, the choice on how many flight attendants are present in each flight is on the airline side, as long as the minimum requirement is respected. This
choice depends greatly on the level of service that the airline wants to provide. Liebeck et al. suggest using a 1/35 ratio for US domestic flights and a 1/30 ratio for international flights. Other authors provide just a single number for all kinds of operations, although they recognize that it typically ranges from 1 flight attendant per 30 seats to the minimum 1 per 50. Also for cabin crews there are limitations on their flight times, but they are not as strict as those for cockpit crews, hence this factor is not considered.

Also in this cost category the salaries vary widely between countries and airlines. Other factors, such as training, overheads and stop-overs, influence the expenses with flight attendants. As with the pilots and co-pilots, these factors can be either considered as part of the IOC or a factor can be used to take them into account in the DOC.

d) Landing Fees

The landing fees vary from one airport to another, being higher in more congested airports, and depend essentially on the aircraft weight. Most authors use the maximum take off weight as the weight variable, but there are some that suggest using the maximum landing weight to calculate the landing fees for U.S. airports [31, 38]. It is recognized among the methods studied that the US airports have lower taxes than those in the rest of the world. If no information on the actual fees can be found, Roskam [17], Liebeck et al. [31], Harris [38] and the CeRAS methodology [37] present equations to calculate them.

e) Navigation Fees

The navigation fees are charged by air traffic authorities of each country to pay for the costs of providing air navigation services, including costs of maintenance, operation, management and administration of that service. Thus, these fees vary from country to country. ICAO suggests a set of policies to be used when calculating the fees to be imposed to the airlines. The main rule is that the users, and the users only, should pay for their share of the costs aforementioned. The criteria to evaluate the share of costs of each user (or flight) should be clear, non-discriminatory between users/airlines of different countries (although variations in the charges collected by different regions are accepted if consistent with the air traffic management costs), and take into account the relative productive capacities of the different aircraft types. It is suggested to use the distance flown within a defined area and the aircraft weight as measures to quantify the navigation charges.

In most methods, the fees vary in fact with the maximum take off weight of the aircraft and with the distance flown. Most methods were developed by US authors, which means that they reflect much more the reality of the north American airlines. However, some of these methods based on the American airlines are discriminatory regarding the domestic/international nature of the flight. Roskam [17] suggests a fee per flight, regardless of the distance flown or the aircraft weight. Liebeck et al. [31] use a method based only on the first 500 nm of the trip for international flights and that depends on the MTOW. Both authors consider the domestic US fee to be zero. Jenkinson [34] does not make the distinction between domestic and international flights, and his equation depends on the stage length and on the MTOW. The CeRAS method [37], on its turn, is based on European airlines economics. It depends on the distance flown, on the MTOW, and applies different rates depending on the area the aircraft is flying (domestic European flights, transatlantic flights or far east flights).

f) Emissions and Noise Taxes
None of the existing methods considers the taxes associated with noise and emissions, mainly because this is a very recent concern and most of the methods already have a few decades. Noise and emissions tend to decrease with newer technology aircraft. However, since the air traffic is increasing rapidly, the total amounts of emissions and noise effects have been increasing too.

Traditionally, given that noise problems arise mainly at the vicinity of airports, operating restrictions at airports have been the solution to reduce the impact of noise on the populations nearby. For instance, in the eleven busiest airports in France, airlines have to pay a tax for each take off. The value due depends on the airport, on the aircraft MTOW, on its noise certification and on the local time of departure [40]. Italy has created the IRESA tax, which depends mainly on the MTOW and noise certification of the aircraft, but only one region has already confirmed its intention to apply this tax [41]. The fact that this is not a global tax, and that it varies even within countries, creates a further difficulty in deciding the level of tax that should be used in a model.

Regarding the emissions costs, the only restrictions existing today are those imposed by the EU on European domestic flights through the EU-ETS [4]. ICAO members are preparing a report on a global scheme to tax emissions that is going to be presented on the 39th ICAO Assembly in 2016 [5]. The EU-ETS scheme is not a tax on the emissions, but rather a system of allowances that each airline buys in order to be able to emit a certain amount of greenhouse gases. The calculation of the amount of allowance spent on each flight, and thus the cost of emissions, is very difficult to make, mainly because the major part of the allowances are auctioned and if one airline exceeds its limit it has to buy more allowances from another airline.

g) Other Fees

Other fees, such as ground handling fees, security fees, transfer and non-transfer passenger fees, or gate fees, are not considered by most authors to be part of the DOC, and will not be considered either in this thesis. This decision is arguable, but stands on the fact that these fees depend much more on the airline level of service than on the aircraft design.

Maintenance Costs

The maintenance costs are probably the most difficult DOC element to model. While the flight costs can be allocated explicitly to each flight and the ownership costs can be relatively easily divided by every year of a defined life span of the aircraft, the maintenance costs cannot be treated in either way with as much simplicity. The maintenance of an aircraft is made through various checks, which usually depend on the number of hours flown or on the flight cycles, with different levels of complexity and with different time schedules. They can go from simple transit checks after every flight, which last around 15 minutes to half an hour, to major maintenance processes where the aircraft has to be completely taken apart for a thorough inspection of all of its parts, and these can last as much as 2 or 3 months. In between, there are other levels of maintenance that happen every night, or once a week, or once every 12 to 18 months. Unscheduled checks may also be needed if some extraordinary event or anomaly has occurred during flight or already on the ground that justifies an evaluation of the aircraft structures, engines or components.
The great variability of the maintenance needed by an aircraft from month to month, and from year to year, means that a method to predict the maintenance costs in a given time period has to capture the expenses in a long-term basis and not exactly those of that particular period, which may be higher or lower. The maintenance schedules can vary from one airline to another, and from one aircraft model to another. Some airlines may choose to divide the heavier maintenance checks into smaller parts and perform them along with the lighter and more frequent checks. This creates the possibility of not having downtimes of weeks or months in a row, and possibly not having that much downtime at all, since the divided checks can be performed overnight. Although there are maintenance requirements by airworthiness authorities, the schedules can be arranged between the airline, the manufacturer and the airworthiness authorities, so this flexibility may exist.

One further problem in the estimation of maintenance costs has to do with the inclusion of the non-revenue cost due to the downtimes, when not only an expense is being incurred but also the aircraft is not generating any revenue. Some authors take this into account [17], but most do not even consider it. Schilling et al. [42] show that reductions in maintenance time, even if they come with further expenses, can be compensated by the revenue obtained with the extended available flight time, thus reducing the non-revenue cost effect. Here again each airline has its own policy, making it more difficult to model this effect.

Maintenance costs are essentially divided into costs of labour and costs of materials, with an approximately even distribution between them [43]. However, burden costs, associated with overhead costs, administration costs or holding of spare parts, among others, are a big part of the maintenance costs. Harris [38], from the data gathered in his study, allocated the burden costs proportionally to the airframe and engine maintenance costs. Liebeck et al. [31] and the CeRAS method [37] estimate a burden cost of two times the labour costs, both for the airframe maintenance and engine maintenance. This shows how influential the burden costs are on the total maintenance costs (in Liebeck’s examples, they amount to around 50% of the airframe maintenance costs and around 25% of the engines maintenance costs). The fact that it is not easy to breakdown into identifiable items such a great component of the maintenance costs might create a difficulty in optimizing them in a realistic way. Some airlines may choose to outsource all or part of its maintenance. When this happens, burden costs will come already on the maintenance price contracted, and the causes of differences in prices are even more difficult to track.

Regarding aircraft systems, maintenance costs can be divided into the following areas: airframe, engines, and other components, such as the avionics, landing gear or the APU. Figure 1.6 shows the distribution of the direct maintenance costs (which exclude burden costs) obtained by International Air Transport Association (IATA) for the financial year 2013 [43]. It can be seen that the engines maintenance costs are the highest ones, but the airframe maintenance costs are not much lower. The costs with the other components still have a significant role on the total maintenance costs. However, the publicly available methods [17, 31, 34, 37, 38] divide the maintenance costs only into airframe and engines costs. The remaining components maintenance costs are included into the airframe costs.

The estimation of the airframe maintenance costs is based on the airframe weight (manufacturer’s empty weight minus engines dry weight) for most methods, except in the CeRAS method, where the
operating weight empty is used instead. Regarding the engines maintenance costs calculation, the Sea Leve Static Thrust (SLST) and the number of engines on the aircraft are the parameters used. In all the methods there is an effect on both the engines and airframe maintenance costs that is attributable to the flight hours and another one due to the flight cycles. The explanation for this is that, while the wear and deterioration of the aircraft systems depend on the time of operation, the aircraft will always have to perform the take off, climb, descent and landing for each flight cycle and these stages are almost completely independent of the trip length.

Recently, the use of composite materials in the primary structures of the newest aircraft (such as the Boeing 787, the Airbus 350XWB or the Bombardier CSeries families) has increased significantly. Around 50% of the materials used in these three families are composite materials. These materials offer several advantages relatively to the traditional metal materials, since it is possible to decrease the overall weight of the aircraft structure maintaining the necessary mechanical characteristics and have improved fatigue tolerance and corrosion resistance [44]. These advantages, apart from decreasing the flight costs, due to the inherent reduction in fuel consumption, also lead to a reduction in the frequency of the maintenance checks, decreasing the costs with scheduled checks [45]. On the other side, unlike metal structures, the damages caused by impacts, such as dropped tools or collisions during flight or on the ground, can be critical for composite structures. The assessment of the extend of the damages in these situations is still difficult to make [44], and the costs of repair or replacement of the damaged parts can be much higher than those for metal parts. Since this trend of using composites in primary structures for commercial aircraft is very recent, there is not sufficient information on the costs of maintenance and repair of structures primarily made out of these materials, and none of the methods studied addresses this factor.

**Total Direct Operating Costs**

While a detailed consideration of the operations costs is needed in order to make a targeted optimization of the elements to which cost is most sensitive, a general operational cost optimization may come
handy in the early stages of the optimization process, mainly due to the low amount of data available.

Swan and Adler [39] present two different equations dependent on the trip distance and on the seat capacity of the aircraft: one for narrow body aircraft in high density seating configuration for trips between 1000 and 5000 km and another one for wide body aircraft in a 2-class seating configuration.

Ali and Al-Shamma [35] present an even simpler relationship, which is a second order polynomial dependent on the take off weight of the aircraft.

Whichever type of method is chosen (either a more detailed or a more simplistic one), there are further considerations not related to the aircraft itself but rather to the airline or the region of operation that influence greatly the DOC. It may appear that these considerations should be considered only on the IOC part of the operational costs, but the truth is that a given aircraft may be the optimal design for a given mission profile of a given airline but not for another airline with different mission profiles. As an example, a certain European airline must be concerned with the level of noise and emissions of the aircraft, placing a higher emphasis on the efficiencies of the engines relatively to an American airline. Other factors, such as the fuel prices differences among the different regions of the world, the labour costs, the materials costs, the navigation or airport taxes, or the access to financing, influence as well how determinant is each of the DOC elements for a given airline.

Apart from the differences among the world regions, differences in the nature of the airlines may dictate significantly different optimal designs for each one of them. For example, low cost carriers tend to turn the aircraft from one flight to another much quicker, which allows them to make 20% more trips per year [39]. This changes the weight of the ownership costs in the overall DOC.

1.3 Approach and Planning

The description of this thesis outline is given next:

Chapter 2 will present models designed to estimate the market price of an aircraft based on some of his physical and performance characteristics with most economical relevance.

Chapter 3 will detail the construction of the operating cost models for estimating the costs of operating the aircraft depending on its characteristics and on the routes and missions that it serves.

Finally, in Chapter 4, the models will be submitted to three different tests, where it is shown the comparison between the costs estimated for different missions, for different aircraft and where the suitability of two different designs is checked for two different real airlines.
2 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 perceives the aircraft will provide him 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 Kilometres (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. Apart from this, other characteristics that are not so easy to determine in an objective way or that are external to the aircraft design, such as the appeal and comfort of the aircraft and the degree of commonality of the fleet, respectively, also influence the value perceived by one given airline.

Before designing the models, a database was built with information gathered for all of the aircraft currently being sold by the four major aircraft manufacturers: Airbus, Boeing, Bombardier and Embraer. The main performance and physical characteristics of each aircraft were gathered from the respective manufacturer website. The same proceeding was done with the engines, collecting the necessary data from the websites of the engine manufacturers that equip the aforementioned aircraft. Regarding the prices of the aircraft and engines, while it was easy to assess the prices of the Airbus and Boeing aircraft, since they provide a list with the selling prices updated every year, the same did not happen with the Bombardier and Embraer aircraft and with the engines manufacturers because the selling prices are not explicitly available. The press releases of the last 4 or 5 year of these latter manufacturers were reviewed in order to determine, from the statements on new deals, the prices of the aircraft and engines. Since not seldom the total amounts of the deals were provided instead of the individual item price, some rounding errors were incorporated in the prices collected, and in some cases a reliable value could not be achieved. One further difficulty in the case of the engines is related to the choice of the maximum rated output at sea level. For one engine, different models with different outputs are available, but the prices disclosed or inferred are relative only to the engine, and are not detailed by model. This created a difficulty on matching the prices with the thrust outputs, and the criterion chosen was to take into account...
To design the acquisition price models, an analysis was conducted first to understand the influence of each of the performance and physical characteristics of the aircraft on their list prices. This way, it was possible to get a better perception of the importance of each of them for the airlines. Afterwards, since the purpose is to create a model that includes as many characteristics (that are interdependent) as possible in order to capture the influences of the various changes in the aircraft design, models with more than one variable were created, and divided by degree of complexity, or, in other words, by the amount of data needed.

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 example, 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.

### 2.1 Range

The first variable tested was range. This is one of the variables that play a major role on setting the aircraft price, along with passenger capacity, because it determines the routes that can be served by each aircraft. If the range itself is not the most important factor for a given airline, longer range capacities allow to fly more weight for the same range than another aircraft, and this may bring more cargo capacity or more luggage capacity for the passengers.

Figure 2.1 shows the list prices of the aircraft on the database as a function of range. Freighter aircraft were excluded since they tend to have a much lower range for approximately the same list price.

![Figure 2.1: Aircraft List Prices (2014) versus Range of the aircraft (excluding freighters).](image_url)
mance characteristics are enhanced and their ranges are typically higher. An exponential curve has been fitted to the data, providing the equation

\[ ALP [\text{\$M}] = 32.7 \times e^{1.53E-4 \times \text{Range}}, \]

(2.1)

where the Aircraft List Price (ALP) is in millions of dollars (2014).

One thing that immediately meets the eye is the fact that, when families have 2 or 3 aircraft, and mainly with Airbus and Boeing families, there is generally one aircraft below the fitted curve and the remaining 1 or 2 are above that same curve. It is possible to understand that 2 different curves could be designed, one for the aircraft under the fitted curve and another one for the aircraft above the fitted curve. However, this poses the problem of determining with which curve should an aircraft price be estimated.

In Figure 2.1, it can be observed that above the curve are generally the original version of each family and their stretched versions, and below are the shrunk versions. Exceptions, talking about only the Airbus and Boeing aircraft, are the B787 family, which has its original version B787-8 and a first stretched version B787-9 below the fitted curve, and the B737 family, which has its original New Generation version also below the fitted curve. The B737MAX family is just a direct replacement of the B737NG family, so no aircraft is the original version. None of the aircraft of the B777 family present in the database is the original one, since they are all already extended versions of the first ones that are now off the Boeing catalogue. Since there are so many exceptions, the fact that an aircraft is the original version of a family should not be used to further assess its market price.

However, it can be seen that the aircraft above the fitted curve generally have lower ranges but higher prices. The fact that these are longer versions means that they have more seats, which is highly valued by airlines, but on the other hand they also tend to have a higher MTOW and thus a reduced range. This shows that, although a first good approximation can be obtained with this curve, there are other factors that greatly influence the list price of the aircraft, and apparently one of the main factors is the seat capacity.

