The Design of a Large Scale Airline Network

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Delft University of Technology

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The Design of a Large Scale Airline Network

Proefschrift

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Preface

The research presented in this thesis has been supported by the National Council of Science and Technology of Mexico (CONACyT), and the Faculty of Mechanical, Maritime and Materials Engineering, Delft University of Technology. The study has been developed at the department of transport engineering and logistics (TEL). I want to thank both institutions for supporting me during the development of this PhD thesis.

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To Prof. Dr. Angelica Lozano and Dr. Milan Janic, since we met and besides they were not my thesis director or supervisor, they always were opened to discuss my project, and make important observations that had a huge impact on the development of this thesis.

To all my colleagues in the department of Transport Engineering and Logistics enormous thanks, I have enjoyed working at this department, and I will always remember our chats, discussions, jokes, dinners, and pubs. I had a great time.

Finally, I thank my parents, Rafael and Veronica, who always support me and my brother in any decision we have taken in our lives. They always encourages us to pursue high goals always keeping in mind that happiness is the most important thing in life, and teaching us that family is what we will always have. I am very grateful to my mother because she has been always a great mom. I am thankful to my father because he has thought me how to analyze, identify and solve any problem. His advices during the development of this thesis impressed me, because he always understands what I am doing. His explanations and suggestions of mathematical modeling were important for the developing of this thesis. My brother Alejandro and his wife Gabriela, they always have supported me deeply on my decision. I want to thank to my grandparents, uncles and cousins “the pilots” for their support, their explanations of how aircrafts flight help me to understand and develop the models presented in this thesis. Lastly, I want to thank God.

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1 Introduction

Air transportation industry refers to the movement of people and cargo through the air from an airport origin (ORI) to an airport destination (DES). Air transportation industry can be divided into air passenger transportation industry and cargo transportation industry. The air passenger transportation industry refers to the movement of people. The cargo transportation industry refers to the movement of cargo or goods.

The air transportation industry is a key factor for any country to achieve economic growth. It provides thousands of jobs and increases the connectivity and enhances the economic relationships between cities, states and countries [Tam and Hansman, 2002]. In 2007, The United States of America (US) Federal Aviation Authority (FAA) has estimated that the US air transport system accounted for over 1.3 trillion dollars, or 5.6 percent of the total US economy. The aviation industry provided eleven million jobs in aviation-related fields, earning a profit of 396 billion dollars in the US [FAA, 2009]. Figure 1.1 shows the relationship between the US economic growth (in Gross Domestic Product, GDP) and the demand for air travel in revenue passengers per kilometer (RPK's). As the economy grows, the demand for air transport grows too. From 2001 to 2005 an economic contraction or slowdown, caused by the 9/11 terrorist attacks in New York, can be noticed.

Figure 1.2 illustrates the basic macroeconomic functionality of air transportation industry. Basically a travel need is generated by the market which causes an increase in the demand of air transport operation services. The supply of the demand, in turn, provides access to passengers, markets, new airline businesses and investment and thus partly allowing the economy to function. The gray box in Figure 1.2 shows the internal structure of the air transport industry based on the profitability of the airline industry. Airlines have the power to control the supply of air transportation by modifying prices, networks, and schedules. This increase or decrease the demand for air transport services. Finally, Figure 1.2 also illustrates how the economy manipulates the capacity of the airlines to finance their operations, and how the airlines impact directly or indirectly the national economic growth [Tam and Hansman, 2002].

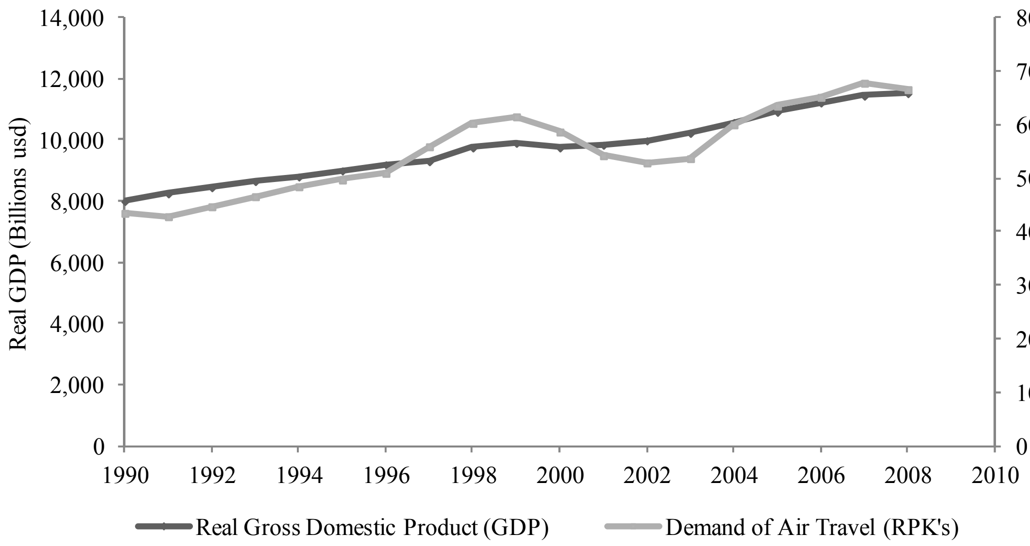


Figure 1.1 US GDP and air transport demand [Bureau of Economic Analysis, 1991-2009] [Bureau of Transport Statistics, 2000-2009] [FAA, 2009]

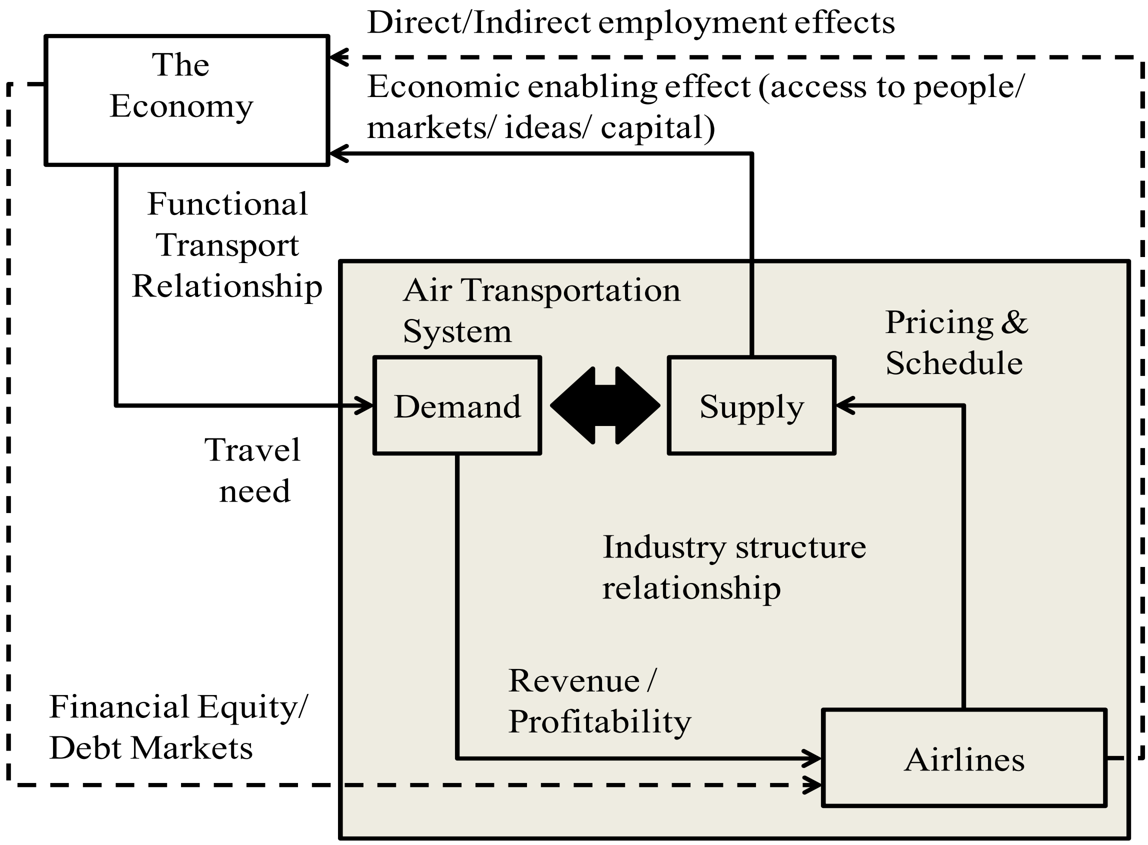


Figure 1.2 Relationship between the economy, air transportation demand and airlines supply [Tam and Hansman, 2002]

Airline operations also impact regional economies that benefit from the increasing number of people into the region and the job opportunities that these visitors create [Maertens, 2009]. The addition of the region to an airline network increases mobility for the local community as well [Donzelli, 2009].

The air transport passenger (pax) growth is enhanced by certain variables that local economies might or might not have such as population, wealth, income, GDP, traveling culture, airport capacities and infrastructure, and communication facilities. Strong relationships exist between these parameters and the development of local economies [Macario et al, 2007]. Macario, Viegas and Reis [2007] divide the impacts of airlines services on regional economies into three main classes:

1. Direct effects, which correspond to the increase in employment directly related to the air transport industry: airlines, handling, maintenance, catering companies, airports, shopping, restaurants and parking facilities. Burke [2004] estimated that for every million passengers through an airport, approximately 1,000 jobs are generated.
2. Indirect effects correspond to the increase in employment, and economic activity in the region. It is a result of the increase of activities such as tourism and businesses.
3. Catalytic effects, attraction and retention of incoming investment and the stimulation of the tourism industry. The increases in commercial activities enhance local economies competitiveness by attracting passengers either for business or leisure purpose. Ultimately, this will lead to sustainable economic, income and employment growth.