Another thing that can be easily observed from Figure 2.1 is that the absolute errors in the wide body aircraft zone are much higher than those in the narrow body region. The summary of the information regarding the maximum relative errors in absolute value and the average relative errors in absolute value for the different manufacturers is displayed in Table 2.1. For the narrow body aircraft, it is possible to see that, except for Embraer, the average of the absolute values of the relative errors is lower than that for the wide body aircraft. With the exception once again of Embraer, the narrow body aircraft with larger price errors are those with more seats, which are underestimated. This supports again the importance of the seat capacity in the price of the aircraft. The Bombardier aircraft with highest error was in fact the Q400NG, but since it has a different means of propulsion (turboprop), it was not considered in this comparison. Looking once again to the average of the errors, it can be concluded that, in fact, the narrow body aircraft list prices are a bit better estimated by the curve obtained.
2.2 Seats

The number of seats in an aircraft is one of the variables most valued by the airlines. As it was seen in the previous section, even aircraft of the same family (which means they will have approximately the same efficiencies) with lower ranges could be sold by considerably higher prices, and the number of seats available was one of the main differences between them.

There are two opposite ways of looking to seats capacity: either the typical capacity arrangement, where, depending on the aircraft size, there can be 2 or 3 classes; or the maximum capacity arrangement, where the seats pitches (distance from two equivalent points on consecutive seats) are reduced as much as possible to increase to the maximum the capacity of the aircraft and thus the revenue obtained by the airline for a given flight. In Figures 2.2 and 2.3 are represented the variations of list prices with the typical and maximum seat capacities, respectively.

![Figure 2.2: Aircraft List Prices (2014) versus Number of Seats in a typical cabin configuration.](image)

It is possible to see in both Figures that a linear fit approximates the list prices relatively well for most of the aircraft in both situations. Equations 2.2 and 2.3 represent the linear fitted curves for the typical seating arrangement and for the maximum seating arrangement, respectively:

\[
ALP[\text{\$M}] = 0.974 \times Seats_{Typ} - 39.692
\]  
(2.2)

\[
ALP[\text{\$M}] = 0.595 \times Seats_{Max} - 5.261
\]  
(2.3)
On the typical seating capacity plot, one stays under the impression that the narrow body aircraft prices tend to grow slower with increasing capacity, while with maximum capacity the trend is almost clearly linear. Furthermore, the wide body estimations seem to be a little more scattered for the maximum capacity situation than for the typical seating arrangement.

Although airlines have been applying the increasing seat capacities strategy in order to enhance their economics, the arrangements not always lie neither on the manufacturer specified typical arrangement nor on the maximum arrangement. In fact, the airlines that most make use of the maximum seating arrangements are the lowcost companies, since people are willing to give up the extra leg space in exchange for the reduced fares. These airlines, given that they operate on shorter ranges, tend to have only narrow body aircraft, mainly the A320 and B737 families, but some of them also have Bombardier and Embraer aircraft. The other airlines, although not configuring their narrow bodies to the maximum capacity, also increase their seat count above the typical arrangement capacity, since these narrow body aircraft also are the ones that usually make the shorter trips, where people can stand a little bit more of tightness.

For this reason, it was decided to fit two different curves, one for the narrow body group and another one for the wide body group, with maximum capacity and typical capacity, respectively. Figure 2.4 shows the results.

At first sight, it seems that the results obtained with the two different logarithmic fits in Figure 2.4 provide worse results than either of the unique linear fits in Figures 2.2 and 2.3 because the $R^2$ are lower. Equations 2.4 and 2.5 represent the logarithmic fitted curves for the narrow body aircraft and wide body aircraft, respectively:

$$ALP_{NB}[^M] = 78.182 \times ln(Seats_{Max}) - 309.62$$ \hspace{1cm} (2.4)

$$ALP_{WB}[^M] = 255.29 \times ln(Seats_{Typ}) - 1178.1$$ \hspace{1cm} (2.5)
Analysing the errors like it was done in Table 2.2, however, we can see that the conclusions will point on the opposite direction. The maximum relative errors for each family in each region are lower for the two logarithmic equations than for both linear equations. The same happens with the average errors. With the exception of the Embraer aircraft, the logarithmic equations seem to make good estimations of the list prices of the aircraft, since the absolute values of the relative errors are always below 15%, and the average of those errors is always lower than 7%.

Table 2.2: Maximum and average of the absolute values of the relative errors of equations 2.2 (Lin.Typ.), 2.3 (Lin.Max.), and 2.4 and 2.5 (Log. Mix.).

<table>
<thead>
<tr>
<th>Lin. Typ.</th>
<th>Narrow Bodies</th>
<th>Airline</th>
<th>Lin. Max.</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>Embraer</td>
<td>E170 CRJ900NG A321neo 737-900ER A380-800 777-8X</td>
<td>39% 15% 61% 37% 18% 16%</td>
<td>E195 CS300 A319neo 737-MAX7 A330-300 777-8X</td>
<td>49% 73% 42.3% 29.2% 4.9% 12%</td>
</tr>
<tr>
<td>Bombardier</td>
<td>A330</td>
<td></td>
<td>25.9% 17.5%</td>
<td>737-900ER A380-800 777-8X</td>
</tr>
<tr>
<td>Airbus</td>
<td>A333neo A350</td>
<td>37% 18% 16%</td>
<td>A333neo A350</td>
<td>18% 16%</td>
</tr>
<tr>
<td>Boeing</td>
<td>747 767 777X</td>
<td>15% 61% 37%</td>
<td>777X</td>
<td>61% 49% 73% 49% 91% 52%</td>
</tr>
<tr>
<td>Wide Bodies</td>
<td>A350 777X</td>
<td>18% 16%</td>
<td>A380-800 777-8X</td>
<td>9.7% 9.2%</td>
</tr>
<tr>
<td>Boeing</td>
<td>767 777X</td>
<td>15% 61% 37%</td>
<td>777X</td>
<td>12% 7.7% 13% 4.9% 12%</td>
</tr>
<tr>
<td>Average</td>
<td>A330-300 777-8X</td>
<td>17.3% 6.2% 3.1% 6.7% 3.0% 5.1%</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Looking once again to Figure 2.4, it is possible to see that there are only a few outliers for each of the curves: the EJet Embraer Family, as backed by the results on Table 2.2; and the 2 aircraft from 777X Boeing family, which seem to follow the trend of the curve but slightly above it. The rest of the aircraft lie acceptably close to the curves.

The Airbus and Boeing narrow body families follow closely the curve. It is possible to see here that the newest versions of these families have similar seating capacities to the older ones - particularly the Boeing aircraft, which have exactly the same seats count - and their prices are higher. Besides the
enhanced performance characteristics, this can be also due to other factors such as range, which has already been analysed.

Regarding the wide body aircraft, families tend to follow the curve, even if sometimes a bit above or below it.

In general, if considered alone, the seat capacity of the aircraft, the maximum for the narrow bodies and the typical for the wide bodies, makes alone better estimates of the list prices than the range alone. Both the maximum errors and the average error for each family are lower if the prices are estimated as a function of the number of seats than if they are to be estimated as a function of the range of the aircraft. Besides, the fact that the estimations are much less scattered around the curve offers a higher confidence on the results provided by the equations 2.4 and 2.5.

2.3 Maximum Take Off Weight

Some authors, such as Roskam, believe that aircraft prices can be estimated as a function of their weight. Although some approximations can lead to acceptable results, this approach does not capture the main drivers of the aircraft price. As it has been seen before, what drives aircraft prices are mainly the characteristics that directly influence the revenue that a given aircraft can provide to an airline company, and, as in most markets, the supply and demand. The Maximum Take Off Weight is a physical characteristic that determines to some extent the dimensions of the aircraft (both in terms of size and weight) and thus the possible number of seats. On the other hand, a higher MTOW means that, all other things equal, the aircraft will fly shorter distances for the same amount of fuel spent.

Therefore, MTOW is much of a link between the seat capacity and the range of the aircraft. If these two variables, as shown, can be already related to each other, the use of MTOW as an additional variable increases even further problems of multicollinearity, and the impact of each of the variables on the aircraft price is harder to assess. Thus, it may be more difficult for the optimizer to understand which way leads to the lower aircraft price, if that becomes relevant throughout the optimization process.

Even if the use of MTOW seems implausible, due to the fact that it does not reflect any particular characteristic relevant to the economical performance of the airlines, its effect alone on the aircraft price has been studied, since it may become handy at the earlier stages of the design process, where good estimates of the seats capacity and range are not yet available.

Figure 2.5 shows the list prices of the aircraft in the database versus the MTOW in tonnes and the curves fitted to those points.

Once again, one can see that the narrow body aircraft follow a more consistent pattern, while the wide body aircraft points are more scattered. The narrow bodies lie clearly on a straight line, thus the fitting of a linear curve to those points, but the wide bodies prices tend to increase less with increasing MTOW, thus the use of a logarithmic curve. Furthermore, the scattered points show that MTOW does not explain plainly the variations in price, since, for example, Boeing 777-8X and 777-9X have the same MTOW but considerably different prices. One other fitting curve tested - not shown in Figure 2.5 for purposes of clarity - was a polynomial one, which followed closely the behaviours of both the straight
Figure 2.5: Aircraft List Prices (2014) versus Maximum Take Off Weight (in tonnes) for the narrow body aircraft and the wide body aircraft.

Line and the logarithmic curve. The advantage that seems more relevant of this approach is that one single curve allows the designers to have uncertainty regarding the configuration of the aircraft - if narrow body or if wide body - until later phases of the project. Table 2.3 shows the comparison of the two cases. There is no clear trend that reveals whether the use of the polynomial makes better estimates or not. Furthermore, it is difficult to find a pattern that correlates the aircraft with higher errors.

Following, equations 2.6, 2.7 and 2.8 describe, respectively, the linear curve for the narrow bodies, the logarithmic curve for wide bodies, and the polynomial curve for all the aircraft:

\[
ALP_{NB}[\$M] = 1.3059 \times MTOW - 7.7525 
\] (2.6)

\[
ALP_{WB}[\$M] = 205.88 \times \ln(MTOW) - 876.62 
\] (2.7)

\[
ALP_{All}[\$M] = -0.001050 \times MTOW^2 + 1.332 \times MTOW - 5.656 
\] (2.8)

<table>
<thead>
<tr>
<th>Aircraft model</th>
<th>Narrow Bodies</th>
<th>WB</th>
<th>BO</th>
<th>BO</th>
</tr>
</thead>
<tbody>
<tr>
<td>NB</td>
<td>Maximum</td>
<td>19%</td>
<td>18%</td>
<td>13%</td>
</tr>
<tr>
<td></td>
<td>Average</td>
<td>9.7%</td>
<td>10.4%</td>
<td>5.6%</td>
</tr>
<tr>
<td>WB</td>
<td>Maximum</td>
<td>20%</td>
<td>15%</td>
<td>11%</td>
</tr>
<tr>
<td></td>
<td>Average</td>
<td>10.1%</td>
<td>9.7%</td>
<td>6.1%</td>
</tr>
<tr>
<td>All</td>
<td>Maximum</td>
<td>20%</td>
<td>15%</td>
<td>11%</td>
</tr>
<tr>
<td></td>
<td>Average</td>
<td>10.1%</td>
<td>9.7%</td>
<td>6.1%</td>
</tr>
</tbody>
</table>
Whichever equation is to be used, the results are very similar. All the aircraft are estimated with errors below 20%, which is a very good maximum error for a model to be used in the earlier phases of the optimization. Furthermore, the average errors are almost all smaller than 10%.

2.4 Speed

While speed seems to be an important variable when determining the price of military aircraft (although the prices of these aircraft depend greatly on their mission type), in civil commercial aviation, where cruise speed is more or less equal among almost all aircraft, this variable offers no trend that can be used in assessing the aircraft price.

2.5 Thrust

The engines are a component in the aircraft that plays a very significant role in the operations costs, since their efficiencies determine to a great extent how much the airline will spend in fuel costs. Besides, it is a component that requires different levels of maintenance depending on the engine ratings, which ends up being relevant in the maintenance costs as well. These factors, just as the aircraft performance characteristics contribute to its price, have a major role on the engine price, and ultimately on the whole aircraft price.

Just like in the entire aircraft system, there are various characteristics of the engine that can influence its value. The most relevant is probably fuel efficiency. This is, however, a value that is not disclosed neither by the manufacturers nor by the airlines. Claims of relative fuel savings are issued whenever new engines are developed, but the real efficiencies are only confirmed by the airline after a good amount of flight hours, and if they do not match the contracted efficiencies, it comes with a penalization to the manufacturer. Thus, real absolute values are never disclosed.

One characteristic that may not be directly linked to the engine performance but which reflects to a certain degree the complexity of the engine is the thrust provided. Obviously, if one airline can choose between a set of engines to equip on an aircraft, they all must have more or less the same thrust characteristics. It is also clear that they will not necessarily have the same efficiencies. It is here that the negotiation process begins. Although small variations may exist between two different engines that can equip one particular aircraft, the general characteristics will be similar and thus their prices will be more or less of the same magnitude. Acknowledging that the price estimated will not reflect the performance characteristics as it would be desired, it is already good to have an indication of the variations with thrust.

Another factor that influences the engine price is the bargaining power of the airlines. For some aircraft models, more than one engine type is available to choose from, usually two or three, from different manufacturers. When there is only one possible engine, its price may be higher, since it is either that one or no one. Although this seems to be the real case, no evidence of this phenomenon was found in the data gathered. Two factors may be in the origin of this: 1) the quality of the data (list prices and thrust rates) is not perfect, which means that these small effects may be more difficult to be
captured; or 2) the list prices, much like in the whole aircraft case, do not reflect the actual prices paid by the airline, and the bargaining power is very likely to take effect only on the discounts obtained, i.e., discounts are higher when there is more than one engine option available.

Before presenting the relationship obtained, it is necessary to refer that the list prices were obtained through estimates using the press releases on the respective manufacturer’s web site. For some engines, there were several press releases available and an average of those values was used, reducing thus the errors. For the engines where only one or two press releases were available, it is more difficult to know whether the list prices obtained are in accordance with the actual list prices. The thrust values refer to the take off thrust and were obtained in the manufacturer’s web sites.

Figure 2.6 shows the list prices of the jet engines as a function of the take off thrust. A linear curve was fitted to the data, providing the following equation:

\[
ELP_{jets}[\text{\$M}] = 0.0619 \times \text{Thrust}_{TO} + 3.0951, \tag{2.9}
\]

where Engine List Price (ELP) is in millions of 2014 U.S. dollars.

It is possible to see from Figure 2.6 that, while most of the points follow the linear trend, some of them are somewhat distant from the trend line. The highest price errors are amongst the engines that equip the Bombardier and Embraer aircraft. The average of the errors of these engines is 40%. These are some of the prices where there was more uncertainty in the obtained values, thus the high errors are probably due to errors in the data gathered. Regarding the Airbus and Boeing aircraft, there are errors in the estimated prices as high as 35%, but most of them are below a 20% difference. The average of the errors is 11%, which shows that, as a whole, the linear fit yields good approximations.

Still in Figure 2.6, one can see that there are several plateaus, which represent different ratings for the same engine model, all at the same price. This, as discussed previously, may be one of the factors that contribute to the errors, since these points cross the trend line almost perpendicularly.

Finally, one thing that was noted is that all the engines in the aircraft amount to about 20-35% of the aircraft price. In the low end of this range are the larger aircraft, while on the high end are the narrow
bodies. So, another way of estimating fairly quickly the engine price is setting it to be around one fifth to one third of the aircraft estimated price.

### 2.6 Fuel Efficiency

The aircraft fuel efficiency is, along with range and seat capacity, one of the most important factors on determining how much is an airline willing to pay for an aircraft. In fact, the aircraft economics are often measured in dollars spent by available seat-kilometre. Today, fuel costs represent a big slice of the operating costs pie, and an aircraft spending less fuel for the same number of passengers carried and miles flown than another one is expected to bring more value to the airline company.

Fuel efficiency depends essentially on two things: the engine efficiency, and the aerodynamic efficiency. The first factor was already discussed in the previous section. The aerodynamic efficiency determines how much thrust the engines are required to provide, which in turn means that it influences the amount of fuel spent. Much like the engines efficiencies, its is very difficult to obtain hard data on the aerodynamic efficiency of the aircraft. These values are only available to the manufacturer and are not disclosed. The only way for the airlines to know exactly both the aerodynamic and engines efficiencies is by keeping track of the fuel consumed and comparing these values to the promised by the manufacturers. The airlines do not disclose the values they obtained either.

This means that, without objective values upon which to rely, it is impossible to devise any kind of relationship that links the aircraft price with its fuel efficiency.

### 2.7 Offer and Demand

As in most markets, supply and demand conditions are a great determinant of a product’s price. In the air transportation industry things work alike. If a given type of aircraft has a great demand, it is not but normal that the manufacturers raise the prices of their models in that category. On the other hand, if for another given type of aircraft sales are low across all manufacturers, they will most probably lower their prices or make higher discounts or give extra benefits.

Here lies one of the difficulties of quantifying the effect of supply and demand on aircraft prices. In this market, unlike a supermarket where people pay for a certain product and have nothing else to do with the company that produced it regarding that unit, airline companies maintain a close relationship with the manufacturer. This means that, even if the list prices are not lowered for an aircraft with less demand, the airline may receive benefits - such as on maintenance, on crews training, etc. - that would not receive on other models, or they may get higher discounts.

Furthermore, for having a clear understanding of how demand and supply affect aircraft prices, and since this is not a static phenomenon, a historic of the aircraft orders and prices, at least, would be necessary. While the amount of orders through the years for the different models being sold today can be relatively easily obtained, the same does not happen with the prices of the aircraft. Airbus provides on its website its list prices since 2012, but Boeing only makes available 2014 information and Bombardier
and Embraer do not even disclose their list prices. To really assess the impact of demand on the prices, information since the aircraft launch would be necessary. This information could not be obtained with sufficient quality. Moreover, to use a model that would depend on data that is external to the project will create an additional difficulty to estimate the aircraft price, and the effort dedicated to this task may not be compensated in the increase of quality on the estimation.

In conclusion, although it is recognized that supply and demand conditions may affect the aircraft prices, the difficulty of getting data allied with the amount of uncertainty of the data available do not seem to justify the integration of this variable into the model.

2.8 Final Models

After considering all the factors aforementioned - their weights on the estimation of the price and their benefits and drawbacks -, it was sought a model that could be not only as accurate as possible, but also simple enough to be used in the preliminary design phase, i.e., a model that is realistic, that reflects the influences of each of the factors, and where the necessary variables can be easily obtained with the already available data.

Next, a summary of the variables and their effects on the aircraft price is listed:

- **Range** - An exponential fit can explain substantially well the evolution of price with the range of the aircraft. This is a value that is most likely to be part of the aircraft requirements, so in most cases it will be available very early in the design phase. This variable alone cannot explain certain differences in prices of aircraft of the same family, that most of the times lay in opposite sides of the curve. This points to the need of an additional variable to explain these differences.

- **Seats** - This is the variable that, alone, can explain the best the variations in price. However, two different logarithmic fits were devised, one for the narrow body aircraft, considering the maximum seat capacity, and another one for the wide body aircraft, considering the typical arrangement capacity. This is the main drawback of this variable, since this information may not be already defined in the earlier stages of the design. To overcome this, other approximations can be used, with not so good quality, but that may suffice. One good point about this variable is that it tends to estimate the price of aircraft of the same family with the same trend of the actual list prices, which means that there is much less perpendicularity of the points against the curve when compared with the Range.

- **Maximum Take Off Weight** - The MTOW is a measure that reflects very closely the changes in range and in seats capacity. Thus, its use along with these two variables should be restrained. To avoid problems of multicollinearity, which would prevent the optimization process of determining the best path to optimize the aircraft characteristics relatively to its price, this variable should be used separately to determine the price in the earliest stages of the design process when not even seat capacity or range may be already both defined with great confidence.
• **Thrust** - The thrust characteristics influence the choice of the engines, which amount to a very considerable percentage of the whole aircraft price (20-35%). Furthermore, the thrust required by an aircraft, when compared with other similar aircraft, is a good indicator of how fuel efficient it is. However, information about thrust may not be available early in the design process, so it will come handy just later.

Three models will be presented: one for the earliest stages of the design process using MTOW, a second one for the next phase, using seat capacity and range information, and a third one using both these variables and additionally thrust.

### 2.8.1 Early model - MTOW

This is exactly the polynomial curve presented previously in the Maximum Take Off Weight subsection, which was chosen because it does not require determining whether the aircraft is a narrow body or a wide body one, and because it yields results similar to those obtained with the separate curves for narrow bodies and wide bodies.

Next, equation 2.8 is reproduced:

\[
ALP_{Early}[M] = -0.001050 \times MTOW^2 + 1.332 \times MTOW - 5.656
\]  
(2.10)

The errors compared to the aircraft list prices in the database, as analysed before, are almost always lower than 15%, which is already acceptable, with exception of the Embraer and Bombardier aircraft, and this may be due to their smaller size, since the highest errors of the Airbus and Boeing aircraft are also on the smaller aircraft. Thus, results provided for aircraft with an MTOW lower than 70 tonnes must be more carefully considered.

### 2.8.2 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 results provided by the equations 2.1 and 2.4 and by equation 2.5 resulted in overall lower differences between the estimated prices and the list prices relatively to the estimations using Range or Seats Capacity alone. Several types of equations were studied to incorporate the two variables into one prediction function, but the one that resulted in the major gains in accuracy, which is presented next, was a function where is applied a weighted sum of the equations 2.1 and 2.4 or 2.5, depending on whether the aircraft is a narrow body or a wide body, with an 85% relevance for the seats equation and 15% for the range equation:

\[
ALP_{Interm_{NB}}[M] = 0.85 \times [78.182 \times \ln(Seats_{Max}) - 309.62] + 0.15 \times [32.7 \times e^{1.53E-4 \times Range}]
\] 
(2.11)

\[
ALP_{Interm_{WB}}[M] = 0.85 \times [255.29 \times \ln(Seats_{Typ}) - 1178.1] + 0.15 \times [32.7 \times e^{1.53E-4 \times Range}]
\] 
(2.12)
It is possible to see from these equations that the Seats approximation has a higher preponderance on the final estimating function.

A comparison of the errors of the estimations obtained with these equations with those of the estimations for range and seats capacity alone is presented in Table 2.4.

Table 2.4: Comparison of the errors of the Intermediate Model estimations with those of the Range and Seats Capacity models alone.

<table>
<thead>
<tr>
<th></th>
<th>Embraer</th>
<th>Narrow Bodies</th>
<th>Wide Bodies</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Airbus</td>
<td>Boeing</td>
</tr>
<tr>
<td>Seats</td>
<td>Maximum</td>
<td>33.4%</td>
<td>12.1%</td>
</tr>
<tr>
<td></td>
<td>Average</td>
<td>17.3%</td>
<td>6.2%</td>
</tr>
<tr>
<td></td>
<td>St. Deviation</td>
<td>10.8%</td>
<td>4.3%</td>
</tr>
<tr>
<td>Range</td>
<td>Maximum</td>
<td>36.2%</td>
<td>18.2%</td>
</tr>
<tr>
<td></td>
<td>Average</td>
<td>19.9%</td>
<td>9.8%</td>
</tr>
<tr>
<td></td>
<td>St. Deviation</td>
<td>11.5%</td>
<td>6.5%</td>
</tr>
<tr>
<td>Int. Model</td>
<td>Maximum</td>
<td>28.7%</td>
<td>9.8%</td>
</tr>
<tr>
<td></td>
<td>Average</td>
<td>13.8%</td>
<td>5.8%</td>
</tr>
<tr>
<td></td>
<td>St. Deviation</td>
<td>9.4%</td>
<td>3.3%</td>
</tr>
</tbody>
</table>

One can see from the table that the maximum absolute value of the errors, the average of the absolute value of the errors and the standard deviation of the absolute value of the errors are lower in the Intermediate Model for almost every type of aircraft by manufacturer. The best decreases of the errors can be accomplished in those aircraft that had the higher errors, namely the Embraer and Bombardier aircraft.

Furthermore, almost all aircraft prices can be predicted by the model with an error lower than 10%. The exceptions are the Embraer aircraft, which have much higher errors than the other families (this can be due once again to the quality of the data obtained), and the still to be introduced Boeing aircraft - the 737 Max family and the 777X family. These aircraft prices are underestimated, and this may point to the fact that newer aircraft, due to the expected increases in fuel efficiency, are worth more. They are underestimated in around 7-12% of their actual list price, so, since it is not possible to devise a model that includes efficiencies, it seems like a correction of this magnitude could be made, although not enough data is available to support it.

2.8.3 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 why a model that uses thrust is designed 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 two aircraft have similar seats and range capacities, an engine with higher thrust rate will be priced lower, inversely to what was discussed in the Thrust subsection. 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. As seen before, 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 2.11 and 2.12 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:

\[
\frac{c}{\left(\frac{T_{TO_{max}}}{S} \right)^N e S R},
\]

where \(c\) is a coefficient to be determined that is different for narrow bodies and for wide bodies, \(T_{TO_{max}}\) 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 \(c\), expression 2.13 was equalled to the values gathered for the actual engines prices. An average of \(c_{NB} = 0.005\) and \(c_{WB} = 0.008\) was obtained. These values will be slightly changed later to better fit the whole aircraft prices.

The next step is determining how much the engine price amounts in the entire aircraft price. As seen before, 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 2.11 and 2.12. 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. Figure 2.7 shows that, excluding the red dots which represent outliers, there is a seemingly exponential relationship between the two variables.

Figure 2.7: Variation of the weight of the engines price on the entire aircraft price as a function of the seats capacity (maximum for narrow bodies and typical for wide bodies). Red dots represent outliers and were not taken into account when creating the fitting curve.
The exponential fitted curve gives 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).

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

(2.14)

It is important to note that few data points exist for the Bombardier and Embraer aircraft - only six - and four of them are among the outliers. This means that probably the relationship obtained is not the best for these aircraft, and their estimated prices may have lower quality when compared to the Airbus and Boeing aircraft.

After having the percentage of the engines on aircraft price, a few corrections to the obtained coefficients were made, in order to get the best fit to the data, and the following relationships were obtained for narrow bodies and wide bodies, respectively:

\[
\begin{align*}
ALP_{\text{LateNB}}[\$M] &= (1 - 2.1 \times \text{Seats}_{\text{Max}}^{-0.445}) \times \{0.85 \times (78.182 \times \ln(\text{Seats}_{\text{Max}}) - 309.62) \\
&\quad + 0.15 \times (32.7 \times e^{1.53E-4 \times \text{Range}})\} + \frac{0.0046}{\text{TO}_{\text{Max}} + \text{N}} \times \frac{\text{Ne} \times \text{Range}}{\text{Seats}_{\text{Max}}}
\end{align*}
\]  

(2.15)

\[
\begin{align*}
ALP_{\text{LateWB}}[\$M] &= (1 - 2.1 \times \text{Seats}_{\text{Typ}}^{-0.445}) \times \{0.85 \times (255.29 \times \ln(\text{Seats}_{\text{Typ}}) - 1178.1) \\
&\quad + 0.15 \times (32.7 \times e^{1.53E-4 \times \text{Range}})\} + \frac{0.0081}{\text{TO}_{\text{Max}} + \text{N}} \times \frac{\text{Ne} \times \text{Range}}{\text{Seats}_{\text{Typ}}}
\end{align*}
\]  

(2.16)

Figure 2.8 shows that, although there could be the problem of estimating lower priced engines with higher thrusts with expression 2.13, this is the case only for those with very high maximum take off thrusts. The points of the estimates follow relatively well the trend of the actual prices, excluding those for four-engines aircraft and the ones with \(\text{TO}_{\text{Max}}\) higher than 400kN. On the narrow body zone, the estimates are roughly coincident with the actual prices. Concluding, the estimation of the prices of the engines provides good results with this approximation.

Table 2.5: Comparison of the errors of the Late Model estimations with those of the Intermediate Model.

<table>
<thead>
<tr>
<th></th>
<th>Embraer</th>
<th>Narrow Bodies</th>
<th>Airbus</th>
<th>Boeing</th>
<th>Wide Bodies</th>
<th>Airbus</th>
<th>Boeing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Int Model</td>
<td>Maximum</td>
<td>28.7%</td>
<td>9.8%</td>
<td>4.7%</td>
<td>12.3%</td>
<td>4.9%</td>
<td>10.3%</td>
</tr>
<tr>
<td></td>
<td>Average</td>
<td>13.8%</td>
<td>5.8%</td>
<td>2.5%</td>
<td>6.1%</td>
<td>2.2%</td>
<td>4.7%</td>
</tr>
<tr>
<td></td>
<td>St. Deviation</td>
<td>9.4%</td>
<td>3.3%</td>
<td>1.6%</td>
<td>5.2%</td>
<td>1.7%</td>
<td>3.0%</td>
</tr>
<tr>
<td>Late Model</td>
<td>Maximum</td>
<td>17.4%</td>
<td>18.6%</td>
<td>4.9%</td>
<td>7.9%</td>
<td>5.9%</td>
<td>9.9%</td>
</tr>
<tr>
<td></td>
<td>Average</td>
<td>10.2%</td>
<td>12.6%</td>
<td>2.8%</td>
<td>4.3%</td>
<td>2.4%</td>
<td>4.9%</td>
</tr>
<tr>
<td></td>
<td>St. Deviation</td>
<td>5.4%</td>
<td>5.2%</td>
<td>1.5%</td>
<td>2.7%</td>
<td>2.1%</td>
<td>3.6%</td>
</tr>
</tbody>
</table>

The errors of the estimating relationships are shown in Table 2.5, where it is possible to see that the two models provide results with a similar overall quality. While the errors on the Embraer aircraft are
much smaller - both the maximum and the average -, the Bombardier aircraft errors increase significantly. Airbus aircraft data have slightly worse results, with more emphasis on the Wide Body aircraft, and Boeing errors decrease a few percentage points, mainly in the narrow body category. Overall, no aircraft is having errors higher than 20% now, and the Airbus and Boeing aircraft, which have the most reliable data, are with errors always smaller than 10%.

Analysing the errors more individually, it could be observed that the Boeing aircraft with higher errors were the 737MAX, the 777X and the 787 families. All the prices of the aircraft in the first two families were underestimated with equations 2.15 and 2.16. This may be due to the fact that these aircraft are still under development, which means that they will have newer technologies that could not be taken into account in the relationships developed. Regarding the 787 family aircraft, the models -8 and -9 are over evaluated, with a difference of around 10% to the actual list price, and the model -10 is very close to the list price. No connection between this difference and the variables available (seats capacity, range, and take off maximum thrust) could be found.

Regarding the Bombardier and Embraer aircraft, the problem may lie once again in the difficulty of getting quality data. The price behaviour on these aircraft may be simply connected to some business strategy, but it may also be due to the different characteristics, such as the fact that they are smaller aircraft or that they have increased performance, that cannot be used in the models created, but rather would need different models just for them. Since not enough data is available, this hypothesis cannot be tested.

Lastly, there could not be found any relationship between the aircraft price and the use of composites, which, as seen before, offer less frequent maintenance schedules, and thus should be seen by the airlines as a good characteristic. The aircraft with higher use of composites are the ones in the Boeing 787 family, which is on two out of the three models overestimated. Next comes the Airbus A350XWB family, and one out of the three is overestimated, another one is almost very well estimated and a third one is
underestimated. Since it was not possible to find a relationship between the errors in the estimates and the use of composites, its inclusion was not considered.

In conclusion, the models designed can estimate the aircraft list price with relatively good quality. The first model is very simple, but can be valuable in the earlier phases of the design process, while the other two models are sensible to changes in the seat capacity of the aircraft, in its range, and, in the case of the Late model, it is sensible to changes in the aircraft overall efficiency, which can be reflected by the take off thrust capacity.

The best results were obtained for the Airbus and Boeing aircraft. The errors were always lower than 10% in the so-called Late Model for any of the aircraft of these families. It is expected that the prices of aircraft built in the same conditions as these manufacturers’ ones can also be well estimated. However, no manufacturer besides these two can build aircraft in their conditions, which means not being able to have as much savings from experience from past programmes or from such high economies of scale.