The increases of airline operations also have a direct impact on airports. An important part of a passenger ticket price consist of airports fees. These fees will increase or decrease depending on the efficiency of airlines and airports in establishing fast aircraft turnaround times for short-haul routes and having enough airport capacity and infrastructure for long-haul operations.

The airline airport relationship is enhanced by certain factors. The most important is the geographical location. The location advantage comes either from a large economy or population base or other sources that may be attractive to passengers [Guillen and Lall, 2004].

The market expansion has made it possible for secondary airports to develop and grow by convincing low-cost carriers to open new routes to these airports. This has changed the airport airline relationship. Airports have changed from generating their main profits from airlines to reducing fees to airlines in order to increase passenger flow and generate non-aeronautical revenues. Thus, airline passengers are their main customers because they generate non-aeronautical revenues. On the other hand, depend on airlines providing these customers.

The air transport markets have shown growth since the beginning of the 20th century [Radnoti, 2001] (i.e. US market, Figure 1.1). Lately, the main causes that have changed the airline industry are the deregulation and liberalization (privatization) of the air transportation system. Deregulation refers to the significant reduction of government policies that control airline or airport companies to raise or drop prices and enter and exit markets [Neufville and Odoni, 2003]. Before the deregulation, fares were regulated by governments' bilateral agreements [Alderighi et al, 2004] allowing only few Full Service Carriers (FSC's) to operate on certain routes. Since then, FSC's have stopped enjoying the governments' regulations that control airport operations [Barret, 2004].

The deregulation first happened in the United States of America (US) during the 1970s [Alamdari and Fagan, 2005]. In the European Union (EU) it took place during different phases 1987: (fare restrictions were reduced), 1990 (3rd, 4th and 5th freedoms[1], inter-European flights with a stopover in third Nations), 1992-1993 (all EU carriers were allowed to serve any international route within the EU) and 1997 (8th freedom, all EU carriers can operate any domestic route within the EU) [Burghouwt and De Wit, 2005]. Then, regulated fares and routes where removed allowing EU airline companies to fly any route inside the EU territories [Graham et al, 2003]. In March 2007, the US and EU skies were opened up towards the creation of a single aviation market. The agreement allows any carrier of the EU and any carrier of the US to fly between any airport in the EU and any airport in the US. US carriers can fly intra-EU flights but EU carriers cannot fly intra-US flights nor can EU carriers acquire a controlling stake in a US operator (i.e. Lufthansa has invested in JetBlue and in the past KLM invested in Northwest Airlines that today merged with Delta Airlines). EU carriers are allowed to serve routes between US airports and non-EU countries like Switzerland [IACA, 2007] [European Union, 2007] [Reals, 2010]. Many routes have been opened between different cities in Europe and the United States after the agreement (i.e. Amsterdam-Houston by Lufthansa, New York Newark – Paris Orly by British Airways). London has also been opened to allow operations to the US by third nation's carriers with incumbent fifth freedom of the air (i.e. Los Angeles – London by Air New Zealand, New York – London by Air India and Kuwait Airways). The competition between different airlines has increased [Guillen and Lall, 2004] as a result of the deregulation. It has produced a new air transportation system environment allowing airlines to operate new routes and find new networks opportunities.

The deregulation has changed the air transport system from a system of FSC's and charter airlines, operating in a regulated market, to a dynamic and open market industry. As a result, it has produced new airline business models and increased the competition between airports sharing or competing in the same catchment area[2] [Pestana and Dieke, 2007].

On the carrier side, the competition between airlines has increased. Airlines have improved their business models developing new business strategies to reduce operational costs, fares and maximize profits to be able to compete and widen their air traffic market. Airlines can be classified into four main airlines business models: FSC's, Low-cost Carriers (LCC's), Charter carriers [Carmona Benitez and Lodewijks, 2008a], and regional airlines. An FSC is a carrier that typically offers a high service quality such as a business class, a frequent flyer program (FFP), airport lounges, meal services and in-flight entertainment (i.e. United Airlines, Air France-KLM). A charter carrier is a company that operates flights outside normal schedules usually to tourism markets by signing arrangements with particulars customers such as hotel companies (i.e. Million Air). An LCC is an airline that does not offer many services (i.e. frills), minimize operation costs (i.e. turnaround times) and offers normally low fares (i.e. Southwest, Ryanair). A regional airline connects cities within a geographical region. Regional airlines provide services on routes without enough air passenger demand.

Nowadays, it is more difficult to differentiate between airline business models because to compete against LCC's, FSC's are reducing costs applying LCC strategies in short-haul operations [Harbison and McDermott, 2009] showing competitive low fares in routes with high LCC competition and increasing fares on those routes without LCC competition [Carmona Benitez and Lodewijks, 2010a, 2010b, 2012]. Charter carriers achieve the lowest costs and recently high quality new airlines have appeared for the business class market (i.e. Emirates, Etihad).

[1] Appendix A: The Freedoms of the Air [ICAO, 2011]

[2] The catchment area of an airport is the geographic area or land where the major proportion of airline passengers using the airport originates.

After the 9/11 New York terrorist attack, the air passenger demand fell down drastically, causing airlines to put their growth ambitions on hold and to reduce their capacities. Hence, increasing the number of flights on routes and opening new routes was not as attractive as it was in the late 1990s for the FSC's [Schnell, 2003]. Contrary to FSC's, when the world was affected by terrorist attacks, high fuel prices and economic recessions, LCC's grew up from 7.7% of the complete market to 22% (66 millions seats, Figure 1.3). This means that the economic downturn has affected less the LCC model than the FSC model creating opportunities for LCC's. Thus, from 2001 to 2009 the overall global air transport capacity growth is for the majority accredited to LCC's and when the current economic recession is ended, LCC's are expected to grow even faster than FSC's [Harbison and McDermott, 2009].

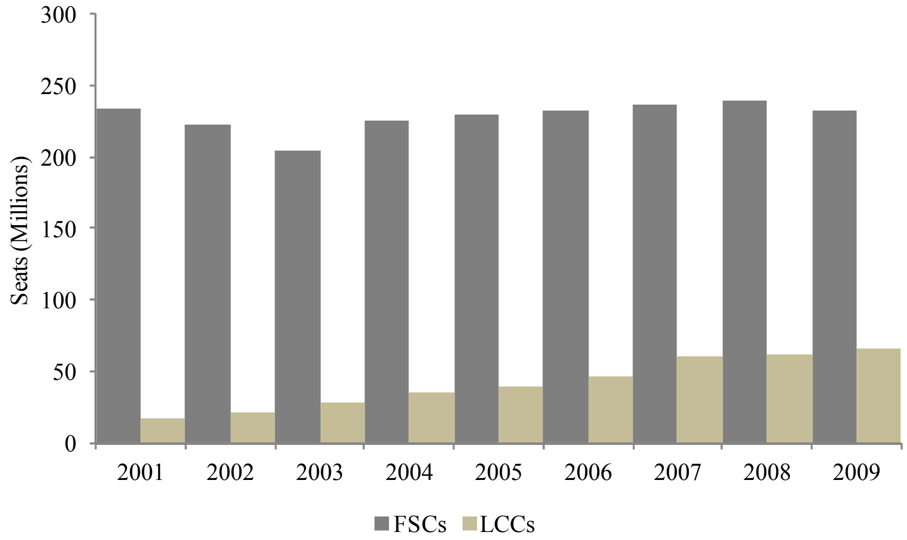


Figure 1.3 Expansion of worldwide capacity (seats) [Harbison and McDermott, 2009]

From the airport side, the competition between airports has also increased together with the number of passengers (pax) to serve per year. Airports are highly complex units that provide service for passengers, airlines and other airport users. Their main interest is to increase the number of connections with other airports to increase pax flow and thus aeronautical and non-aeronautical revenues. Aeronautical revenues include only revenues generated via services and facilities related to aircraft operations, pax and cargo. Non-aeronautical revenues are the ones produced by commercial services and facilities at the airports [Neufville and Odoni, 2003]. Thus, airports have become more commercial, and along with the optimization of the labor force (i.e. baggage handlers, dispatchers), the non-aeronautical revenues have become a much more important source of profits. For example, the cases of Las Vegas Airport (LAS), Weeze Airport (NRN) and Amsterdam Schiphol Airport (AMS) pier H show the benefit to provide more service to LCC's, increase pax flow and air transport services.

LAS increased its domestic pax flow from 28.7 million in 2005 to 29 million pax in 2007. In 2008, during the economic downturn, LAS showed a decrease to approximately 27.5 million domestic pax. In 2005, the number of domestic pax per year carried by LCC's was nearly 12.6 million operating 79 routes whilst FSC's served around 16.1 million pax serving 426 routes. In 2007, LCC's served more pax per year than FSC's operating fewer routes. LCC's increased their pax flow to approximately 14.6 million whilst the number of carried pax of FSC's decreased to nearly 14.4 million pax. In 2008, LCC's lost more pax flow (13.6 million of pax in 93 routes) than FSC's (13.9 million of pax in 390 routes) [DOT US Department of Transportation, 2005-2008]. From 2005 to 2008, LAS airport increased its total revenues and expenses from 431,907 and 312,201 million dollars (usd) to 624,599 and 495,091 million usd respectively. FSC's lost domestic pax flow but LCC's recovered and increased the number of domestic pax and revenues [McCarran Las Vegas airport website, 2005-2008].