As a last note, the discounts offered by Airbus and Boeing, although not being public, are almost definitely higher than those offered by manufacturers with lower sales. This also may influence the aircraft list price, since it may be inflating the Airbus and Boeing prices, a phenomenon that cannot be taken into account in the same way for the other manufacturers. Anyhow, these discounts were not considered, so there are two possibilities: the estimated aircraft price is either used as is; or an estimation of the discounts is applied when calculating the ownership costs in the optimization.
3 Operating Cost Model

3.1 Flight Costs Model

3.1.1 Fuel

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. This means that a very good estimation of these costs is necessary given their influence in the overall cost optimization process. 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 engines 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\(^1\), 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 from month to month and from year to year depending on countless factors, it is impossible to devise a relationship that could forecast the fuel prices. There are available various projections, ranging from very optimistic ones to the most pessimistic. It is advised the consultation of these projections (for instance the ones from EIA or from the 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.

Apart from the fuel prices, the other component of the fuel costs is the fuel consumption during the entire flight, which, as mentioned before, should be provided by the engines module. However, if for some reason this information is unavailable at some point during the optimization, there must be alternatives. For calculating the fuel consumption during cruise, the Breguet Equation can be used:

\[
\text{Range} = \frac{V}{g \times SFC} \frac{L}{D} \ln \left( \frac{W_i}{W_f} \right)
\]

(3.1)

Here, \(V\) is the cruise speed in \(m/s\), \(g\) is the gravity acceleration in \(m/s^2\), \(SFC\) is the specific fuel consumption during cruise in \(kg/(s.N)\), \(L/D\) is the lift-to-drag ratio and \(W_i\) and \(W_f\) are the cruise initial and final weights of the aircraft. Having the velocity, the range, the specific fuel consumption (or a first approximate estimation) and the cruise initial weight, it is possible to calculate the fuel spent during the cruise phase.

\(^1\)http://www.iata.org/publications/economics/fuel-monitor/Pages/price-analysis.aspx
The problem now lies on knowing how much fuel is spent during taxi-out, take-off, climb, descend, landing and taxi-in (and if there is hold it should be considered too). Table 3.1 shows the decreasing percentages of the aircraft weight in each flight phase relatively to the weight when that phase has begun. The absolute differences are thus the weight of fuel spent.

The endurance equation used for the hold phase is presented next:

$$\text{Endurance} = \frac{1}{g \cdot \text{SFC}} \frac{L}{D} \ln \left( \frac{W_i}{W_f} \right)$$  \hspace{1cm} (3.2)

The forth column, named “Fuel Model”, is a model developed using data from different values of fuel consumption for different stage lengths of an aircraft designed in the context of the NOVEMOR project. The fuel consumptions of these model are considerably lower for some of the stages of the flight. The fact that all the other models are considerably old helps explaining this difference.

Table 3.1: Ratio between the final and initial weight of the aircraft for the different flight stages. The difference between the initial and final weights for each of the stages is the fuel consumed during that stage.

<table>
<thead>
<tr>
<th>Stage</th>
<th>Corke</th>
<th>Roskam</th>
<th>Raymer</th>
<th>Fuel Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Taxi out</td>
<td>—</td>
<td>0.980</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Take off</td>
<td>0.970</td>
<td>0.995</td>
<td>0.970</td>
<td>0.995</td>
</tr>
<tr>
<td>Climb</td>
<td>1.04(M_c)</td>
<td>0.980</td>
<td>0.985</td>
<td>0.985</td>
</tr>
<tr>
<td>Cruise</td>
<td>Breguet</td>
<td>Breguet</td>
<td>Breguet</td>
<td>Breguet</td>
</tr>
<tr>
<td>Descend</td>
<td>—</td>
<td>0.990</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Hold</td>
<td>Endurance</td>
<td>Endurance</td>
<td>Endurance</td>
<td>Endurance</td>
</tr>
<tr>
<td>Landing</td>
<td>0.975</td>
<td>—</td>
<td>0.995</td>
<td>0.995</td>
</tr>
<tr>
<td>Taxi in</td>
<td>—</td>
<td>0.992</td>
<td>—</td>
<td>—</td>
</tr>
</tbody>
</table>

The results obtained should be multiplied by the number of flight cycles in one year to obtain the yearly costs with fuel.

3.1.2 Cockpit Crews

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 not taken into account to calculate their wages. Cockpit crew members generally start out as first officers in regional airlines, earning a lower base salary, and, as they fly more hours, they tend to earn more. Then they become captains, and their salaries increase. However, to go to a major airline, they often have a cut in their wages but have the possibility of reaching higher salaries on the long run. With more and more experience, they tend to fly even larger aircraft and
their salaries increase. In all of the models reviewed in literature, the expenses with pilots are considered to increase with the aircraft weight. It is, however, difficult to say if the increased weight of the aircraft is the cause for increased salaries or if the pilots which have more experience, and hence earn more, are the ones that are chosen to fly those larger aircraft, since given the higher number of passengers transported more responsibility is required. Whichever way, there is a correspondence between the weight of the aircraft and the pilots wages.

To design a model for the estimation of cockpit crew expenses, information about the spendings of different US airlines with cockpit crews (total, and not just the salaries) for different aircraft types was gathered from databases existent on the United States Department of Transportation Bureau of Transportation Statistics\(^2\). These databases were built using data provided by the US airlines through the submission of a form (Form 41) with detailed aircraft operating expenses. The data gathered from the previous 5 years was studied to design relationships between the MTOW of the aircraft and the total expenses with cockpit crews (considering all the crew members aboard) by flying hour. The results are presented in the form \(a + b \times MTOW\) and are very similar between the years studied, with only slight differences in the value of \(a\) which may be due to inflation and on the value of \(b\) mainly in international flights, which may reflect differences from one year to another on the currency exchange rates that affect costs such as the ones with hotels and meals. Differences between Major and Regional airlines could not be unequivocally found, nor between low cost carriers and traditional airlines.

Figure 3.1 presents the data distribution separated by regions where the routes were flown. Each data point represents the average of the cockpit crew expenses for a given aircraft among all the airlines. Values between airlines not seldom varied considerably, and the data points are also a bit scattered in the plot. However, it is possible to see that the slopes are very similar amongst the different regions. Domestic and Latin America flights are very similar to one another. Then Pacific and Europe flights are a bit more costly. Finally, the international flights, which cover the ones to any other region different from the ones aforementioned, are the most expensive. This is due to the fact that these increased distances imply the need for more cockpit crew members on the flight.

Equation 3.3 shows the model to estimate the expense with cockpit crews for US airlines. In this equation, MTOW is in metric tonnes and \(c_1\) is a factor to account for the different destination of the flights, where Domestic and Latin America flights have \(c_1 = 1\), European and Pacific flights have \(c_1 = 1.35\) and International flights have a \(c_1 = 2.1\). Since the results are the hourly expenses, the multiplication for the number of flight hours in a year \((FH/Year)\) must be done to provide the yearly costs:

\[
\text{CockpitCrewsUS} = (c_1 \times 585 + 2.2 \times MTOW) \times (FH/Year). \tag{3.3}
\]

Regarding the remaining regions of the world, no data could be found to draw individual models. However, some evidence was found that expenses with pilots tend to be higher in the US and in Europe\(^{[46]}\). The comparison between the US expenses with pilots and that for European airlines could not be assessed. Furthermore, information on how lower are the expenses with pilots from other regions of the world could not be found.

\(^2\)http://www.transtats.bts.gov
Figure 3.1: US airlines cockpit crews expenses for the year 2014 as a function of the MTOW of the aircraft for flights for the different regions of the world.

Equation 3.3 should then be used with a factor that the user feels to be appropriate when taking into account other regions than North America. Instead of the Domestic/Latin America, Europe/Pacific and International destinations, they could be seen as a correspondence to short-haul Domestic/Regional flights, medium to long-haul flights (where no more than 2 cockpit crew members are needed) and very long-haul flights (with 3 cockpit crew members). To unequivocally distinguish these different stage length classifications, the number of flight hours is used: short-haul Domestic/Regional flights are those with less than or equal to 6 hours; between 6 and 8 hours are the medium to long-haul flights; the long-haul flights, where 3 pilots are needed, are the ones with more than 8 hours.

3.1.3 Cabin Crews

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 for different ratios of passengers-by-flight attendant and for different destinations around the world is shown on Figure 3.2.

It can be seen that European and Pacific flights are a bit more expensive than domestic flights and these are more expensive than Latin America Flights. To simplify, it was chosen to estimate domestic and Latin America flights in the same manner and use the same multiplication factor for both European and Pacific flights. A logarithmic fit to the average of the expenses on domestic and Latin American flights was performed to relate the expenses with the passengers by flight attendant ratio. Equation 3.4 shows the model for estimating the cabin crews costs as a function of the value of this ratio and the
total number of crew members. The factor \( c_1 \) is equal to 1 if the flights are domestic or to/from Latin America, and equal to 1.1 if they are to/from Europe or through the Pacific. No data on flights for other regions (the so-called International flights on the previous subsection) could be found, so it is advised to use the value of 1.1 too. The variable \( \#\text{FlightAttendants} \) represents the number of flight attendants on board. To have the yearly costs, the results must be multiplied by the number of flight hours per year, represented by \( FH/Year \).

\[
CabinCrews_{US} = c_1 \times 40.413 \times \exp\left(0.0239 \times \frac{\text{Passenger}}{\text{FlightAttendant}}\right) \times \#\text{FlightAttendants} \times (FH/Year)
\] (3.4)

As with cockpit crews, sufficient data on the expenses with cabin crews on regions other than the North America could not be found to draw individual models for these regions. However, according to an article by The Guardian\[47\], European low cost airlines are hiring flight attendants from America and Asia. Once again, it is not possible to quantify the differences between the US level of expenses and that level in other parts of the world, but this reality should be kept in mind when defining the optimization settings.

### 3.1.4 Landing Fees

Landing fees are charges paid by the airlines to the airports for each landing that an aircraft performs at that airport. 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 this thesis since, for a given airport, it depends solely on the aircraft characteristics - namely its certified maximum take off weight, along with its noise and emissions characteristics in some cases -, while the others, such as the passenger charges, the parking charges or the ground handling charges, depend on the type of service that the airline is offering and the load factors of its operations, i.e. are external to the aircraft itself.

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. Designing a single model for all the airports in the world would yield high errors given the great variability across the different regions of the globe. However, inside most of those regions, the landing fees are less scattered. This is the reason why it was decided to divide the world, a priori, into the following different regions: Europe, North America, Latin America, Africa, Middle East, Asia and Oceania. In the following paragraphs, the landing fees models designed for each of these regions are presented. As a note, all the landing fees calculation formulas were converted from the local currencies to US dollars in order to have the same basis of comparison. The way chosen to make this conversion was through the use of a 2014 average exchange rate. Furthermore, in the US the measure used to assess the landing fees is the Maximum Gross Landing Weight (MGLW), instead of MTOW used in the rest of the world. The US formulas were corrected to the MTOW by dividing them by 67% (the average proportion of the MGLW against MTOW).

**Europe**

In Europe, the landing fees formulas from 38 of its busiest airports (in terms of passenger traffic) in 17 different countries were analysed to cover as much diversity as possible. A great variability was present amongst the different airports. It must be noted that some airports charge the landing fees based solely on the noise rates of the aircraft, and that different rates are applied to different times of the day or even between summer and winter. To have a consistent basis of comparison, the base noise rate, the off-peak hours and the summer-time rates were chosen. The results were plotted against the passenger traffic, but no relationship between the two parameters could be found. Overall, although considerably scattered, the data points seem to form a constant trend. The averages for different values of MTOW were taken and a straight line could be fitted into these points with Equation 3.5. The ratio between the standard deviation and the average of the charge values for different MTOW's was equal to around 30% for MTOW values higher than 20 tonnes, which means that this estimation relationship should be used only for aircraft with weights higher than 20 tonnes.

\[
\text{Landing Fees}_{\text{Europe}}[\text{U.S.}] = 8.34 \times \text{MTOW (tonnes)}
\]  

(3.5)

**North America**

In North America, it could only be found information for 14 of the busiest US airports and for 7 of the busiest Canadian airports. Still, two different trends were identified: one for the airports in the most important/populated cities or pairs of cities (New York/Newark, Chicago, Washington/Baltimore, Dallas/Fort Worth, Los Angeles/San Francisco and Toronto); and one for the second tier cities in the US and Canada. It was not possible to gather information about the landing fees of airports from smaller cities, so these fees are probably not completely suitable for regional airlines.

The aforementioned trends are both linear and were designed using the average of the landing fees for each of the sets of airports for different values of MTOW. Equation 3.6 presents the landing fees estimation relationships for the major and the second tier North American cities. In the cases of US airports, since the fees are charged based on MGLW instead of MTOW, the first should be used instead.
The ratio between the standard deviation and the average of the charges values for the different MTOW values is around 20% for both cases, which is slightly better than what was obtained for Europe.

\[ \text{LandingFees}_{\text{North America}}[\text{U.S.\$}] = \begin{cases} 15.66 \times \text{MTOW}/\text{MGLW}(\text{tonnes}), & \text{if major cities} \\ 7.02 \times \text{MTOW}/\text{MGLW}(\text{tonnes}), & \text{if second tier cities} \end{cases} \] (3.6)

**Middle East**

In the Middle East, information about 6 of the airports with highest passenger traffic was gathered and the results are very similar amongst them. The same procedure was applied to these data, and a linear curve was obtained relating the landing fees values with the MTOW. Equation 3.7 presents this relationship. The standard deviation divided by the average of the charges for each value of MTOW is always smaller than 10%, which represents a good approximation.

\[ \text{LandingFees}_{\text{Middle East}}[\text{U.S.\$}] = 3.96 \times \text{MTOW}(\text{tonnes}) \] (3.7)

**Latin America**

The landing fees database from Latin America comprises 10 of its busiest airports in terms of passenger traffic, 5 of which are from Brazil. The charges values across the different airports are not very different, except for the values of the Mexican airports. Once again, the averages of the landing fees values across all the airports in the database for different values of MTOW were used to form a linear relationship, as shown in Equation 3.8. The standard deviation is around 30% of the average of the values of the charges for every MTOW value higher than 20 tonnes.

\[ \text{LandingFees}_{\text{Latin America}}[\text{U.S.\$}] = 7.26 \times \text{MTOW}(\text{tonnes}) \] (3.8)

**Asia/Oceania**

For the Asian region, information was gathered from the 11 busiest airports. However, in Australia and New Zealand, unlike the rest of the world, the landing fees are calculated as part of the passenger charges, and are thus not directly dependent on the MTOW. Only two airports could be found with landing fees as a function of the aircraft weight: the Brisbane airport and the Auckland airport. For this reason, it was decided to analyse the data of these two regions together.

After analysing the different charges, it was decided to draw two different formulas: one for the airports in developed countries and another one for airports in developing countries. The latter set of airports comprises the airports in China, India, Malaysia, Indonesia and Thailand, while the rest of the airports are the ones in Japan, South Korea, Hong Kong, Singapore, Australia and New Zealand.

Equation 3.9 shows the linear relationships obtained through the same process used in all the other regions. The ratio between the standard deviation and the averages of the charges values for the different MTOW values is around 30% for both cases.
\[
\text{Landing Fees}_{\text{Asia/Oceania}}[\text{U.S.$}] = \begin{cases} 
11.80 \times \text{MTOW}(\text{tonnes}), & \text{if developed country} \\
4.70 \times \text{MTOW}(\text{tonnes}), & \text{if developing country}
\end{cases}
\quad (3.9)
\]

**Africa**

In Africa, the landing fees from 11 of its busiest airports were studied and a linear fit based on the average of the different charges for different values of MTOW provided the results found in Equation 3.10. However, there is a considerable variability on the charges values that cannot be explained neither by geographical reasons nor development reasons. For every MTOW value, the standard deviation is never smaller than 40% of the average of the charges values across the different airports, which is more than what was found in every other region.

\[
\text{Landing Fees}_{\text{Africa}}[\text{U.S.$}] = 5.41 \times \text{MTOW}(\text{tonnes})
\quad (3.10)
\]

Finally, the results obtained with the landing fees cost estimating relationships should be multiplied by the number of landings in a year in each of the regions in order to have the yearly costs.

### 3.1.5 Navigation Fees

According to ICAO, air navigation service charges, or en-route charges, 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.

In this subsection, similarly to what was done in subsection 3.1.4, the world is divided in different regions, roughly the different continents, where the air traffic has similar characteristics or is organized in similar manners. As it should be obvious, differences always exist even within regions if there is not a single entity managing the charging mechanisms in that region, but a too refined division of the world would lead to problems later on the definition of the missions when optimizing the aircraft. One of the most notorious difficulties when dealing with en-route fees is the definition of the air space distances of each region that the aircraft crosses throughout a certain mission. For example, if one aircraft is going from New York to London, it should be determined which part of the route should be calculated with the US formula and which part should be calculated with the European formula. This is even more difficult if a considerable part of the mission is flown over oceanic air space, which usually has lower charges. To simplify the calculation, the oceanic rates were neglected in all the regions, but this introduces an overestimating error in the estimation of the en-route charges.

**Europe**

In Europe, the air traffic management services are a task for the Eurocontrol, an intergovernmental-
Aval organisation with 41 member states. Eurocontrol collects the route charges for the different Flight Information Regions (FIRs) according to the following formula:

\[ RC = \sum_{n} r_{i} \]  

(3.11)

where \( RC \) is the total route charges of a given flight, and \( r_{i} \) are the route charges of each FIR that the aircraft has crossed.

The individual charge \( (r_{ci}) \) can be calculated through:

\[ r_{ci} = d_{i} \times p \times t_{i} \]  

(3.12)

where \( d_{i} \) is the distance factor, equal to one hundredth of the great circle distance, in kilometres, between the entry and exit points of the respective FIR (for each landing or/and take off, 20km should be subtracted to this distance), \( p \) is the weight factor, equal to the square root of the MTOW expressed in metric tonnes divided by fifty (Equation 3.13), and \( t_{i} \) is the unit rate of each FIR.

\[ p = \sqrt{\frac{MTOW}{50}} \]  

(3.13)

Unit rates can vary slightly from one year to another, according to traffic forecasts. During one given year, they are generally constant in the local currency, which means that unit rates can vary from month to month in countries that do not use Euros, the currency in which the route charges are collected by Eurocontrol. However, across the different Eurocontrol member states, due to different traffic characteristics and densities, the unit rates can vary considerably. For instance, the Swiss \( t_{i} \), the highest one, is around ten times higher than that of Santa Maria FIR, the lowest one.

In order to have a unit rate representative of the European air space, so that it could be used by the optimizer without a need for detailed information on which countries the aircraft is going to cross on its missions, a weighted average of the individual unit rates relatively to the utilization of each of the individual air spaces was performed. Ideally, the weighting would be done using the total amount of distances flown in each air space in a given time interval. However, this information could not be found. Two other metrics were found instead on the Eurocontrol website: the number of movements (which include internals, arrivals, departures, and overflights); and the service units, which is \( p_{i} \times d_{i} \). The problem with the first is that it does not take into account the distances flown, and the problem with the second is that it is influenced by the weights of the aircraft. As an example, to show how different can the individual proportions using the two metrics be, both Germany and France have 10% of the movements amongst the Eurocontrol member states, but when it is the chargeable service units that are taken into account Germany represents 9% and France 14%. However, the unit rates weighted averages using the proportions of both metrics provide similar results: 62.4EURO and 57.4EURO for the movements and service units metrics, respectively. Thus, a navigation charge equation representative of the whole European air space would have the form of Equation 3.14.
It is noted that, for a simpler interpretation of the equation and to be in accordance with the equations to be presented for the other regions, now it is used $D$, which represents the distance flown in kilometres, instead of $d_i$, and that the MTOW is no longer divided by 50, but is still measured in metric tonnes. These changes are already incorporated on the coefficient 0.113, which also incorporates the exchange from EUR to USD.

**North America**

In North America, the way Canada (through NAV CANADA) and the US (through FAA) charge the en-route fees is considerably different. While in Canada the fees depend on the distance flown and on the weight of the aircraft, in the US, they only depend on the distance flown. In both countries, however, there are different en-route fees for overflights in domestic airspace and in oceanic airspace. It was chosen to present only the equations relative to the domestic airspace, and separately for each of the countries:

For Canada:

\[
\text{Navigation Charge}_\text{Canada}[\text{US$}] = 0.0307 \times D \times \sqrt{\text{MTOW}}
\] (3.15)

For the US:

\[
\text{Navigation Charge}_\text{US}[\text{US$}] = 0.3070 \times D
\] (3.16)

In these equations, $D$ is the distance flown in the airspace being considered in kilometres and MTOW is in tonnes. In both equations, the values are in US$.

**Middle East**

In the Middle East, most countries levy the navigation charges based only on MTOW intervals. The distance is used only in a few cases, so the estimating formula was devised using only MTOW also. To overcome the different MTOW intervals definitions, a linear curve was fitted to the points obtained with the different individual country formulas in a wide spectrum of MTOW values, and Equation 3.17 was obtained.

\[
\text{Navigation Charge}_\text{Middle East}[\text{US$}] = 0.553 \times \text{MTOW} + 105
\] (3.17)

Here, MTOW is in tonnes and the results are provided in US$. As it can be seen, there is an offset of 105$, which reflects the fact that most of these airports have a minimum fee (or that there is a flat rate up until a certain value of MTOW). In order to have a simpler relationship, this plateau was ignored and the offset usage was chosen instead.

**Latin America**

In Latin America, most countries use a navigation charge formula similar to the one used by Euro-
control, where the charges are proportional to the distance flown and vary with the square root of the
MTOW. Also in Latin America the charges vary quite significantly from one country to another. It was
not possible to find data that could be used to make a weighted average based on the traffic on each of
the countries. For this reason, a simple average was performed, and Equation 3.18 presents the Latin
American navigation charges calculation formula in US$.

\[
Navigation\text{Charge}_{\text{Latin America}}[\text{US$}] = 0.062 \times D \times \sqrt{\text{MTOW}}
\] (3.18)

Here, MTOW is in tonnes and D is the great circle distance flown by the aircraft in the Latin American
airspace measured in kilometres.

Asia/Oceania

In the Asian and Oceanic regions, the methods to calculate the en-route charges vary significantly
from one country to another. However, unlike in the landing fees case, there is no clear tendency that
points to a difference between the charges levied in developed countries and in developing countries.

To overcome the difficulty in having a uniform method to calculate these charges in Asia and Oceania,
it was decided to have a formula that, as in ICAO recommendations, would vary proportionally with
distance and less than proportionally with weight. The countries that most contribute to the air traffic
in Asia/Oceania were selected (China, Australia, Japan, India, South Korea, Malaysia, Hong Kong and
Singapore) and the relative weight of each of them on this set was calculated. Lacking data on the total
amount of air distance travelled in each country, this calculation was based on the number of aircraft
movements on their respective airports. This is an approximation which introduces two main errors:
first, not all the airports for every country were taken into account, just the most significant ones; and
second, this way the overflights, where an aircraft does not land on an airport of the country, but which
use the air navigation services, are not taken into account. However, since this happens for every
country in the set, the approximation was assumed to be good enough for the needed purposes. Next,
Equation 3.19, derived from the fitting of the data processed as explained above, is presented:

\[
Navigation\text{Charge}_{\text{Asia/Oceania}}[\text{US$}] = 26 + 0.11 \times D \times \text{MTOW}^{0.27}
\] (3.19)

Here, D is once again the great circle distance travelled in kilometres and MTOW is in metric tonnes.
The exponent of MTOW is not as high as in the previous regions, but it was the one that fitted the best
the data available in order to provide a model representative of the entire Asian/Oceanic region.

Africa

In Africa, the majority of the countries studied applied a formula to calculate the en-route charges
equal or very similar to that of Eurocontrol. Besides that, some countries in West Africa are part of
ASECNA, an organization with a similar role as the Eurocontrol. The countries studied were the ones
with airports amongst the busiest in terms of passenger traffic in Africa, and are listed next: South Africa,
Egypt, Morocco, Ethiopia, Kenya, Algeria and Nigeria. The rates of each country for the combination of
Table 3.2: Summary of the en-route charges in the different regions in the form $\text{NavigationCharge} = c_1 + c_2 \cdot D^{c_3} \cdot MTOW^{c_4}$

<table>
<thead>
<tr>
<th>Region</th>
<th>$c_1$</th>
<th>$c_2$</th>
<th>$c_3$</th>
<th>$c_4$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Europe</td>
<td>0</td>
<td>0.113</td>
<td>1</td>
<td>0.5</td>
</tr>
<tr>
<td>Canada</td>
<td>0</td>
<td>0.0307</td>
<td>1</td>
<td>0.5</td>
</tr>
<tr>
<td>US</td>
<td>0</td>
<td>0.307</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Middle East</td>
<td>105</td>
<td>0.553</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Latin America</td>
<td>0</td>
<td>0.062</td>
<td>1</td>
<td>0.5</td>
</tr>
<tr>
<td>Asia/Oceania</td>
<td>26</td>
<td>0.11</td>
<td>1</td>
<td>0.27</td>
</tr>
<tr>
<td>Africa</td>
<td>35</td>
<td>0.036</td>
<td>1</td>
<td>0.5</td>
</tr>
</tbody>
</table>

a wide spectrum of MTOW values and distance flown values were compared to each other and, due to the lack of information on either the distances flown yearly in each country or the aircraft movements in their airports, a simple average of the values was performed to arrive at Equation 3.20.

$$\text{NavigationCharge}_{\text{Africa}}[\text{US$}] = 35 + 0.036 \cdot D \cdot \sqrt{MTOW}$$  \hspace{1cm} (3.20)

In Table 3.2 is presented a summary of the Equations 3.14 to 3.20, where the coefficient values of $\text{NavigationCharge} = c_1 + c_2 \cdot D^{c_3} \cdot MTOW^{c_4}$ are listed for the different regions.

These results should be multiplied by the number of flight cycles in a year to obtain the yearly costs with navigation charges. If different missions are performed, they should be multiplied each by the respective number of trips made and then summed up.

3.1.6 Noise Charges

From all the regions analysed, it was only in Europe that most airports had noise charges or surcharges. It will thus be assumed in this thesis that only in European airports these charges are levied.

These noise charges are generally calculated through the classification of the aircraft into noise categories, and it is here, in the categories definition, that the most important difference lies: some airports categorize the noise levels produced by an aircraft according to the standards of ICAO Annex 16, Volume 1, Chapters 2, 3 and 4, while others set categories limits depending on the average noise levels at take off and landing measured in dB (A). Some other airports, in rarest cases, have more complex formulas to calculate the noise level which is subject to charges. Regarding the amount of the surcharge within each category of whichever definition, there are also two ways how this can be done: either the airport landing charges are multiplied by a factor, which can increase or reduce its base value, or an independent charge can be applied.

Apart from this, some airports also have different charges for the take off and for the landing phases, and for different times of the day. In order to have a formula that can be easily applied during the optimization, and to disregard the particularities of the way the different airlines operate, the charges have been assumed to be equal for both take off and landing and to be those of the day time off peak
Since among the cases studied the most consistent approach to applying the noise charges was the one where coefficients are used to increase or decrease the landing charges, this will be the one used to derive the noise charges model. Furthermore, to achieve a straightforward categorization, the ICAO Annex 16, Volume 1 standards will be used to define the categories. This document defines the maximum permitted noise levels for aircraft depending on when their Type Certificate (which grants its airworthiness) was submitted and on their maximum certificated take off mass. There are three different noise limits: at the lateral full-power reference noise measurement point; at the flyover reference noise measurement point; and at the approach reference noise measurement point. For the definitions of each of these points and for the definition of the limits for each aircraft it is recommended the consultation of the ICAO Annex 16, Volume 1 standards.

Aircraft compliant only with Chapter 2 are not allowed to land on most European airports. These are subsonic jet aircraft which submitted the application for their Type Certificate before the year 1977. When they are allowed to land, or when it is an emergency case, the noise surcharges are typically very high. Chapter 3 aircraft are those which submitted the application for the Type certificates from 1977 to 2006. Chapter 4 aircraft are the ones with the application for the Type Certificate submitted from 2006 on. The maximum permitted noise levels at each measurement point for these aircraft are equal to those defined in Chapter 3, but the overall noise limits are more restrictive, since the cumulative differences at all three measurement points between the maximum permitted and the maximum measured must not be less than 10 EPNdB (Effective Perceived Noise in decibels) and the cumulative differences at any two measurement points shall not be less than 2 EPNdB. The aircraft designed in the project of which this thesis is part must then be compliant with the Chapter 4 requirements. Nonetheless, the model will be designed taking into consideration all the categories defined in most airports.

Some airports categorize the noise levels into the following categories, from the most noisy to the less noisy: non compliant with Chapter 3; Chapter 3 high; Chapter 3 base; Chapter 3 low; and Chapter 4. The difference between Chapter 3 high, base and low is the difference between the sums of the maximum permitted noise levels and the certificated maximum noise levels of the aircraft (cumulated noise margin). Margins equal to zero or, in general, less than 4 or 5 EPNdB mean the aircraft is Chapter 3 high. Differences between, typically, 4-5 EPNdB and 9-10 EPNdB fall into the Chapter 3 base category. Higher margins, if not compliant with Chapter 4, fall within the Chapter 3 low category.

Similarly, but not adopting this nomenclature, and not necessarily with the intervals shown above, as they represent a typical case, a considerable number of other airports apply this method to subdivide the different aircraft into more categories according to their noise levels. An average of the coefficient values for the different margins was made and served as the basis for the construction of the model presented in Table 3.3.

The Chapter 3 noise level limits are defined in Appendix A.1. As it has been previously mentioned, Chapter 4 aircraft must have a cumulative margin equal or higher than 10 EPNdB, which means that theoretically these aircraft will never have noise surcharges. However, the cumulative margin is not a sufficient condition to define an aircraft as Chapter 4 compliant. Some airports impose a minimum
margin on each measurement point, but this is not done here because at the design stage these noise levels cannot be calculated with much certainty.

The noise charges cannot be considered individually when optimizing the aircraft, since what they do is changing the amount of the landing charges relatively to the base level, through the multiplication of the landing charges obtained with Equations 3.5 to 3.9 by the appropriate noise coefficient from Table 3.3.

Finally, these charges are relative to one single trip, and should thus be multiplied by the number of landings to provide the yearly costs with noise charges.

### 3.1.7 Emissions Charges

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. The explanation for this is the ICAO Document 9082, which states that "emission-related charges should be levied only at airports with a defined LAQ [local air quality] problem, either existing or projected, and should be designed to recover no more than the costs of measures applied to the mitigation or prevention of the damage caused by aircraft". This means that only airports with a large amount of traffic or located within considerably populated areas are eligible to apply this charge. This does not mean, however, that every airport which meets these criteria is obliged to apply the emission-related charges. The airports found to levy emission related charges are: Luton, Gatwick and Heathrow in the UK; Cologne, Düsseldorf, Hamburg and Munich in Germany; Copenhagen in Denmark; and Geneva, Berne, Lugano and Zurich in Switzerland. This very restricted geographical distribution of the emission-related charges should be taken into account. No information was found regarding the future application of these charges on more European airports.

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, the overall availability of allowances, amongst others. For all these reasons, it is very difficult to allocate a cost to an emission value, and thus this scheme is not going to be considered in this thesis.