In Europe, a good example is the case of the increase of air transport operations at Weeze airport in Germany, mainly provided by LCC's. The pax flow has increased from nearly 0.6 million pax in 2005 to approximately 2.9 million passengers in 2010 [Weeze Airport, 2010].

AMS is an example of a main hub trying to increase pax flow and routes by providing services to LCC's. To be able to serve LCC's, AMS built a low-cost airport terminal (Pier H). A low-cost airport terminal is a terminal that allows carriers to operate under LCC operation strategies (i.e. pax embark and disembark without using loading bridges). Today, the Dutch government is thinking to move half of the LCC operations from AMS, because of future congestion, to a nearby airport, Lelystad. If 50% of AMS LCC pax traffic volume moves to Lelystad, this will result in an increase of 31,000 air transport movements (ATM) and 4.3 million pax per year [Bennebroek et al, 2010]. These examples remark the benefits and effects for airports to increase passenger flow by serving LCC's.

1.1 Aim of the Thesis

Fundamental changes in the air passenger transport system have occurred as a consequence of the government and customer requests for opening new services in new markets. Thus, airlines have to analyze and decide what new routes to operate. First, countries and states with high increments of GDP are more attractive to open airline services (i.e. China, Brazil). Second, the level of deregulation at different countries allows airlines to find new routes and new networks to invest in other carriers or open services (i.e. Copa and Continental Airlines). Third, low fares, offered by LCC's, appear to be the main cause of the increase passenger flow worldwide (Figure 1.3). Fourth, the evolutions of the LCC's have increased the possibilities of airports to increase their revenues and pax flow by opening more routes operated by LCC's. Finally, points one to four will occur in many countries after their Civil Aviation Authorities eliminate restrictions on routes and fares giving the opportunities for airlines, airports, federal governments, states and investors from other countries to find new opportunities by identifying the right networks to serve. In other words, a new airline has to know what routes represent good possibilities to subsist or succeed in a very competitive market. These five points lead to with the main research question:

What passenger's airline networks represent business opportunities and are attractive for an airline to open new air services?

To answer this question, is important to investigate the following 10 questions:

1. Where to fly? What routes represent a new market opportunity for an airline with better possibilities to succeed or subsist?
2. What is the demand of passengers between origin and destination?
3. Which airports to operate?
4. How long and how to perform the turnaround processes?
5. How much is the airline going to charge per route? What is the average fare per passenger?
6. What aircraft type is the most convenient for the network? How many aircraft does the airline need to operate?

7. What is the optimal number of frequencies?
8. How many cabin crew and pilots are required to operate the aircraft?
9. How many staff members (engineers, ground staff and sales team) are required?
10. What is the operating cost per route?

The main research question and the above considerations lead to the next sub-questions:

1. What are the main parameters that determine airline route fares, airline operational costs and airport charges between two airports/cities?
2. What are the main parameters that determine the passenger demand per route between two airports/cities?
3. What are the main consequences of the competition between different airline business models FSC vs. LCC?

Besides the differentiation in FSC's and LCC's, airline business models can also be differentiated depending on the routes lengths. Routes can be classified into different hauls: short-haul, medium-haul and long-haul. In this thesis, a short-haul flight is a flight on a route shorter than 805km (500mi). The Association of European Airlines (AEA) has defined that a long-haul flight is a flight that last 6 hours (over 8,047km equal to 5,000mi) or more. Flights on a route between 805km and 8,047km (500mi and 5,000mi) are called medium-haul [Graham et al, 2007].

Therefore, another important sub question to solve is:

4. Can the low-cost model be implemented to long-haul markets?

1.2 Methodology

To answer the main research question and the four sub questions formulated in Section 1.1, an extensive literature research will be carried out. In addition other sources of information were used including reports, websites from different government offices, such as the Federal Aviation Authority (FAA), International Civil Aviation Organization (ICAO), The Air Transport Association (IATA), Association of European Airlines, Global LCC Outlook Report, Low-cost airport terminal reports, aircraft manufacture websites, reports and aircraft manuals from Boeing, Airbus and Embraer.

In this thesis the following steps are identified to provide answers to the research main question and sub questions:

- Develop models and methodologies to design airline networks by linking the demand of passengers with airline operating costs, route fares, and maximize the net present value of the airline network constrained to airports capacities and infrastructures, aircrafts performance, and levels of services.
- On the basis of the passengers demand, design a traveller demand model. This model consists on different mathematical models that calculate airline route fares, and the induced demand per route. The calculations of these models are used as input parameters to design an airline network. Develop a mathematical model assess the competition between airlines serving same routes. In the traveller demand model, the competitive average and range (min and max) fares are determined. The travel demand model also selects those routes that represent a new market opportunity to open air passenger transportation services.

- On the basis of the production, design a production model. This model consists on mathematical models that calculate airlines and aircrafts cost. The calculations of aircrafts costs are used as input parameters to design an airline network. The calculations of airline operating costs are used to understand the competition between airline business models.
- On the basis of the line service network, develop an optimization model to consider airports capacities and infrastructures, aircrafts performance, and levels of services. The optimization maximizes the net present value (NPV) based on the minimization of the operating costs, and maximization of profits.
- Design a route generator algorithm to re-design the airline network after each optimization iteration. The algorithm selects routes that are part of the network and eliminate routes that are not part of the network. Finally, the route generator algorithm stops when an optimum airline network is designed.

Figure 1.4 shows a diagram that indicates the relation between business parameters (cost, services, and regulations) on the supply side, and the demand side segments with the research questions. The diagram also shows how the research questions interact to solve the main question and the relation between the four sub questions (SQ) and the ten underlying questions (Q).

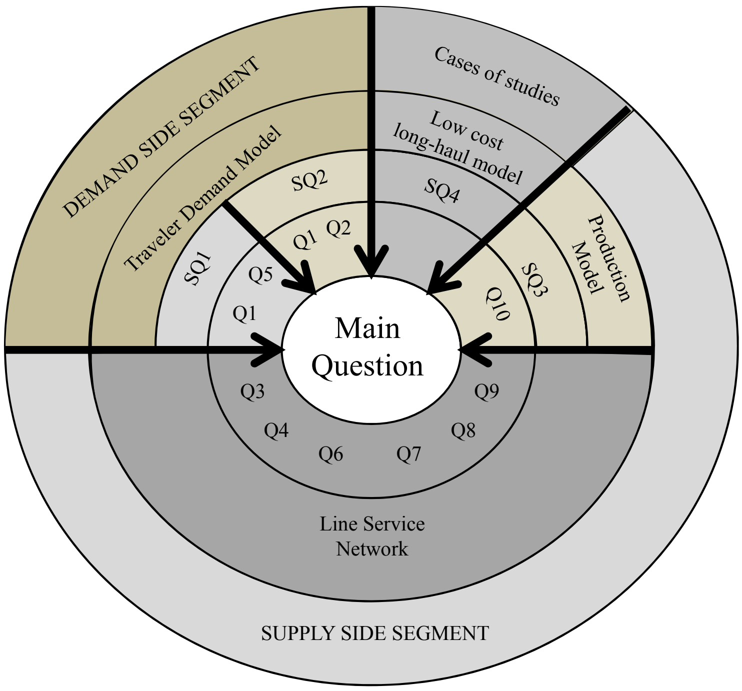


Figure 1.4 Relation between the main research question, the ten underlying questions (Q), the four sub-questions (SQ), and the demand and supply sides

Since no detail free information on European or Mexican aviation was available, this thesis focuses on the US aviation industry. The main data used in this thesis has been gathered from the US Department of Transportation Office of Aviation Analysis database [DOT US Department of Transportation, 2005-2008]. Other empirical data was received from US Bureau of Economic Analysis, US Census Bureau, US Bureau of Transportation Statistics, Research and Innovative Technology Administration (RITA), and AviationDB database.

1.3 Outline of the thesis

First, Chapter 2 presents a review of the airline business model and strategies as a first step to identify the main parameters that airlines use to provide air transport services. In Chapter 3, the airline operation cost model (AOC) and the aircraft operation cost model (AGE) are developed. The mathematical methodology equation (CFEM) to choose routes that represent a good opportunity for a new airline to get into the market and provide new services, or compete against other airlines, is shown in Chapter 4. The CFEM model calculates the minimum, average and maximum fare depending on the competition between airlines. In Chapter 4, also the fare estimation model (FEM) is developed based on a multi-regression analysis. Then, the CFEM and the FEM models are analyzed. Chapter 5 develops the pax forecasting model (PEM). Chapter 6 shows the optimization model that maximizes the net present value, designs and determines the airline network by selecting the most suitable aircraft, the optimum number of passengers to serve in each route, the optimum route load factor and the optimum number of aircraft to invest per year. As study cases, the optimization results are presented for the US domestic market and for a hypothetical long-haul low-cost market created using the mathematical models in Chapter 7. Finally, Chapter 8 lists the conclusions and future work.

The approach is bottom-up from Figure 1.5. It shows the logical steps and structure of the thesis.