Regarding once again the charges levied by the airports, it should be noted that, contrary to what

<table>
<thead>
<tr>
<th>Category</th>
<th>Cumulative Margin relatively to Chapter 3 limits [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</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>
happens with the noise charges, the emission charges 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 on the emission value, which is, in the majority of the airports, calculated using a formula based on the European Civil Aviation Conference (ECAC) recommendation 27-4, developed from the work done by the Emission Related Landing Charges Investigation Group (ERLIG), as presented in Equation 3.21:

\[
\text{EmissionValue}_{\text{Aircraft}} = \#\text{Engines} \times \sum_{\text{LTO-modes}} \left( 60 \times \text{time} \times \text{fuelflow} \times \frac{\text{NOxemissionfactor}}{1000} \right) \times a
\]  

(3.21)

where \#\text{Engines} is the number of engines fitted to the aircraft, \text{LTO-modes} are the landing and take off modes (take off, climbout, approach, and taxi/idle), \text{time} is the time in minutes spend on each mode, \text{fuelflow} is the fuel consumption per mode in kg/sec, \text{NOxemissionfactor} is the measured NOx-Emission factor per mode in g of NOx per kg of fuel, and \(a\) is a factor to take into account the LTO Hydrocarbon emissions and is calculated in the following manner:

\[
\begin{align*}
\text{a} &= 1, \quad \text{if the average Hydrocarbon } D_p/F_{oo} \text{ is less or equal than the current ICAO standard of } 19.6 \text{ g/kN rated output or for unregulated engines.} \\
\text{a} &> 1, \quad \text{if the average Hydrocarbon } D_p/F_{oo} \text{ is larger than the current ICAO standard.} \\
\text{a} &= \text{average measured Hydrocarbon } D_p/F_{oo}/19.6, \text{ with a maximum value for 'a' of } 4.0
\end{align*}
\]  

(3.22)

Here, \(D_p/F_{oo}\) is the mass in grams (\(D_p\)) of the pollutant emitted during the reference LTO cycle, divided by the rated output (\(F_{oo}\)) of the engine. Table 3.4 presents representative values for time and thrust settings for each of the LTO modes as established by the ICAO LTO-cycle standards. These values are solely guidelines, since the actual values depend on various flight conditions, such as the aircraft weight, atmospheric conditions, airport conditions and airline procedures.

<table>
<thead>
<tr>
<th>Mode</th>
<th>Time in minutes</th>
<th>Thrust setting in kN</th>
</tr>
</thead>
<tbody>
<tr>
<td>Take Off</td>
<td>0.7</td>
<td>100%</td>
</tr>
<tr>
<td>Climbout</td>
<td>2.2</td>
<td>85%</td>
</tr>
<tr>
<td>Approach</td>
<td>4.0</td>
<td>30%</td>
</tr>
<tr>
<td>Taxi/Idle</td>
<td>26.0</td>
<td>7%</td>
</tr>
</tbody>
</table>

The final emission charge is calculated multiplying the value obtained with Equation 3.21 by the charge factor. Among the airport studied, it was possible to see a clear difference between the charge factor applied in the London airports comparatively to the remaining airports. Table 3.5 shows the averages obtained for these two sets in US$.

Contrary to the noise charges, the emission-related charges are independent of the landing fees.
Table 3.5: Average emission charge factors obtained for the London airports (Gatwick, Luton and Heathrow) and the remaining European airports that levy emission charges (in US$).

<table>
<thead>
<tr>
<th>Airports</th>
<th>Charge factor (US$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>London</td>
<td>10.30</td>
</tr>
<tr>
<td>Germany/Switz./Denmark</td>
<td>3.30</td>
</tr>
<tr>
<td>Other</td>
<td>0</td>
</tr>
</tbody>
</table>

If the information on the emission characteristics of the engines being optimized is not available, there is a database collected by ICAO[48] with information on aircraft engines that have entered production regarding all the relevant emission data needed to calculate the values of Equation 3.21, and a sufficiently similar engine can be chosen to produce the necessary data.

As a final note, the emission charges equations given earlier are relative to one single trip. The number of flight cycles should be taken into account to yield the yearly costs with emissions charges.

3.2 Maintenance Costs

The maintenance process is complex, not always predictable and not homogeneous over time. The costs involved in this component are, in a simplified way, the labour, material and burden costs for both the airframe and the engines maintenances. Furthermore, the maintenance may be done in house or may be outsourced, to another airline company, to a maintenance company, or to the manufacturer of the airframe or engines. Due to all of this, it is very hard to gather consistent data on costs of maintenance. Doing this would require a rather long work schedule and information sources from inside the airlines.

Lacking data with sufficient quality to produce a model, it was decided to use existing models instead. The models from Roskam [17], Liebeck [31], Jenkinson [34] and CeRAS [37] were compared. The first three provide results in dollars, since they were derived from US airlines and data. The last one provides the results in Euro, and was derived mainly from European airlines data. Despite the geographical data source of the models, one other aspect comes out as more relevant: the time when they were constructed. The first three methods are very close to each other chronologically, from 1990 to 1994 (the maintenance formulas presented in Jenkinson are relative to this year). They were updated from the then-year dollars to 2014 dollars using the Cost Employment Index of aircraft manufacturing industry workers for the components associated with labour and the Producer Price Index of the aircraft manufacturing industry for the components associated with materials and parts. These indexes are available at the US Bureau of Labor Statistics website. When the index had not data as old as required, a linear extrapolation of the data points was performed. The CeRAS model is from 2010, which is much more recent. The results are transformed from 2010 Euro to 2010 US$ using the average exchange rate of that year and then from 2010 to 2014 dollars using the same indexes aforementioned. Ideally, European indexes such as the US ones should be used, but sufficiently accurate and consistent information could not be found.

Regarding the results provided by each of the models, the comparison was made using an aircraft with 58 tonnes of airframe weight (operating empty weight less the engines dry weight), an operating
empty weight of 72 tonnes, a sea-level static thrust of 210kN, with two engines, and a mission of 7 hours. The airframe costs vary in their definition between models, but the overall results are not very different: 5200$ for Liebeck, 3900$ for CeRAS, and 5900$ for Jenkinson. The maximum difference is between these last two, with Jenkinson’s model results being 51% higher than those of the CeRAS model. However, the case for the engines costs is much different. Liebeck’s model provides a value of 3000$ for engines maintenance costs for this mission and aircraft, CeRAS model gives 700$, more than three times lower, and Jenkinson’s model gives 1500$.

The CeRAS model provides consistently lower results. In the case of the airframe maintenance costs, and comparing with the Liebeck’s model, since they both detail between costs with labour and materials, the CeRAS model provides half of the labour costs but twice the materials costs. Since the burden costs are for both methods two times the labour costs, the reduction is more significant for the CeRAS model. These difference, allied with the fact that the CeRAS model is significantly more recent, is aligned with the progressively lower frequency of heavy maintenance checks on the aircraft, and with the use of more expensive materials, such as the composites. For this reason, it seems more logic to use this model updated from the 2010 Euro to 2014 dollars, in order to be consistent with the currency used in the rest of the models. It is believed that, as in the case of the aircraft manufacturers Airbus and Boeing, which, although having different geographical locations, have similar aircraft prices, the maintenance costs do not vary considerably from one region to another, and this is particularly true given the fact that more than half of the maintenance today is outsourced to global companies specialized in this sector.

The models for calculating the yearly maintenance costs (based on CeRAS model) are presented in Equations 3.23, 3.24 and 3.25. It is noted that, unlike the airframe, the engines costs are not divided into labour and materials. To update the costs into 2014 dollars, a weighted average was used with the ratio for labour (including burden costs) being 3 fifths of the total and the ratio for the materials 2 fifths, in a proportion similar to that verified with the airframe.

\[
\text{AirframeMaint}_{\text{Labour}}[\text{US}]= 72.4*(1+B)*[(0.655+0.01*\text{OWE})*\text{FT}+0.254+0.01*\text{OWE}]*\text{FC} \quad (3.23)
\]

\[
\text{AirframeMaint}_{\text{Materials}}[\text{US}]= 1.43*[\text{OWE}*(0.21*\text{FT}+13.7)+57.5]*\text{FC} \quad (3.24)
\]

\[
\text{EnginesMaint}[\text{US}]= 1.45*\text{N}_{\text{eng}}*(1.5*\text{SLST}+30.5*\text{FT}+10.6)*\text{FC} \quad (3.25)
\]

In these equations, \( B \) is the burden rate, which is equal to 2 (the same value used in most of the models aforementioned), \( \text{OWE} \) is the operating empty weight of the aircraft in tonnes, \( \text{FT} \) is the flight time of the mission in hours, \( \text{FC} \) is the number of flight cycles in one year, \( \text{N}_{\text{eng}} \) is the number of engines on the aircraft, and \( \text{SLST} \) is the sea-level static thrust in tonnes.
3.3 Ownership Costs

3.3.1 Depreciation

Depreciation costs vary from one airline to another, depending on their depreciation policies and on their expectations for the future. The two relevant parameters that differ between airlines are the useful life of the aircraft and its residual value. Estimation of these parameters is critical for the calculation of the depreciation rates and thus the depreciation cost of an aircraft.

Typical values for the useful aircraft life vary between 15 to 30 years. These values will depend greatly on the overall aircraft market growth, on the emerging technologies and their potential for cost reduction that will accelerate or not the substitution of existing aircraft, and on the maintenance and airworthiness conditions of the aircraft throughout its life span. It could be tempting to say that the new generation aircraft of today are able to have a longer useful life due to their enhanced systems and materials, but it is very hard to predict how will the future generations be relatively to the present ones. Throughout the years, the useful life of the aircraft is often reconsidered by airlines in the light of all the factors that can influence it. However, for the optimization process, the useful life span must be defined a priori. Most authors consider a depreciation period of around 15 years. A report by the consulting firm KPMG on the costs of ownership of aircraft[49] offers a table with information on the useful life and residual values of different aircraft and engines from several airlines. The most common values are in the interval 15 to 20 years. In this thesis it will be considered the 20 year mark.

Residual value is the amount that an airline expects to receive for the aircraft after the assumed useful life, not accounting for inflation. For most airlines, the aircraft are not used until the very end of their economic life (either by operational needs, changes in market conditions or technological developments), so a second-hand market for aircraft exists. The residual value depends greatly on the conditions of the specified aircraft and the second-hand market. As in any other market, if there is a great number of second-hand aircraft available, which typically happens when there is a worldwide renewal of the fleets, the residual value will be lower. Maintenance conditions (and chiefly the need for heavy checks) will also considerably affect the aircraft residual value. Since there are lots of factors external to the airline company that play a role in the determination of the aircraft residual value, this is very hard to predict with 15 to 20 years in advance. In the same report by KPMG, the residual values mostly used are in the range 0-10% for passenger aircraft. Most literature methods also point in this direction. In this thesis it will be used thus the 10% value.

Different depreciation methods exist, and some are more commonly used in some industries than others. In the airline industry, it is usually utilized the straight line depreciation method. In this method, the aircraft is assumed to be utilized evenly throughout the years, so the same amount of depreciation cost is supported every year. Equation 3.26 shows the yearly depreciation cost using this method and the values for useful life and residual value defined in the previous paragraphs. The $ALP$ represents the Aircraft List Price as obtained with the models in Chapter 2. If a discount on the list prices is considered, then the $ALP$ less the discount should be used in Equation 3.26. When calculating depreciation, the
airframe and engines spares must also be accounted for. In the literature, the AirframeSpares are
worth typically 10% of the airframe price and the EngineSpares are around 15% of the engines price.
These values are merely indicative and should increase or decrease with the smaller or bigger size of
the fleet of that aircraft, respectively.

\[
Depreciation[\text{US}$] = \frac{(ALP + AirframeSpares + EngineSpares) \times (1 - 0.10)}{20}
\]  

(3.26)

3.3.2 Insurance

Insurance covers the risk of losses, either material or life losses, for the company or for third parties.
There are several types of insurance coverage, but the one that is dependent on the aircraft being
designed is the hull loss insurance, which covers total or partial losses on the aircraft, either on the
ground, on the take off and landing phases, or in flight. This type of insurance is, for simplicity, considered
as being dependent only on the aircraft price. Furthermore, there are different types of occurrences that
imply different types of insurance. For instance, war or terrorism insurance is directed solely to losses
due to acts of war aggression or terrorist acts.

Insurance policies are quite complex, and the premiums are variable over time, depending on the
recent historical of claims and their types, on the risk of exposure by region, on the fleet ages and
technology, amongst others.

Although for the design optimization the ideal consideration of the insurance premiums is based on
an individual aircraft, the reality is that insurance is bought by airlines to their entire fleet. In a simplified
manner, the literature reviewed presents the insurance costs as a small percentage of the aircraft price,
typically between 0.5% and 3%. The lower limit is associated with times when the trend for accidents with
considerable losses is going down and when the fleets are being renewed and are growing considerably.
On the other side, the upper limit reflects times of increased accident losses, or losses due to terrorist or
war acts, and when the worldwide fleet is perceived to be ageing considerably. The worldwide premiums
differ from region to region, but their differences are not as significant in the spectrum of premium rates
presented to consider the regions separately.

As premiums are reviewed and insurance coverages are renewed year after year, it seems more
appropriate to consider a value in between the limits presented to make a long term operational opti-
mization. The yearly costs associated with insurance are presented in Equation 3.27.

\[
Insurance[\text{US}$] = 0.015 \times ALP
\]  

(3.27)

In this equation, the insurance premium is 1.5% and ALP is the Aircraft List Price obtained with the
models in Chapter 2. If a discount on the list prices is considered, then the ALP less the discount value
should be used in Equation 3.27.
3.3.3 Interests

To operate an aircraft, the airlines must either own that same aircraft or have a leasing or rental contract with another company. If the aircraft is owned, its purchase is most probably financed by a financial loan, which has interest costs associated with it. In the case of a lease or rental, there are periodic payments to be delivered to the leasing/renting company. In these types of contracts, the airline operating the aircraft does not have depreciation costs associated but the contracts are more expensive. In contrast, the airline does not support the risk of loss of value of the aircraft after an unexpected shorter economic life.

In this thesis, it was opted to assume that the airline owns entirely the aircraft, given that more information is available in this type of operation. To simplify matters, most methods found in the literature reviewed assume that a loan is contracted on the entire price of the aircraft plus spares. It is on this amount that the interest costs should be calculated. Furthermore, the way of calculating the interest costs may vary from method to method. Also to simplify the calculations, it is assumed that an equal amount of interest is paid every year, regardless of the down payments already performed. To calculate this, the total amount of interest must be calculated first. Assuming an equal principal payment plan, the total interest is given by:

\[
\text{TotalInterest} = LA \times IR \times \left( LP - \frac{\sum_{i=0}^{L-1} i}{LP} \right), \tag{3.28}
\]

where \( LA \) is the loan amount, \( IR \) is the interest rate and \( LP \) is the loan period.

The typical rates found in literature point to an annual interest rate of around 5%. Regarding the loan period, most methods point to a value close to that of the depreciation period, so 15 years will be used in the interest costs model. Dividing Equation 3.28 by the loan period gives the yearly costs with interests divided evenly throughout the loan payment schedule, and Equation 3.29 these results with the respective substitutions.

\[
\text{Interest[US$]} = \frac{(ALP + AirframeSpares + EngineSpares) \times 0.05 \times \left( 15 - \frac{\sum_{i=0}^{14} i}{15} \right)}{15} \tag{3.29}
\]

As a final note, all the rates and periods considered in the ownership costs components merely reflect the suggestions found in literature. They can and should be adjusted by the user if he has enough information that points to a given value of rate or period of time that is relevant for the optimization being performed, either because the industry conditions have changed or because he is in possession of some valuable piece of information regarding one airline which will use the aircraft being optimized.
4 Test Cases

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, which are presented in Table 4.1.

Table 4.1: Main characteristics of the aircraft optimized in the context of the NOVEMOR project which will be used to test the cost estimating models.

<table>
<thead>
<tr>
<th>Weights [t]</th>
<th>Format</th>
<th>Cabin</th>
<th>Performance</th>
</tr>
</thead>
<tbody>
<tr>
<td>MTOW</td>
<td></td>
<td></td>
<td>Range [km]</td>
</tr>
<tr>
<td>MGLW</td>
<td></td>
<td></td>
<td>Ch. 3 Cum. Margin [dB]</td>
</tr>
<tr>
<td>OWE</td>
<td></td>
<td></td>
<td>Number of Engines</td>
</tr>
<tr>
<td>Payload</td>
<td></td>
<td></td>
<td>Max. Take Off Thrust [kN]</td>
</tr>
</tbody>
</table>

|        |         |         | 4387         |
|        | 113     | 113     | 10           |
|        | 2       |         | 93.45        |

Apart from these characteristics, in order to assess the Emission Value of the aircraft (see Equation 3.21), the CF34-10E engine, used in the Embraer 190 and 195 jets, was chosen, although the rated output is a bit lower (by 4kN) than the one necessary by the aircraft being tested.

Regarding the ownership costs options, the typical values mentioned earlier were chosen: a discount on the price of the airframe and engines of 0% was considered; the airframe and engines spares amount to 10% and 15% of their respective prices; the depreciation residual value and period are 10% and 20 years, respectively; an insurance premium of 1.5% was chosen; an annual interest rate of 5% and an interest period of 15 years were considered.

Regarding the mission characteristics, it was chosen to use a Payload percentage of 85%, so that the data on fuel consumption for different ranges could be compared with the ones provided by the optimization, a passenger-to-flight attendant ratio of 50, and a fuel price in US dollars per gallon equal to the one of 18 September 2015, i.e. 1.43 $/gal. For all the missions considered, it was assumed that the aircraft was used homogeneously during 320 days of the year, while in the other days it was completely stopped, to take into consideration not only downtimes due to scheduled maintenances, but also unscheduled maintenances and to account also days with less frequent operations.

4.1 Test Case 1 - Comparison of the CASK for 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 3914km 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:

- London City Airport-Madrid, by British Airways CityFlyer: 1264km and 10h/day (EU0-EU10.3)
- Toronto-Edmonton, by Air Canada: 2710km and 12h/day (CA1-CA2)
- Buenos Aires-São Paulo, by Austral Líneas Aéreas: 1676km and 11h/day (LAm-Medium)
- Porto Alegre-São Paulo, by Azul: 852km and 11h/day (LAm-Short)
- Boston-Charlotte, by JetBlue: 1160km and 10h/day (US2-US2)
- Amsterdam-Geneva, by KLM CityHopper: 690km and 11h/day (EU0-EU3.3 Short)
- Sydney-Melbourne, by Virgin Australia: 713km and 8h/day (Asia-Dvpd Short)

Of these routes, two were chosen to be shown in Table 4.2, along with the other two previously mentioned, in order to make a comparison of the CASK between regions and between different mission lengths.

Table 4.2: CASK in US$ cents for 4 different missions: 2 at maximum range and 2 representative of real missions.

<table>
<thead>
<tr>
<th>CASK (US$ cents)</th>
<th>US1-US2 Long</th>
<th>EU0-EU0 Long</th>
<th>EU0-EU3.3 Short</th>
<th>Asia-Dvpd Short</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flight Costs</td>
<td>2.61</td>
<td>3.07</td>
<td>4.74</td>
<td>4.51</td>
</tr>
<tr>
<td>Fuel</td>
<td>0.92</td>
<td>0.92</td>
<td>1.66</td>
<td>1.63</td>
</tr>
<tr>
<td>Cockpit Crews</td>
<td>0.82</td>
<td>0.82</td>
<td>1.08</td>
<td>1.07</td>
</tr>
<tr>
<td>Cabin Crews</td>
<td>0.46</td>
<td>0.46</td>
<td>0.61</td>
<td>0.60</td>
</tr>
<tr>
<td>Landing Fees</td>
<td>0.14</td>
<td>0.11</td>
<td>0.62</td>
<td>0.85</td>
</tr>
<tr>
<td>Navigation Fees</td>
<td>0.27</td>
<td>0.76</td>
<td>0.76</td>
<td>0.36</td>
</tr>
<tr>
<td>Noise Charges</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Emission Fees</td>
<td>-</td>
<td>-</td>
<td>0.01</td>
<td>-</td>
</tr>
<tr>
<td>Maintenance Costs</td>
<td>0.66</td>
<td>0.66</td>
<td>2.17</td>
<td>2.11</td>
</tr>
<tr>
<td>Airframe</td>
<td>0.46</td>
<td>0.46</td>
<td>1.47</td>
<td>1.43</td>
</tr>
<tr>
<td>Engines</td>
<td>0.20</td>
<td>0.20</td>
<td>0.70</td>
<td>0.68</td>
</tr>
<tr>
<td>Ownership Costs</td>
<td>1.90</td>
<td>1.91</td>
<td>3.10</td>
<td>4.67</td>
</tr>
<tr>
<td>Depreciation</td>
<td>1.00</td>
<td>1.01</td>
<td>1.64</td>
<td>2.47</td>
</tr>
<tr>
<td>Insurance</td>
<td>0.30</td>
<td>0.30</td>
<td>0.49</td>
<td>0.74</td>
</tr>
<tr>
<td>Interest</td>
<td>0.60</td>
<td>0.60</td>
<td>0.97</td>
<td>1.46</td>
</tr>
<tr>
<td>Total</td>
<td>5.17</td>
<td>5.64</td>
<td>10.01</td>
<td>11.29</td>
</tr>
</tbody>
</table>

Comparing the first two columns of Table 4.2, one sees that the CASK values are very similar except for the Landing and Navigation fees. The first is slightly higher in the case of the US mission, due to the usage of an airport in one of the major cities. The navigation fees, on their turn, are considerably higher in Europe, being responsible alone for the 17% higher flight costs and 9% overall total operating costs.
Comparing now the European long and short routes, where the second also includes an airport which levies emission fees (Geneva airport), it is possible to see that all components have higher CASK, except the Navigation fees because they depend linearly on the distance flown. The greater increase is seen in the maintenance costs, which depend strongly on the flight cycles, and this increase in flight cycles is reflected on the results. Overall, the CASK is almost double the amount of the route with a distance almost equal to the range capabilities of the aircraft, which is a quite significant difference. This tendency should already be expected, since aircraft are cost optimum for missions as close to their range capability as possible. As a final note on these routes, it is seen that the emission fees are very low when compared with the remaining costs. This is due not only to the fact that the data used for the calculation of the emission value was based on an engine with less than 15 years, with relatively low emissions, but also to the nature of these charges, which are levied on some airports only to make up for damages to the neighbour communities. A clear and unambiguous consideration of the EU-ETS scheme should place more preponderance on the emission fees, but for now those criteria could not be met.

Lastly, comparison between two missions with similar ranges (one in Europe and one in Australia) shows how the utilization in hours of the aircraft influences very strongly the Ownership Costs. Although being slightly longer in distance, with the Flight and Maintenance costs a bit lower than those in EU0-EU3.3 Short mission, the Asia-Dvpd Short mission has about only two thirds of the annual utilization, which means that the costs with interests, insurance and depreciation, which are fixed annually, are divided by less ASK, increasing the CASK for the latter mission.

As a final note on Table 4.2, it can be seen that in none of the European missions there are no noise charges levied (nor on the rest of the world, but these fees do not apply here). This is due to the fact that it was considered that a sufficiently recent engine was used to have a cumulative margin of more than 10 dB relatively to the Chapter 3 limits, i.e. it is Chapter 4 compliant. However, if this is not the case, then the noise charges will be proportional to the landing fees.

From the 7 representative missions plus the 2 fictitious longer US and European missions, the weight of each of the costs groups in the total costs was analysed. The flight costs ranged from 40% of the total costs per ASK on shorter routes to 54% on longer routes. The most relevant components of this group are the fuel costs and the cockpit crew costs, which amount to 15-20% and 9-15% respectively of the total costs. The maintenance costs are generally between 12% on longer routes and 22% on shorter routes. The Ownership costs amount to 30-41% of the total costs, with depreciation being more than half of this amount, and being very similar to the costs with fuel at the price it was tested. The cost proportions for the EU0-EU3.3 Short mission are graphically represented in Figure 4.1.

From these results, it can be seen that the price of fuel is, as expected, very important on the final CASK. In 2015, the price of jet fuel has declined to less than half of the average of the previous 3 years. With a price double the amount used as the base scenario, the fuel costs would go from a weight of 15-20% on the total costs to a weight of 29-36%, and the total CASK would increase, in the 9 missions studied, between 14% and 19%.
4.2 Test Case 2 - Comparison of the CASK between the base aircraft and its shrunk and stretched versions

Next, it was desirable to have different aircraft designs to which it could be possible to apply the cost models developed to determine the differences of CASK calculated for each one of them. However, there was information only for the design already tested above. This way, it was decided to come up with a stretched and a shrunk versions of this aircraft, while maintaining the main characteristics of the rest of the aircraft, mainly the wing and tail. From the aircraft available in the market, the families which had base, shrunk and/or stretched versions were compared in terms of MTOW, maximum take off thrust, price and range as a function of the seating capacity (maximum density for narrow bodies and typical configuration for wide bodies). The number of seats was chosen as the independent variable because this is the most econometric variable and because the stretches and shrinks of actual aircraft are made primarily with the purpose of increasing or decreasing their seating capacity. The following relationships were derived:

\[
\frac{\text{Price}}{\text{Price}_{\text{base}}} = 0.7427 \times \frac{\text{Seats}}{\text{Seats}_{\text{base}}} + 0.2604 \quad (4.1)
\]

\[
\frac{\text{MTOW}}{\text{MTOW}_{\text{base}}} = 0.4950 \times \frac{\text{Seats}}{\text{Seats}_{\text{base}}} + 0.5099 \quad (4.2)
\]

\[
\frac{\text{SLST}}{\text{SLST}_{\text{base}}} = 0.3986 \times \frac{\text{Seats}}{\text{Seats}_{\text{base}}} + 0.5963 \quad (4.3)
\]

\[
\frac{\text{Range}}{\text{Range}_{\text{base}}} = 1.0074 - 0.352 \times \ln \left( \frac{\text{Seats}}{\text{Seats}_{\text{base}}} \right) \quad (4.4)
\]
From the data points used, all the results provided by Equations 4.1 and 4.2 have errors smaller than 10% and the points are all very close to the line. The SLST and range points are more scattered, but the results have an error always smaller than 15% (see Appendix A.2). It is obvious that none of these variables depends solely on the number of seats when such a modification is done in the base aircraft. However, although it was tried to devise relationships based on more parameters, or even dependent on the other variables, results as good as the obtained with Equations 4.1 to 4.4 could not be obtained.

These equations have also their limitations on designing the main parameters of the new versions of the aircraft. First, they only give estimations of the MTOW. The MGLW, Operating Weight Empty (OWE) and Payload had to be estimated based on the proportions that they had to the MTOW on the original aircraft. Secondly, they provide a new necessary SLST, but the emissions parameters have to be found from the ICAO engines database from an engine with a similar SLST. Finally, and more importantly, strong structural modifications would be needed for aircraft above a certain level off stretch or below a certain level of shrinkage, and the limits cannot be defined with certainty. From the aircraft in the database analysed, it was seen that the A319neo has 15.3% less seats than the A320neo, while sharing most of the same aerodynamic and structural characteristics, and that, in the same situation, the A321ceo has 31% more seats than the original A320ceo. It was chosen to apply the aforementioned relationships to a stretched version with more 20 seats for a total of 133 (18% more seats) and to a shrunk version with less 20 seats for a total of 93 (18% less seats), which is more or less inside the limits of the A320 and A320neo families. The shrunk version is slightly outside the limits found but no structural problems may arise; the only disadvantage is that the aircraft is too over dimensioned, and the costs will be considerably higher than what could be achieved with a redesign of the aerodynamic structures.

The main characteristics of these two versions compared to the base design are shown in Table 4.3.

Table 4.3: Main characteristics of the base, stretched and shrunk versions of the aircraft tested.

<table>
<thead>
<tr>
<th></th>
<th>Shrink</th>
<th>Base</th>
<th>Stretch</th>
</tr>
</thead>
<tbody>
<tr>
<td>MTOW [t]</td>
<td>53.234</td>
<td>58.034</td>
<td>63.403</td>
</tr>
<tr>
<td>MGLW [t]</td>
<td>48.648</td>
<td>53.034</td>
<td>57.940</td>
</tr>
<tr>
<td>OWE [t]</td>
<td>31.219</td>
<td>34.034</td>
<td>37.183</td>
</tr>
<tr>
<td>Payload [t]</td>
<td>12.842</td>
<td>14</td>
<td>15.295</td>
</tr>
<tr>
<td>Seats (maximum)</td>
<td>93</td>
<td>113</td>
<td>133</td>
</tr>
<tr>
<td>Range [km]</td>
<td>4720</td>
<td>4387</td>
<td>4168</td>
</tr>
<tr>
<td>Ch. 3 Cum. Margin [dB]</td>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Max. Take Off Thrust [kN]</td>
<td>86.3</td>
<td>93.45</td>
<td>99.6</td>
</tr>
<tr>
<td>Number of Engines</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Engine Used</td>
<td>CFM56-7B</td>
<td>CF34-10E</td>
<td>CFM56-5B</td>
</tr>
</tbody>
</table>

On an absolute basis, the total CASK is higher for the smaller version of the family and lower for the longer version. For the 9 missions studied previously, the shrunk 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 (see Table 4.4). The flight costs are the source for most of
the difference, since they amount to around 50% of the total CASK and the changes are of around 10% higher and lower CASK for the shrunk and stretched versions, respectively. However, the biggest relative differences are on the maintenance costs, with around 14% increases in CASK for the shrunk version and around 10% decreases in CASK for the stretched version. The ownership costs suffer almost no change.

Table 4.4: Comparison of the CASK for the three different versions of the aircraft for the EU0-EU3.3 Short mission.

<table>
<thead>
<tr>
<th></th>
<th>Shrunk</th>
<th>△</th>
<th>Base</th>
<th>△</th>
<th>Stretch</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flight Costs</td>
<td>0.0523</td>
<td>+10.1%</td>
<td>0.0475</td>
<td>−10.3%</td>
<td>0.0426</td>
</tr>
<tr>
<td>Maintenance Costs</td>
<td>0.0247</td>
<td>+13.8%</td>
<td>0.0217</td>
<td>−10.1%</td>
<td>0.0195</td>
</tr>
<tr>
<td>Ownership Costs</td>
<td>0.0306</td>
<td>−1.3%</td>
<td>0.0310</td>
<td>−0.6%</td>
<td>0.0308</td>
</tr>
<tr>
<td>Total</td>
<td>0.1076</td>
<td>+7.5%</td>
<td>0.1001</td>
<td>−7.2%</td>
<td>0.0929</td>
</tr>
</tbody>
</table>

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.

4.3 Test Case 3 - Comparison of the profitability of the base and stretched aircraft for two different airlines

The choice of an aircraft is not dependent solely on the CASK, but it has to be taken into account which one of them suits the best 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 4.2 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. Although not presented in Figure 4.2, the missions were also recorded by departure and destination airport and region. 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 (see Table 4.5). In general, the costs for the European airline are larger than those for the Canadian one.

To assess which aircraft suits the best the operations of each of the airlines, the estimation of the revenues must be done. These depend on the Revenue per Passenger Kilometre (R/PK) and the Load Factor (LF), which is the ratio between the number of passengers carried and the number of seats available on the aircraft. To simplify, a LF of 85% was chosen for all the flights of both companies for the
Figure 4.2: Distribution of the missions of Air Canada and KLM City Hopper performed by their short haul fleet by stage length intervals.

Table 4.5: Air Canada and KLM City Hopper estimated global CASK and total costs for one year of operations using the base version and the stretched version of the test aircraft.

<table>
<thead>
<tr>
<th>Base</th>
<th>Stretch</th>
<th>Base</th>
<th>Stretch</th>
</tr>
</thead>
<tbody>
<tr>
<td>8.08</td>
<td>7.52</td>
<td>15.73</td>
<td>17.17</td>
</tr>
<tr>
<td>13.61</td>
<td>12.63</td>
<td>18.59</td>
<td>20.28</td>
</tr>
</tbody>
</table>

The determination of the LF on the stretched version depends on the elasticity between demand and price. To determine price, it was decided that the R/PK would be the CASK plus 3 US$ cents. Then, based on the R/PK values for the base and stretched versions, the LF of the stretched versions of the aircraft were calculated using:

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

The exponent 2.5 was set to denote a variation of the demand different than linear with the price. It is admitted that this value may not represent accurately the reality and was chosen merely to exemplify the results that the cost models can provide.

Table 4.6: Absolute profit and profit margin estimated for Air Canada and KLM City Hopper when using an entire base version aircraft fleet and an entire stretched version aircraft fleet.