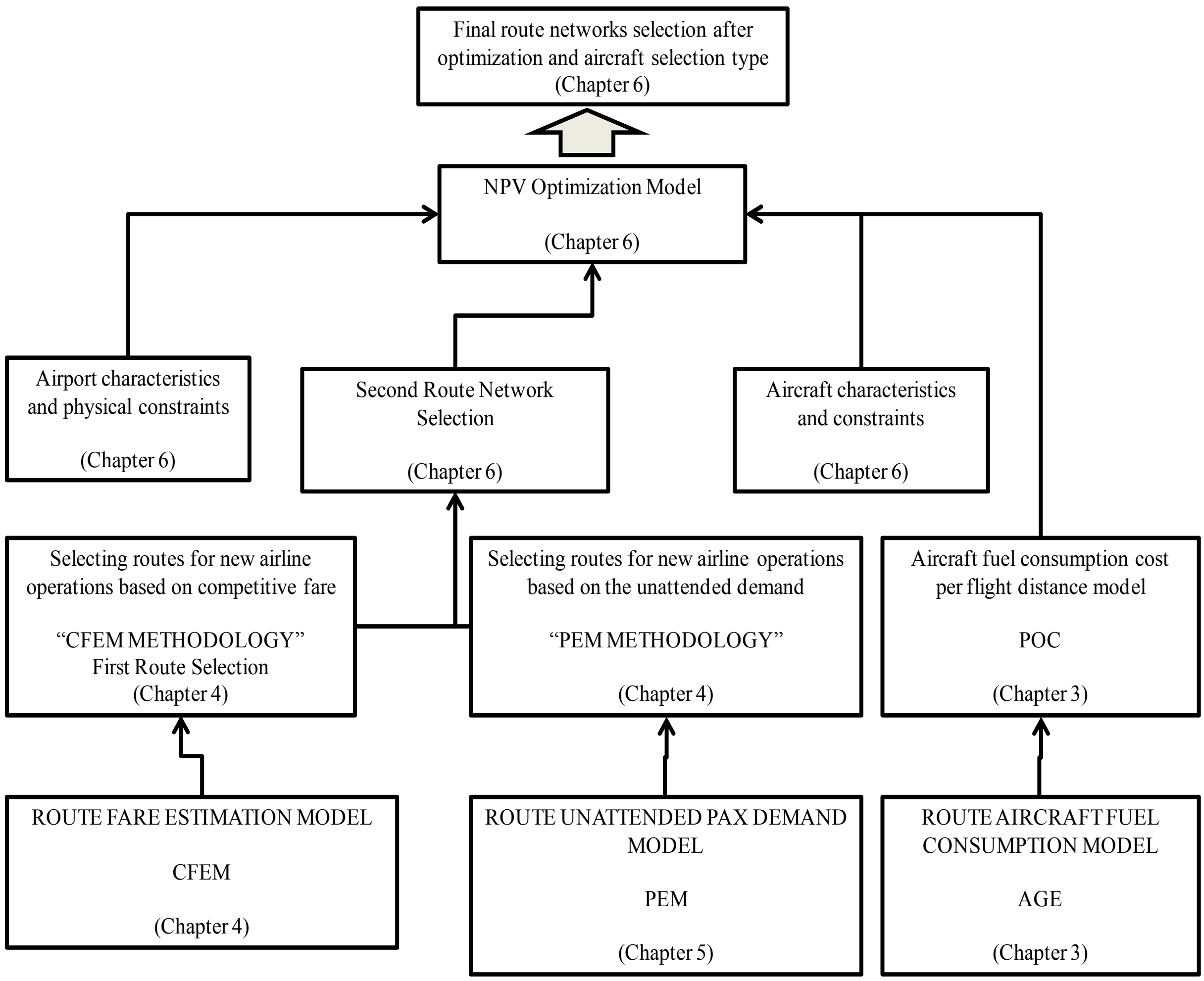


Figure 1.5 Logical steps and structure of the thesis

2 The airline business models and strategies

This chapter presents a review of airline business models and strategies as a step to identify the main parameters that affect the passenger air transport system. There are no standard airline business models. Each airline has its own business model to provide air transportation services and be attractive to different types of passengers. There are however, four generic passenger business models that are commonly recognized in the airline industry: network airlines or Full Service Carriers (FSC's) (i.e. Royal Dutch Airlines (KLM)), Low-cost Carriers (LCC's) (i.e. Southwest Airlines (WN)), charter airlines (i.e. Monarch (ZB)) and regional airlines (i.e. Aeromexico Connect (5D)) [Bieger and Agosti, 2005].

Three airline strategies can be adopted by carriers to have an advantage over competitors: cost leadership, differentiation and focus [Porter, 1985] [Alamdari and Fagan, 2005]. *Cost leadership* is a strategy mostly adopted by LCC's. They offer a standard service and gain competitive advantages by minimizing costs on all operational activities. With a *differentiatio*n strategy an airline is looking forward to be unique in the industry. The airline develops strategies to differentiate itself from other airlines by offering more attractive and higher services. As an example, one single strategic differentiation between Air France-KLM (AF-KLM) and Emirates (EY) is that EY offers a slightly more luxurious seat lay-out service for the premiere or first class passengers [Seatguru.com]. The AF A380 seat lay-out configuration offers 80 lie-flat seats for business class, 9 flat bed seats for premiere (first class) and 449 economy seats. Different, the EY A380 offers 76 lie-flat seats for business, 14 suits with a flat bed in first class with a sliding door and 399 economy seats. Finally, the *focus* strategy is used to add value, or to achieve low production costs [Shaw, 2007]. This strategy consists on adding value to the service and targeting carefully at a niche segment of the market [Porter, 1985]. For example, Ocean Sky is a private jet company in Europe that offers luxurious and private services for business or pleasure [Oceansky.com]. Table 2.1 shows the airline business models operation characteristics.

In this chapter, Section 2.1 explains the main characteristics of the FSC. Section 2.2 explicates the characteristics of regional carriers. In Section 2.3, the characteristics of the LCC's business model are. Section 2.4 examines the potential for long-haul LCC's. Section

2.5 spells out the characteristics of the charter airline model. Finally, Section 2.6 concludes this chapter.

Table 2.1 Airlines businesses operation models[3]

Operation Model	*FSC*	*LCC*	*Charter*
Strategy	Differentiation	Cost leadership	Focus
Alliance	Yes with other FSC's	Not normally	No
Network structure	Hub and spoke/Multi hub and spoke; Mix of short, medium and long-haul flights; Connections	Point to point, no connection, short-haul flights	Point to point, no connection short, medium and long-haul flights
Fleet[4]	Multiple aircraft types, large from 300 – 650 aircraft, i.e. American Airlines 606 aircraft	Uniform aircraft type, from 50 – 150 some are bigger than FSC's, i.e. Southwest 550 aircraft	Multiple aircraft types, smaller than FSC's and LCC's, i.e. Thomas Cook 40 aircraft
Aircraft route load factor	0.77 for short-haul and 0.80 for long-haul (US) ; 0.65 for short-haul and 0.81 for long-haul (EU)	0.85 for short-haul and for 0.77 long-haul (US) ; 0.80 short-haul (EU), etc.	0.92 for Thomas Cook Airline
Aircraft utilization	Approx 10 (US) and 7.6 (EU) hrs per day short-haul ; around 15 hrs per day long-haul flights	Around 11.5 (US) and 10 (EU) per day short-haul	Around 10 hrs per day (US)
Aircraft seat lay-out configuration	Aircraft with no high dense seat configuration to allow more pax comfort	Aircraft with high dense seat configuration no assignment, small pitch	Aircraft with high dense seat configuration with pre-bookable assignment
Route frequency	Moderate	High	Seasonal
Check-in and Distribution	Ticket or ticketless via online, direct, travel agent booking	Ticketless via online direct booking	Paper ticket via travel agents
Target Markets	Business and Leisure market	Cheap air pax sector market, leisure and some low fare business market	Leisure
Services	Multi-classes from 2 to 4, extensive in-flight services depending on distance haul	One single class, no food and drinks, no in-flight services or pay for extras	Vary from 1 to 3 classes, basic in-flight service, some offer meals
FFP[5]	Yes	No (mostly)	No (mostly)
Airport	Normally hubs and primary	Typically secondary	Commonly secondary
Turnaround[6]	Long times (congested airports)	15 – 20 minutes	Low
Fare	Revenue management[7]	Low prices (around 60% or more FSC's)	Fares are included in holidays packages

2.1 Full Service Model

A full service carrier is an airline that provides a wide variety of services before, during and after the flight. These airlines offer different service classes. They usually operate an international route network with a hub-and-spoke system that includes short and long-haul flights and that connects domestic and international flights [Ehmer et al., 2008] [Doganis, 2006] [Franke, 2004] [Burghouwt and De Wit, 2005].

[3] Table sources: Williams [2001], Alamdari and Fagan [2005], O'Connell and Williams [2005], Doganis [2006], Papatheodorou and Lei [2006], Hunter [2006], Dennis, [2007], Hanlon [2007], Humphreys et all [2007], Bruggen [2007], Carmona Benitez and Lodewijks [2008a], Wensveen and Leick [2009], RITA [2001-2009], Global airline industry program, MIT.

[4] Short-haul: B737 family, A320 family, Embraer; Long-haul: B747s, B767s, B777s, B787s, A330s, A340s, A350s and A380s (airplanes has different engines that allow to flight longer or shorter distance routes).

[5] FFP = Frequent Flier Program.

[6] The turnaround time process involves the taxi-in time, time spent at the gate, and the taxi-out time [Gillen and Lall, 2004]. Chapter 4 explains in detail the turnaround process.

[7] Revenue management: sell seats to the right customers at the right time for the correct price [Zeni, 2001].