<table>
<thead>
<tr>
<th></th>
<th>Profit %</th>
<th>Total Profit (US $ millions)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Base</td>
<td>Stretch</td>
</tr>
<tr>
<td></td>
<td>Base</td>
<td>Stretch</td>
</tr>
<tr>
<td>Air Canada</td>
<td>19.4%</td>
<td>17.7%</td>
</tr>
<tr>
<td>KLM City Hopper</td>
<td>6.8%</td>
<td>7%</td>
</tr>
<tr>
<td></td>
<td>3.05</td>
<td>3.04</td>
</tr>
<tr>
<td></td>
<td>1.26</td>
<td>1.42</td>
</tr>
</tbody>
</table>

The results for this test are shown in Table 4.6. While in the Air Canada case the total profit is almost unchanged between versions (despite the margins being slightly lower), in the case of KLM City Hopper profits increase around 13% when using the stretched version. These differences are caused by the
distinct mission profiles and cost structures. Although different assumptions on variables such as the R/PK value or the exponent on Equation 4.5 would lead to different results and variations, this exercise serves the purpose of showing that this tool can identify between a set of different aircraft the one that best suits the mission profile of a given airline.

However, changing the values of the margin per passenger, i.e., the way R/PK is calculated, and the value of the exponent in Equation 4.5 may lead to different results. These values should be changed to reflect the different realities of each airline. In order to provide an idea of how the results change with changing these parameters, a sensitivity analysis was performed on each of the values independently, keeping the other one equal to the value used above. Furthermore, it was assumed that the airline would use the same margin for both of the aircraft designs.

Keeping the margin at 3 US$ cents per passenger, decreasing the value of the exponent means that the absolute profits of both companies with the stretched version will decrease relatively to the values presented in 4.6, and increasing the value of the exponent increases the profits. The profits with the base version do not depend on the value of the exponent. However, lower exponents will affect much more the profitability of the stretched version relatively to the base version of KLM City Hopper than that of Air Canada. In the opposite direction, increasing the value of the exponent, although benefiting both of the companies, brings a higher increase in the profits for KLM City Hopper. Table 4.7 shows the details of this analysis.

Table 4.7: Profit results (in US$ millions) for the base and stretched versions for both Air Canada and KLM City Hopper varying the values of the exponent from -50% to +50% the value of 2.5 and maintaining the margin per passenger kilometre at 3US$ cents for all the cases.

<table>
<thead>
<tr>
<th>Exponent</th>
<th>Air Canada Base</th>
<th>Air Canada Stretch</th>
<th>KLM Base</th>
<th>KLM Stretch</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.25</td>
<td>1.800</td>
<td></td>
<td>-0.141</td>
<td></td>
</tr>
<tr>
<td>2.00</td>
<td>2.536</td>
<td></td>
<td>0.782</td>
<td></td>
</tr>
<tr>
<td>2.25</td>
<td>2.788</td>
<td></td>
<td>1.099</td>
<td></td>
</tr>
<tr>
<td>2.50</td>
<td>3.052</td>
<td>3.042</td>
<td>1.257</td>
<td>1.421</td>
</tr>
<tr>
<td>2.75</td>
<td>3.301</td>
<td></td>
<td>1.748</td>
<td></td>
</tr>
<tr>
<td>3.00</td>
<td>3.563</td>
<td></td>
<td>2.079</td>
<td></td>
</tr>
<tr>
<td>3.75</td>
<td>4.368</td>
<td></td>
<td>3.105</td>
<td></td>
</tr>
</tbody>
</table>

Regarding the sensibility of the margin, the stretched version is more profitable (or gives less loss) than the base version for KLM City Hopper, with a difference of around 160US$ thousands, but for Air Canada the differences between the base version profit and stretched version profit are very small. This means that the gain in absolute profit between the two versions has a low sensitivity to the margin per passenger kilometre chosen. Table 4.8 shows the details of this analysis.

Concluding, the values assumed for the exponent of Equation 4.5 affect considerably the profitability estimations of each of the aircraft versions. Care must be taken when choosing this value and performing this analysis. If this simulation is being performed for any given airline, values correspondent to its activity must be used. However, since the absolute profits do not depend greatly on the margin chosen, this is one less variable with which one should be concerned.
Table 4.8: Profit results (in US$ millions) for the base and stretched versions for both Air Canada and KLM City Hopper varying the values of the margin per passenger kilometre from -50% to +50% the value of 3 US$ cents and maintaining the exponent at 2.5 for all the cases.

<table>
<thead>
<tr>
<th>Margin</th>
<th>Air Canada Base</th>
<th>Air Canada Stretch</th>
<th>KLM Base</th>
<th>KLM Stretch</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.5</td>
<td>0.345</td>
<td>0.357</td>
<td>-0.766</td>
<td>-0.586</td>
</tr>
<tr>
<td>2.4</td>
<td>1.969</td>
<td>1.968</td>
<td>0.448</td>
<td>0.617</td>
</tr>
<tr>
<td>2.7</td>
<td>2.511</td>
<td>2.505</td>
<td>0.853</td>
<td>1.019</td>
</tr>
<tr>
<td>3.0</td>
<td>3.052</td>
<td>3.042</td>
<td>1.257</td>
<td>1.421</td>
</tr>
<tr>
<td>3.3</td>
<td>3.594</td>
<td>3.581</td>
<td>1.662</td>
<td>1.823</td>
</tr>
<tr>
<td>3.6</td>
<td>4.136</td>
<td>4.119</td>
<td>2.067</td>
<td>2.225</td>
</tr>
<tr>
<td>6.0</td>
<td>5.760</td>
<td>5.733</td>
<td>3.281</td>
<td>3.431</td>
</tr>
</tbody>
</table>

Finally, a comparison of the results obtained with the real CASK for different airlines is performed. Unfortunately, it was not possible to gather CASK data solely for the Embraer 190 and 195 and similar aircraft. The data gathered was obtained from the financial reports of different airlines from around the world for the year 2014 (available on their respective websites). In these results, operating costs external to the aircraft, such as the desk costs, operations management and others are included, as well as a higher contribution (slightly above two times more of what was calculated in the tests performed) of the fuel expenses, which reflects the prices more than two times higher of the fuel in 2014. Table 4.9 shows the CASK from different airlines in US$, as exchanged using the average 2014 exchange rate. It is possible to see that the CASK obtained for both the base and the stretched versions of the aircraft in a 1200 km mission in the US is between 15-40% higher than that of the North American airlines but in a 700 km mission in Europe is between the European airlines CASK. Ideally, a comparison of each component of the total CASK would be desirable to understand where these differences are originated, but once again the data obtained was not as detailed as to allow such a comparison, unless in some cases for the fuel costs, which are overestimated in less than 15% for the North American case. A reason for the considerably overestimated costs in the US but well estimated in Europe is hard to find. It may be due to the different mission lengths performed, since it is being taken into account the entire company CASK and not only the CASK for regional flights. However, it is not possible to ensure this. Nevertheless, the estimates obtained are apparently coherent with the actual costs of the different airlines.
Table 4.9: Comparison of the CASK between the test cases results and 7 airlines for the year 2014. The fuel costs for the test cases results reflect the average fuel prices of 2014.

<table>
<thead>
<tr>
<th></th>
<th>Total CASK</th>
<th>Fuel CASK</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test Aircraft (Base) 1200 km distance mission in the US</td>
<td>8.80</td>
<td>2.75</td>
</tr>
<tr>
<td>Test Aircraft (Stretch) 1200 km distance mission in the US</td>
<td>8.17</td>
<td>2.56</td>
</tr>
<tr>
<td>Southwest Airlines</td>
<td>6.75</td>
<td>2.18</td>
</tr>
<tr>
<td>American Airlines</td>
<td>7.07</td>
<td>2.41</td>
</tr>
<tr>
<td>JetBlue</td>
<td>6.36</td>
<td>2.41</td>
</tr>
<tr>
<td>Air Canada</td>
<td>6.30</td>
<td>-</td>
</tr>
<tr>
<td>Test Aircraft (Base) 700 km distance mission in Europe</td>
<td>11.83</td>
<td>3.49</td>
</tr>
<tr>
<td>Test Aircraft (Stretch) 700 km distance mission in Europe</td>
<td>10.98</td>
<td>3.23</td>
</tr>
<tr>
<td>British Airways</td>
<td>10.80</td>
<td>-</td>
</tr>
<tr>
<td>KLM</td>
<td>11.84</td>
<td>-</td>
</tr>
<tr>
<td>Virgin Australia</td>
<td>9.65</td>
<td>-</td>
</tr>
</tbody>
</table>
5 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 components of the operating costs are: the flight costs, where are included costs with fuel, flying crews, taxes and fees; the maintenance costs, for both the airframe and engines; and the ownership costs, namely the depreciation, insurance and interest costs, which are dependent mainly on the aircraft price.

First, three models for estimating the aircraft market price, in the context of the current market conditions, were designed. Between these models the level of complexity is their greatest difference, since the simplest one uses only the MTOW of the aircraft as a variable, the intermediate one is dependent on the design range and the number of seats, and the one that is most complex adds to the latter the maximum take off thrust capacity. This last model also calculates the price of the airframe and the engines separately. Overall, the three models provide good approximations of the market prices of the aircraft available on the market as of 2015. The errors are typically smaller than 10%, although reaching values as high as almost 30% for the smallest aircraft in the database analysed.

Then, the operating cost models were designed. The fuel costs are highly dependent on the price of the fuel, which varies quite significantly through time on an unpredictable manner. The fuel consumption during flight must be provided by the optimizer, but lacking this information a model for fuel consumption adapted from data of an aircraft optimized in the context of the NOVEMOR program was designed. The cockpit and cabin crews cost models were designed using real US airlines information, but no data could be found regarding the costs for the rest of the world, so these costs are assumed to be constant throughout the world. The landing, navigation, noise and emission fees were derived for several regions of the world using actual data on the airport and navigation service providers policies. Data on maintenance costs could not be found, but a 5 year old model was updated using the ratios of the labour and materials costs from the then year to 2014. Finally, the ownership costs were calculated using the aircraft market price calculated previously and the typical values for rates, premiums and periods in the airline industry.

To test the models, three different test cases were performed. In the first, the aircraft designed in
the context of the NOVEMOR project was tested for different mission lengths and locations, and the results were compared. As expected, longer and with more utilization missions yielded lower CASK values. Differences in the different cost components, such as the landing or navigation fees, could also be noticed to change slightly the total CASK from one region of the world to another. However, as expected, the greatest influence on the operating costs comes from the fuel price. Doubling the price of the fuel from the September 2015 price to the average 2014 prices means increasing the total CASK of the aircraft by an amount between 14% and 19%.

The second test consisted of the comparison of the aforementioned design with designs with different characteristics. Two other aircraft, one shrunken 20 seats and the other stretched also 20 seats from the original one, were roughly designed, providing the essential physical and performance characteristics for allowing the test to be performed. The results for different missions showed that, once again as expected, the CASK values are lower for the stretched aircraft and higher for the shrunken one since, although the bigger the aircraft the more expensive it is to operate on an absolute basis, the highest seat capacity overcomes these extra costs.

Finally, it is reckoned that the CASK is not per se a sufficient metric to evaluate the suitability of a given design to a given airline, since the revenue in a certain mission may not change enough to overcome the higher absolute costs if a different aircraft is used. For this reason, the regional missions of two real airlines (Air Canada and KLM City Hopper) were compared using each of the base and stretched versions of the aircraft, assuming a profit margin per passenger equal to both of the airlines and a demand-price elasticity also equal to both. For Air Canada, changing from an all base version aircraft fleet to an all stretched version aircraft fleet would reduce slightly both the profit margin and the absolute profit. The same change would, however, increase the profits by more than 10% for the KLM City Hopper.

The CASK values obtained in all of the different 3 tests are in line with those collected from the financial reports of several airlines from different regions of the world, which means that the results are, even if not completely accurate, at least of the same magnitude. It is also shown the capabilities of this tool to identify from a set of different aircraft designs the one that is more adequate for an airline with a given set of missions. Furthermore, if the task is only to reduce the operating costs during an optimization, these models also provide the relative weight of each of the cost components and the characteristics upon which they depend, as to facilitate the choice of the parameters that must be changed during the optimization.

5.1 Future Work

The cost models developed are good estimating relationships for the operating costs of passenger aircraft powered with jet engines. It would also be of interest to gather more information on turboprop aircraft and on cargo aircraft to develop cost models for these cases too.

On the flight costs models, the cockpit crews and cabin crews costs relationships were designed based on information from US airlines. It would be desirable to have relationships that could more
accurately predict these cost components for the remaining regions of the world. Furthermore, the flight costs models were devised primarily to be used with aircraft that are already capable of flying short to medium haul distances. Smaller aircraft, of up to 50 passengers, for instance, belonging to only regional airlines, would have different costs since the airports where they operate are smaller, the propulsion is done with turboprop engines, and the costs with cockpit and cabin crews are typically lower for regional carriers.

Regarding the maintenance costs, the cost models presented are simply an update from other models. It would be desirable to design these models from scratch, taking into account factors such as the percentage of composite and other advanced materials structures used in the aircraft. Information about these costs is very hard to find in public domain, hence the need to establish contacts close to the companies and groups that make the maintenance of airframes and engines.

Although it has been proven that the models are capable of providing different outputs for different aircraft and airlines, it would be very valuable the comparison between the results obtained with the test cases and real cost data from a real airline to validate the accuracy of the models designed.

Finally, the adaptation of these cost models, chiefly the Acquisition Price models and the Maintenance Cost models, to advanced concepts and novel configurations should be pursued in order to analyse the suitability of these aircraft to the use in commercial transportation. This task seems to be rather complicated since no information on costs for this type of designs is available from which cost models can be drawn.
Bibliography


A Appendixes

A.1 ICAO Annex 16 Volume 1 Noise Limits

The certification of aircraft according to ICAO Annex 16 Volume 1 requirements depends on the noise levels of the aircraft measured in three different points: Flyover (TKO), Sideline (LAT) and Approach (APP). In order to receive Chapter 3 certification, an aircraft must comply with the limits for all three points. These limits are set depending on the Maximum Take Off Weight of the aircraft (MTOW), and in the case of the Flyover point it also depends on the number of engines on the aircraft. Equations A.1 to A.5 define the Chapter 3 limits.

\[
LAT[dB] = \begin{cases} 
94, & MTOW \leq 35[t] \\
80.87 + 8.51 \log(MTOW), & 35[t] < MTOW \leq 400[t] \\
103, & MTOW > 400[t] 
\end{cases} \tag{A.1}
\]

\[
APP[dB] = \begin{cases} 
98, & MTOW \leq 35[t] \\
86.03 + 7.75 \log(MTOW), & 35[t] < MTOW \leq 280[t] \\
105, & MTOW > 280[t] 
\end{cases} \tag{A.2}
\]

\[
TKO_{1/2\text{Engine}}[dB] = \begin{cases} 
89, & MTOW \leq 48.1[t] \\
66.65 + 13.29 \log(MTOW), & 48.1[t] < MTOW \leq 385[t] \\
101, & MTOW > 385[t] 
\end{cases} \tag{A.3}
\]

\[
TKO_{3\text{Engines}}[dB] = \begin{cases} 
89, & MTOW \leq 28.6[t] \\
69.65 + 13.29 \log(MTOW), & 28.6[t] < MTOW \leq 385[t] \\
104, & MTOW > 385[t] 
\end{cases} \tag{A.4}
\]

\[
TKO_{4+\text{Engines}}[dB] = \begin{cases} 
89, & MTOW \leq 20.2[t] \\
71.65 + 13.29 \log(MTOW), & 20.2[t] < MTOW \leq 385[t] \\
106, & MTOW > 385[t] 
\end{cases} \tag{A.5}
\]

The individual margins relative to the ICAO Annex 16 Volume 1 Chapter 3 are calculated as the
values measured minus the limits set by the equations above. The cumulative margin is the sum of the three individual margins.

Chapter 4 compliant aircraft must have a cumulative margin not less than 10 EPNdB. Furthermore, the sum of the differences at any two measurement points between the measured level and the Chapter 3 limit levels must not be less than 2 EPNdB. For simplicity, in this thesis this last rule was neglected, standing only the cumulative margin of all the three measurement points.
A.2 Relationships between the main characteristics of the adapted and base versions of the aircraft and the seats ratio

Figure A.1: Variation of the price of the aircraft with the number of seats for a stretched or shrunk version.

Figure A.2: Variation of the MTOW of the aircraft with the number of seats for a stretched or shrunk version.
Figure A.3: Variation of the Sea Level Static Thrust of the aircraft with the number of seats for a stretched or shrunk version.

Figure A.4: Variation of the Range of the aircraft with the number of seats for a stretched or shrunk version.