The privatization and deregulation of the air transportation system increased the number of airlines operating HS networks in the US [Barros et al, 2007]. An airline operating a HS system offers air transport services between its hubs airports (1 or more) and its spoke airports [Danesi, 2006] Figure 2.1. A HS system consolidates traffic from different origins, sorts it and then sends it to different destinations. A HS system allows spoke cities to have better service at lower prices while hub cities have better service at higher fares due to the fact that non-stop connections are possible. The HS system enables the airline to serve more routes and gain market power at the hub. It allows the airline to sponsor operations outside the hub with lower fares and to be more competitive [Ehmer, 2008]. There are three advantages. Firstly, as the number of origin-destination (OD) routes increases, the load factor of connecting flights increases too. Therefore, it yields lower unit costs per hour. Secondly, higher demands reduce the unit costs per seat. Thirdly, a centralized operation allows having maintenance facilities, personnel and aircraft to back up at the hub. The main problem is to avoid flight delays on connecting flights during peak airport hours [Ehmer, 2008]. To perform an effective hub and spoke routing system, it requires that flights coming from different airports (spokes) arrive at the hub airport at approximately the same time [Danesi, 2006]. Thus, aircraft are on the ground at the same time, in order to make the rapid connection of passenger and baggage possible. Then, flights depart to the spokes in a faster sequence [Danesi, 2006]. Figure 2.2 illustrates the hub and spoke system of American airlines (AA) at Dallas Forth Worth airport (DFW).

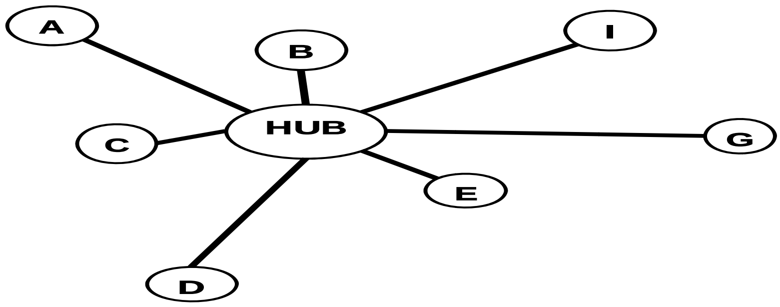


Figure 2.1 Hub and spoke network

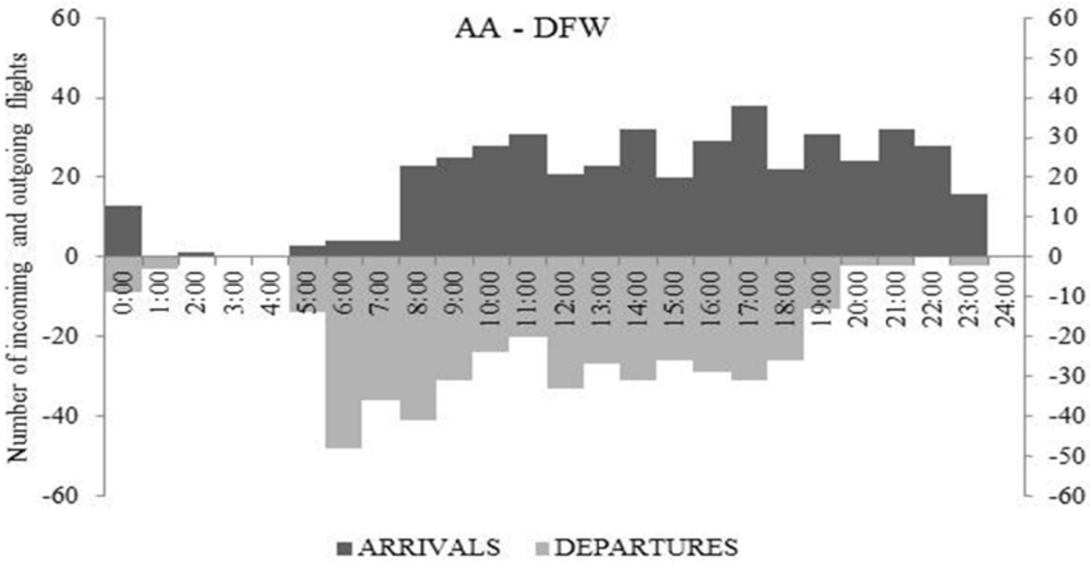


Figure 2.2 Schedule structure of American Airlines (AA) hub in Dallas Forth Worth (DFW) 31th January 2005 (Hub and spoke) [RITA, 2005-2008]

In the EU, some HS routing systems are different from the US systems. In the EU, hub networks operate under a wave-system structure, with better performance because of higher connectivity. This structure consists of the number of waves, the timing of the waves and the structure of the individual waves. These connection waves are a set of incoming and outgoing flights such that all incoming flights are equal in number of all outgoing flights schedule in time [Burghouwt and De Wit, 2005]. The main purpose of a wave-system network is to maximize connectivity by offering better timetable co-ordination. A hub timetable co-ordination is the action of organizing a hub schedule according to an order pattern of arrivals and departures during one day. So, connectivity can be increased without increasing the number of flights [Danesi, 2006]. Figure 2.3 shows KLM hub in Amsterdam Schiphol airport. The wave-system pattern of KLM at AMS airport, based on a 4-wave-system structure can be observed. The challenge is to set up an operation that allows for minimal connecting times. This is where airline-airport relationship plays a crucial role.

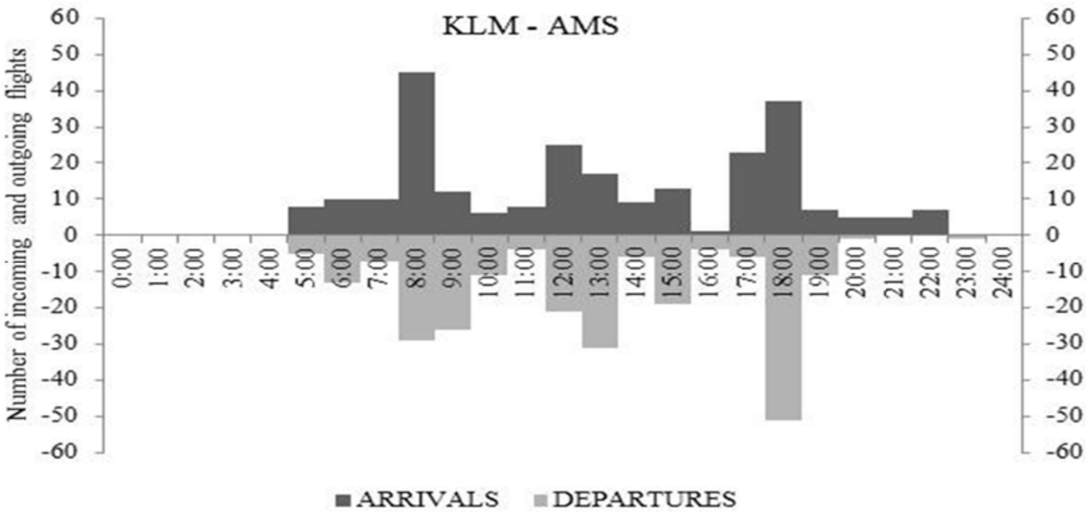


Figure 2.3 Schedule structure of Royal Dutch Airlines (KLM) hub in AMS 19th January 2005 (Wave-system network) [Danesi, 2006]

The FSC model appears no longer an effective business model in short-haul markets but appears to be effective for long-haul routes providing a high value service to many customers [Tretheway, 2004] whilst being competitive (Figure 2.4). In the case of the long-haul market, Figure 2.4 shows that FSC's are sensitive to economic struggles since they showed losses in 2007 and 2009, but in other years, the FSC model seems sustainable for long-haul operations. Nowadays, FSC's have been forced to put attention in the minimization of airline operations costs and to reduce fares to be more competitive in a new scenario, mainly affected in short-haul operations by the LCC's. For these reasons, FSC's are applying LCC's operation strategies to minimize operation costs and lower fares in short-haul markets. Table 2.1 shows that FSC's have increased their passenger load factor up to 77% in short-haul markets, and they show higher load factors for long-haul routes. Table 2.1 also shows the maximization of FSC's daily aircraft utilization around 10 hours per day what is very close to the LCC's, 11.5 hours. However, also they are using differentiation strategies [Hunter, 2006] that are opposite to the LCC model such as the expansion of the share of capacity allocation to high fares and business class by increasing seating quality. Airlines applying these strategies are called "Premium" such as Cathay Pacific (CX), Emirates (EY) and British Airways (BA). FSC should only apply those LCC strategies that do not affect the quality of service they usually offer to their passenger like frequent scheduling, inter-flight flexibility and ground service linkage, comfort on-board, in-flight entertainment (IFE), free meal and drinks, use of major airports or hubs and frequent flight programs (FFP). Business passengers are the main customers of this type of airlines in both short and long-haul markets.

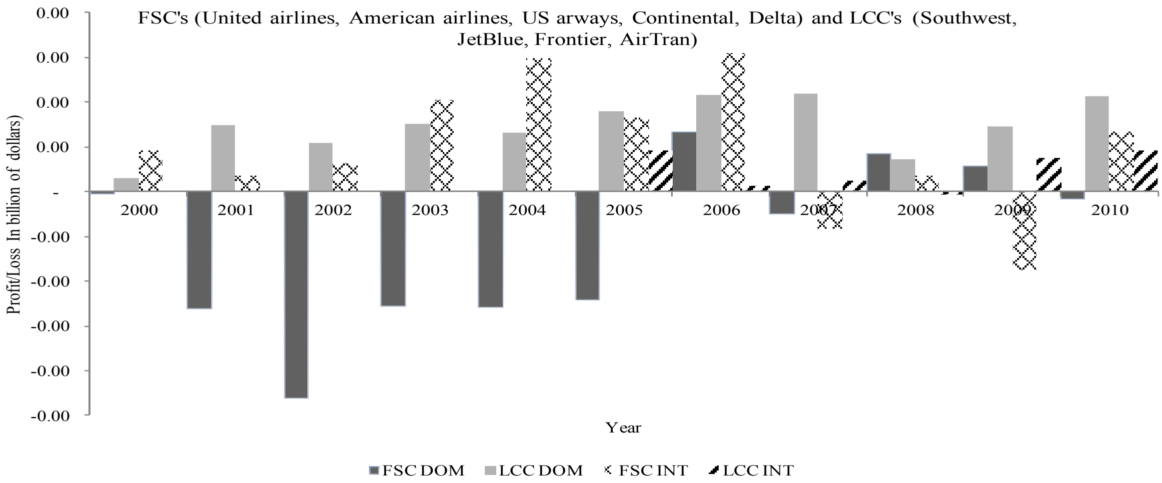


Figure 2.4 Profit/Loss US FSC's and LCC's dom and int markets [RITA, 2000 - 2010]

FSC's have recognized the advantages of the LCC business model in short-haul markets. To reach a competitive cost structure, FSC strategies are oriented to the reduction of the labor costs, increase productivity, transfer services to regional partners, franchises or alliances (i.e. SkyTeam, Star Alliance) and or establish LCC subsidiaries (i.e. Jetstar Airways, Qantas), hiring new staff on less generous contracts and outsourcing more activities (catering, ground handling, and aircraft maintenance). For example, Lufthansa has a base in Budapest to conduct heavy maintenance lowering costs [Dennis, 2007]. Other changes are paid for catering in economic class (i.e. Aer Lingus and SAS) or offering just non-alcoholic and pay for alcoholic beverages in short and long-haul routes (i.e. Continental) [Dennis, 2007]. In general, FSC's are finding more sources to increase revenues than low fares, see Table 2.2. FSC's can also use their control of slots at the hub facilities or capacity to keep LCC's out of the hub operations. The majority of the FSC's has not used the reduction of the flights and cabin crew to lower costs. Instead, FSC's crews have to work early flights from other countries or local flights to reduce accommodation cost [Dennis, 2007].

Table 2.2 FSC revenue sources [Radnoti, 2001]

Revenue Account	*Medium*	*Revenue Account*	*Medium*
Passenger	Passenger Traffic	Charter	Available aircraft time
Freight	Freight Traffic	Duty-Free	On-board sales
Mail	Government contracts	Services	Maintenance handling for other airlines
Excess baggage	Passenger Traffic	Lease Income	Lease of equipment to other airlines

Variables that are well known to affect the FSC's operations are the seat allocation, number of handled baggage and the use of loading air bridges (not used by LCC's) because they delay the turnaround time of the aircraft [Dennis, 2007]. Loading bridges, for example, improve higher level of passenger service. The problem is that loading bridges slow down boarding, due to the use of just the front entrance/exit. The minimization of the number of baggage encourage people to have more hand baggage in the cabin, and it takes people more time to put it into the overhead compartments. Therefore, FSC's have to apply other strategies to counteract the turnaround delay problems giving passenger more time and getting more passenger satisfaction as a FSC brand. Finally, offering business and economy class, be compatible with the long-haul products for connecting passenger, the strategy of concentrated at major hubs and off-loading peripheral routes are the most successful strategies for FSC network carriers [Dennis, 2007].

2.2 Regional carriers

Regional carriers normally use small aircraft (i.e. Embraer and Fokker) with a seat lay-out between 20 to 100 seats. Their networks system is limited to a geographical area. Their main purpose is to connect cities within the geographical region without sufficient demand and with a point to point network system [Ehmer, 2008]. Their business model operates mainly in two different ways:

1. Use as airline feeder for FSC's by operating service from small cities to a main airport hub (i.e. Aeromexico connect (5D) – Aeromexico (AM), Continental express (CO) – Continental Airlines (CO), Eurowings (EW) - Lufthansa (LH)). They are part of an FSC's group. Their tickets are distributed together with the FSC's partner.
2. As an independent airline, providing service to small, medium or large cities without enough air passenger demand (i.e. PenAir (KS) Alaska region, Aeromar (VW) Mexico and south US, City jet (WX) Benelux, Germany, Ireland and the United Kingdom regions).

2.3 Low-cost model

The LCC model refers to the low-cost scheduling airlines or no-frill sector. LCC main customers are leisure and price sensitive passengers [Williams, 2002]. An LCC is an airline that tries to create opportunities for new travelers. Their passengers are usually more budget conscious people than FSC's passengers. LCC's allow them to fly often with charging low fares. To keep fares down, LCC's turnaround operations are minimized by increasing aircraft utilization to keep fares down. Table 2.3 shows in which unit cost categories, LCC reduces operation costs. The LCC has been a successful business model during the last ten years (Figure 2.4). It has earned profits even during an economic downturn, and a fuel price increment. Today, some LCC's are almost the biggest airlines in the world, in number of aircraft in their fleet, origin-destinations (OD) and passenger flow (i.e. Southwest airlines (WN) transports 106.2 million passengers from the total 717.6 million, in the US).

The key main drivers of the LCC model are short-haul, domestic, single aircraft type, aggressive cost control, low fares, no connectivity, dense routes, alongside network airlines and infrastructure supplied by others at low-cost [Harbison and McDermott, 2009].

The LCC's are organized in a point to point routing system (Figure 2.5). Normally, LCC's do not focus on connection traffic, even though they are not completely out of it, but passenger must do it by themselves [Gillen and Lall, 2004]. As they grow, some LCC's point to point networks fall into a quasi hub and spoke systems, with only one way fare (i.e. Southwest Airlines) [Alamdari and Fagan, 2005]. This allows LCC's networks expansion and increase the number of destinations making independent flights (point to point) to a hub [Alamdari and Fagan, 2005]. The LCC's initially just focused on short-haul services, but today some of them are flying medium-haul routes (i.e. Southwest Airlines (WN) flies from Providence to Las Vegas, which is 4,718km (2,718mi) and Ryanair (FR) flies from Stockholm to Gerona, which is 2,221km (1,380mi)).

Table 2.3 LCC's main operation costs strategies (H: high, M: medium) [Ehmer, 2008] [Harbison and McDermott, 2009]

Cost category	*Fleet*		*In-flight services*			*Airports*			*Distribution*		*Employees benefits*	
Cost (pax per km)	Single aircraft type	New tech.	High seat density lay-out and single lay out configuration	No catering services, no FFP	No seat allocation	Small and secondary airports	Rapid turnaround times	Point to point networks, no flights connection, mainly short and medium-haul routes	Ticketless, Internet base booking	Low fares, including very low promotional fares	Variable bonus depending on performance	Outsource non-core activities (maintenance, baggage handling)
Importance	H	H	M	M	M	H	H	H	H	H	H	M
Maintenance	X	X	X									X
Fuel		X	X			X						
Staff	X	X	X				X	X			X	X
Airport Costs			X		X	X	X	X				X
Air traffic control costs			X									
On-board services			X	X								
Investment and rental	X		X		X	X		X				X
Sales distribution			X			X			X	X		
Expenses	X		X	X	X		X	X			X	X

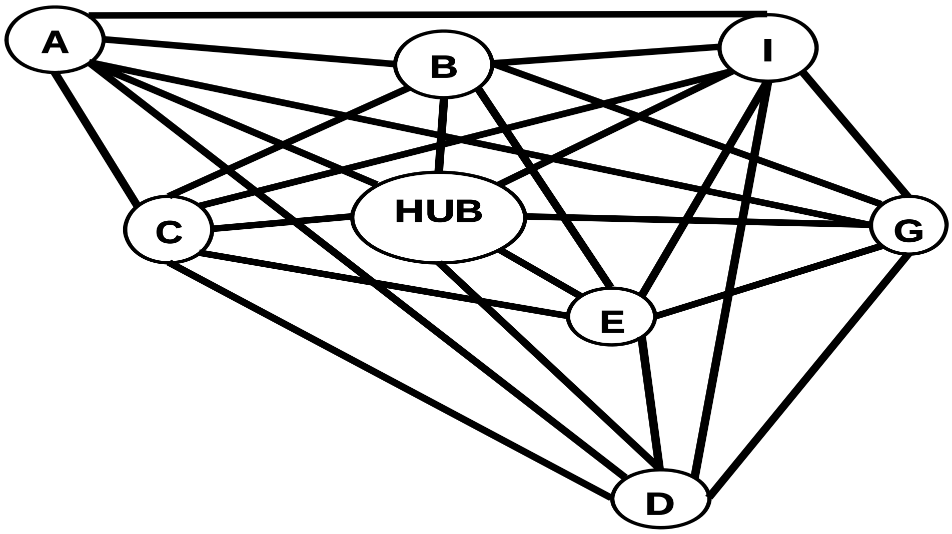


Figure 2.5 Point to point network

LCC's have higher risk when entering or targeting untested airports and routes. Airlines need to research what markets to target because high fare markets may be less price sensitive. Therefore, they need to tap in the regular business traveler market seeking lower fares in short-haul markets [Harbison and McDermott, 2009] (i.e. easyJet route from Gatwick airport (LGW) to AMS).

LCC's have a ticketless internet-based distribution, website and direct sales centers that lower sales costs avoiding agency charges. Normally they do not make alliances or interlining because it decreases the on-time performance and alliance costs [Harbison and McDermott, 2009]. Some LCC's have alliances with FSC's such as Deutsche BA (DI) was partner with British airways (BA) and JetBlue airways (B6) is allied with Lufthansa (LH).

The main aircraft operation strategies for a LCC are: minimize turnaround times, increase flying hours, maximize aircraft utilization (Figure 2.6) and increment the number of seats to the maximum possible. Table 2.1 explains the operation strategies for the LCC model. The variables that affect the LCC model are the number of flights, number of destinations, connections, frequency and number of routes. If an LCC is not big enough they will not be able to have a big network to compete against other LCC's or FSC's [Dobruszkes, 2006].

An operational strategy applied by some airlines such as Ryanair and EasyJet is the outsourcing of everything other than cabin crew, pilots, reservation agents, head office functions and to some extent maintenance [Carmona Benitez and Lodewijks, 2008a]. This strategy, allows airlines to have an aggressive expansion, advantage negotiation with airports and signing long-term contracts. It also reduces employee and infrastructure costs [Harbison and McDermott, 2009]. On the other hand, other LCC's, like Southwest Airlines, do not outsource looking for common labor interest, loyalty, and high quality service [Gillen and Lall, 2004].

Every LCC applies its own LCC model. Not all of them are the same, and not all LCC's are using the strategies mentioned in Table 2.1. The closest carrier to the original Southwest Airline model is Ryanair (Table 2.4). Some LCC strategies to get revenues are: advertising on seatback trays, food, jet ways, FFP (i.e. Southwest Airlines and Germanwings), refund, travel agents, print tickets, connections, head rests, car rentals, travel insurance, etc. [Carmona Benitez and Lodewijks, 2008a]. Figure 2.7 shows the average ancillary services charges by US airlines in May 2009. As can be noticed, ticket change, pet in the cabin, oversize bag and additional bag represent a big source of revenues for both LCCs and FSCs [Harbison and McDermott, 2009].

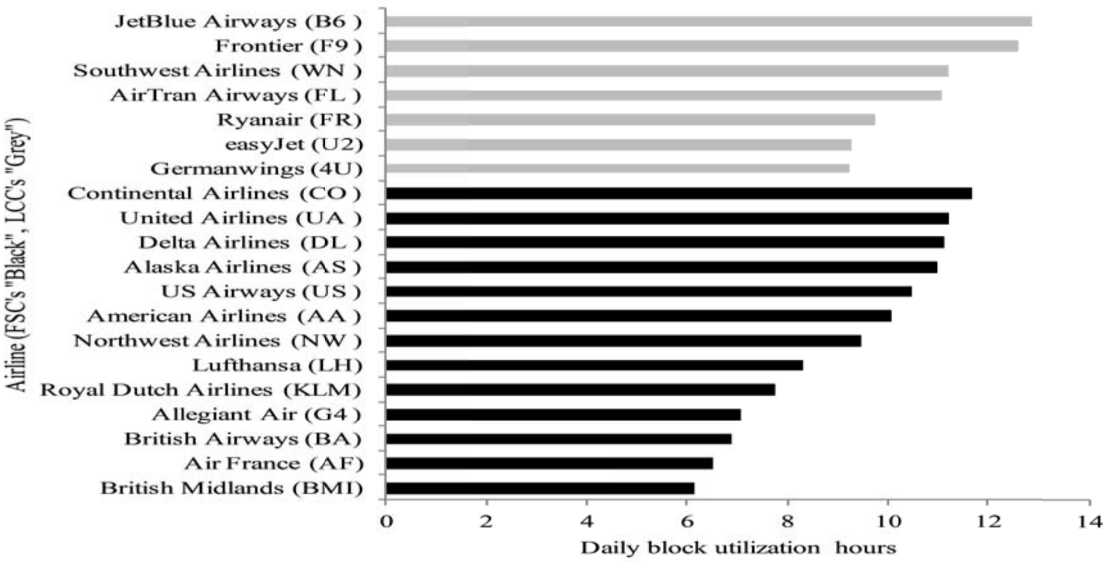


Figure 2.6 EU (short-haul aircraft) and US average daily block utilization [Ehmer, 2008] [MIT]

As it has been mentioned, all airlines have their own business model. Table 2.4 shows different strategies between three LCC's, WN, FR and U2. The main differences between LCC's are on the quality services and the network they operate. Burghouwt and De Wit [2005] classified the LCC business model into five types: lowest cost carriers (i.e. Southwest, Ryanair), new start-up low-cost carriers (i.e. easyJet), low-cost carriers instigated by tour-operators (i.e. Thomas Cook, Thomsonfly), from charter airline to low-cost carriers (i.e. Air Berlin, Transavia) and low-cost FSC parent companies (i.e. Go – British Airways, Jetstar – Qantas).

Table 2.4 The main differences between WN, FR and U2

LCC	*Southwest (WN)*	*Ryanair(FR)*	*EasyJet (U2)*
Single class	Yes	Yes	Yes
Secondary airports	Yes	Yes	Yes
Midsize airports	Yes	No	Yes
Congested Airports	Yes, i.e. LAS, LAX	No	Yes, i.e. AMS, LGW
Point to point	Facilitate connections by better schedules always performed by pax	Does not facilitate connections	Facilitate connections by better schedules always performed by pax
Focus	Min operation costs	Min operation costs	Max yields and profits
Network strategy	Connect as many airports as possible (72 destinations)	Rapid network expansion and not on frequency (161 destinations, 1,100 routes and 44 bases)	Focus in building network density providing service around int. airports (129 destinations and 20 bases)
Frequency	High (3,100 flights/day)	Normal	High
Code-sharing	Yes, Volaris (Y4)	No	No
Aircraft daily block utilization (2007 year)	11.19 hours	9.71 hours	9.24 hours
Fleet	B737 – (300, 500, 700)	B737-800	A319 and A320
Fleet Size (aircraft)	547 (+133 orders)	300 (+37 orders)	175 (+58 orders)
Seat density lay-out (max number of seats)	B737 – 300 and 700: 137 B737 – 500 : 122	189	A319: 156 A320: 183
Average load Factor	0.88	0.78	0.81
Turnaround	25 minutes or less	25 minutes or less	25 minutes or less
Employee compensations	Yes	Yes	Yes
Trade Unions	Yes	Not recognized by Ryanair	Yes (Luton airport)
Outsourcing employees	No	Yes	Yes
Fare	60% below FSC's or more	The cheapest possible	Fares increase as the demand does, not necessarily the lowest
Online, direct booking	Yes, no travel agencies	Yes, no travel agencies	Yes, no travel agencies
Check-in	Ticketless	Ticketless	Ticketless
FFP	Yes, start in March 2011	No	No
In-flight catering	Snacks and soft drinks free	No	No
Distance networks	Short and medium-hauls	Short and medium-hauls	Short and medium-hauls
Target market groups	Leisure and some business travellers	Leisure	High time and fare sensitive business pax and leisure

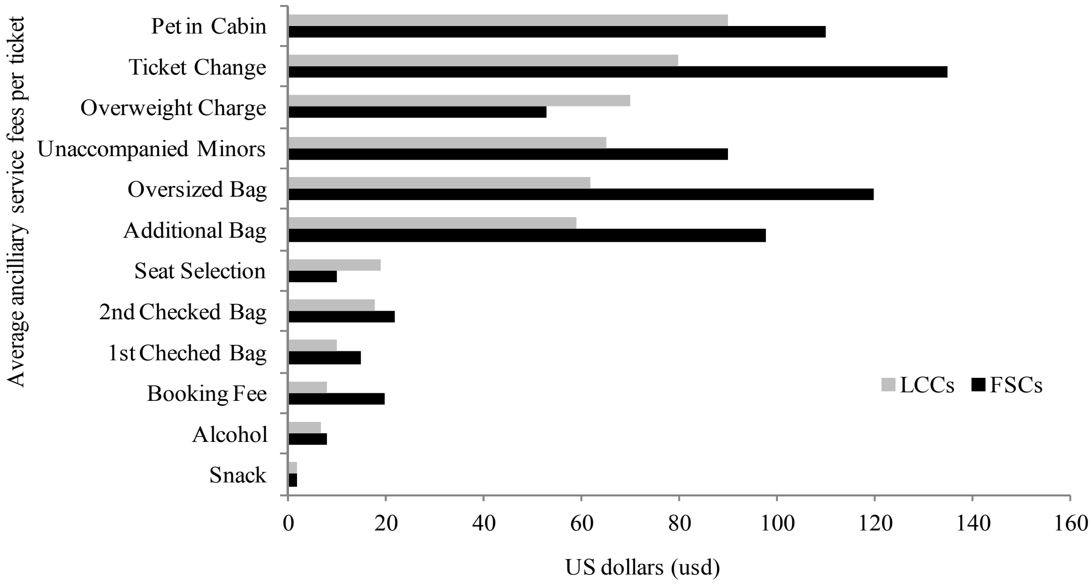


Figure 2.7 US Airlines average ancillary service charges, US Airlines, May 2009 [Harbison and McDermott, 2009]

2.4 Low-cost long-haul model

The Association of European Airlines (AEA) has determined that a long-haul flight last 6 hours or long [Humphreys et al, 2007] [Morrell, 2008]. Southwest and JetBlue show the possibility to operate transcontinental routes in the US of 4-6 hours flights using a Boeing 737 or Airbus A320 [Flint, 2003] [Humphreys et al, 2007]. The viability of operating any international route is subject to the conditions set out by the bilateral air services agreement and obtaining the necessary transit rights[8]. Bilateral provisions would normally include restrictions on the number of airlines allowed, routes to be operated, regarding capacities, frequencies, aircraft type and traffic quotas [Weber and Williams, 2001] [Wassenbergh, 1998]. However, the recent EU/US open skies agreement represents better entry possibilities for an LCC on transatlantic routes [Morrell, 2008] [IACA, 2007] [Reals,2010].

Comparing the FSC with the LCC businesses model characteristics (Table 2.1), it can be said that the LCC operation model is less compatible with long-haul than with short-haul operations. In a long-haul operation, the duration of the flight and the passenger minimum quality service requirements reduce the possibilities to minimize operation costs for long-haul carriers using LCC strategies. Furthermore, some short-haul strategies such as seat pitch size reduction are difficult to be applied in a long-haul operation. FSC's have lower seat per km costs (RPK's) or lower seat per mile costs (RPM's) in long-haul operations than LCC's in a short-haul operation. Hence, they already offer competitive long-haul fares. In flights of more than eight hours flights, catering service is required; in-flight entertainment is important, the number of toilets cannot be reduced as it can in short-haul operations and the amount of baggage to be handled is larger. Finally, a hub and spoke network system is crucial in long-haul flights [Humphreys et al, 2007] to connect different flights and increase the network. On the other hand, e-ticketing and e-marketing is already used by the long-haul FSC.

In the US, FSC's have complete control over the international routes. Even though, today some LCC's are operating new flights outside the US (i.e. AirTran (FL) and JetBlue (B6)).

8 Appendix A: The Freedoms of the Air [ICAO, 2011]

None of them is performing transatlantic operations to compete with FSC's in the long-haul markets (i.e. FL flights to Cancun and Aruba, B6 flights to Dominican Republic). In the international markets, FSC's have shown an increase in the number of passengers transported from 2000 to 2009 (Figure 2.8), but FSC's have lost in the domestic or short-haul market.

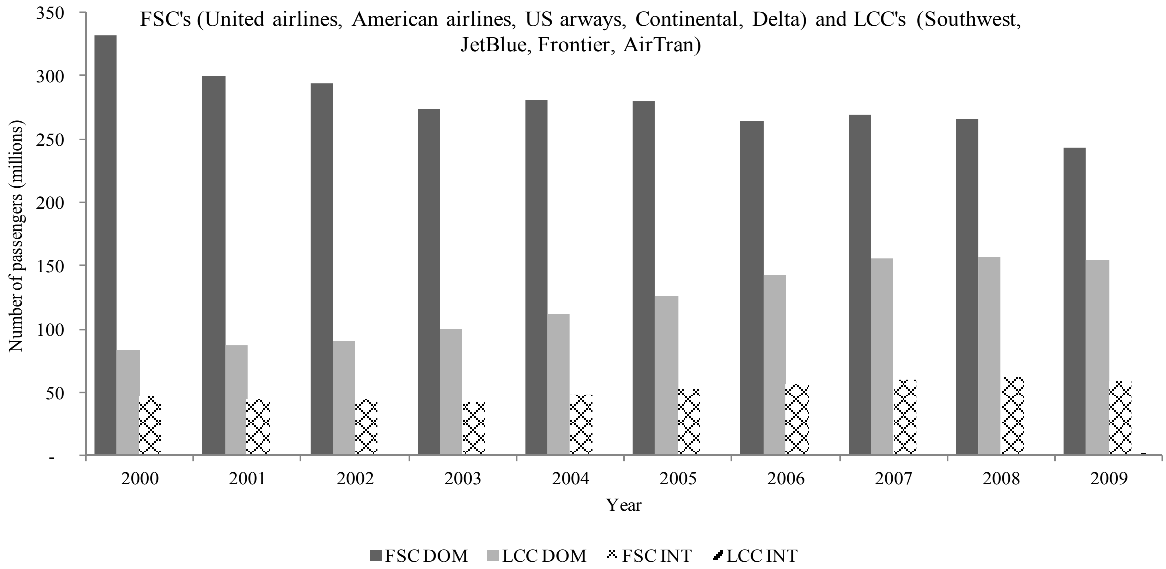


Figure 2.8 Number of passengers FSC and LCC US markets [RITA, 2000-2010]

The main problem for a long-haul low-cost model is that as a distance increases, the operating cost rises and unit costs decrease. According to Williams, Mason and Turner [2003], shorter routes offer more opportunities to achieve cost competitiveness over FSC's. Aspects that increase fares and costs in long-haul operations are: fuel, crew cost, maintenance cost, passenger service, over-flight, security requirements, airport facilities and turnaround times, route density and distribution challenges. To be successful a low-cost long-haul airline must find advantages in these factors and find markets where lower fares can be profitable. Some characteristics of these models are: strong local catchment areas, affluent leisure and VIP traffic, seasonal and economic balance, availability of peak-time slots and seven to twelve hours length [Wensveen, 2007]. Humphreys et al. [2007] have studied the level to which the low-cost model could be applied to long-haul operations. They concluded that a long-haul low-cost model could only achieve a 20% cost advantage over network carriers compared to 50% on short/medium-haul flights [Humphreys et al. 2007] [Morrell 2008].

Today, new airlines are applying new low-cost long-haul strategies [Humphreys et al, 2007] i.e. Norwegian. The new alliance between companies together with the new airline technologies could overcome the difficulties to develop a new low-cost long-haul business model. For example, the recent tie up of Virgin Australia (DJ) and Singapore Airlines (SQ). Opportunities could exist in developing long-haul in conjunction with solid short-haul networks [Hind, 2007]. One idea is that long-haul low-cost carriers should concentrate on niche markets with the possibility to connect with other markets [Wenseveen, 2007]. Nowadays, some LCC's with an excellent short-haul network have established a code-share partnership with FSC's long-haul operators such as GOL (G3) with AA and B6 with LH [Harbison and McDermott, 2009].

The interest of low-cost carriers to serve or connect long-haul pax is that foreign pax can represent 25% to 30% of domestic travelers [Harbison and McDermott, 2009]. In 2009 and

2010, the international US pax market served by foreign FSC’s was 40% from the total. This 40% represented 8.5% from the total US air passenger transportation market (767 millions). Long-haul carriers apparently have no doubts about connecting pax on quality short-haul LCC’s, since the alliances between FSC’s and LCC’s in long-haul operations are starting to occur (i.e. LH with B6). The main problems in allying LCC with FSC long-hauls are the electronic connectivity and pax and baggage handling. These challenges have prevented some LCC’s to code-share with FSC’s such as WestJet and Air France-KLM. To overcome this problem AirAsia X for example has left passengers to do it by themselves.

2.5 Charter Model

Charter airlines are also called holiday or leisure carriers because their main focus is on the tourism market. Tourism represents a big economic activity and generates a lot of jobs in some regions. Many economies in the world, such as the Caribbean and Mediterranean [Papatheodorou and Lei, 2006], depend on tourism and charter airlines make agreements with hotels and local governments for bringing tourists as a strategy.

Charter carriers have the lowest operating costs of all the models. In fact, charter airlines have lower cost than low-cost carriers and the highest load factor between the airlines business models [Williams, 2002] but at expenses of schedule and less opportunity to get ancillary revenues from luggage [Hind, 2007].

Charter airlines have small margins and their sizes are small compared with FSC’s and LCC’s (Table 2.1). Most of the time, these airlines sell their tickets in holiday packages by tourism agencies or websites. These agencies are responsible for selling all the available seats; they need to have a high load factor to have profits. For this reason, they normally have higher seat occupancy than LCC’s and FSC’s. These packages are usually booked in advance and include the hotel, transportation to the hotel and airports, different holiday activities, etc. Opposite to the FSC’s and LCC’s that charge premium prices for tickets purchased close to the departure dates, charter airlines drop fares as the departure day come closer because the airline needs to fill empty seats offering big discount fares (i.e. last minute offers at very low prices). Due to the necessity of high load factors a charter flight usually has more penalties than the LCC’s and FSC’s. They do not offer a refund on cancellations, but they overcome the disadvantages by allowing people to transfer their ticket to another person charging a small penalty.

Charter airlines operate some routes by schedule and seasonal services [Ehmer, 2008]. Their network routing system focuses on point to point flights. They normally use a mix fleet of medium and large aircraft. Some charter carriers rent an aircraft to fly a specific route on a determined day. Some of them have moved into the scheduled business (i.e. Monarch (ZB)) [Dennis, 2007].

Charter airlines operate few numbers of different aircraft depending on the short-haul (Airbus 320 with 180 seats, B757-200 with 235 seats, and A321 with 220) or long-haul (B757-300). For example, the Monarch (BZ) fleet consists on: A300-600R, A320-200, A321-200, A330-200, B757-200 and it placed an order for six B787-8’s [Williams, 2002].

The majority of charter carriers are owned by tour companies, which incorporate tour operators, travel agencies, airlines, and sometimes hotels and ground transportation companies (Thomas Cook, Monarch, Thomsonfly) [Williams, 2002]. These carriers are more focused to get revenues from leisure business and sometimes they can have losses in their flight operations, but they overcome this with the profits they get from the tourism activities. Some charter airlines rent available seats to other carriers when an aircraft is not full.

2.6 Discussion

This chapter discussed the different airline business models and strategies, advantages and disadvantages as a step to identify the main parameters that airlines use to provide air transport services. In general, four generic passenger business models are commonly recognized: FSC's, LCC's, charter airlines and regional airlines. In reality, each airline has its own business model.

The air fare is the most important parameter or variable. Airlines can use it to get into a market, and increase passenger flow. It also allows people, which would not have traveled with higher fares, to travel often through low fares. This is based on the fact that LCC's pax flow increased, and FSC's pax flow decreased, in short-haul routes during last year's. In long-haul, FSC's pax flow increased, but the percentage of increase per year decreased. LCC's are starting to get into the long-haul markets. So far, the impact has not been as significant as it is in short-hauls. The main problem for a long-haul low-cost model is the distance, as distance increases, operating cost rises and unit costs decreased. FSC's fares are competitive in that case.

Table 2.1 showed the airline business models operation characteristics. From Table 2.1 and the sections 2.1 to 2.5, it is possible to determine other parameters that airlines must consider in a model or methodology that determines what routes to operate. The main parameters are:

- Target market.
- Network structure.
- Size and power of the route network: total demand. The total demand is not the total number of passengers flying on a route; it is the total number of passengers flying and the non served number of passengers.
- Optimum number of passengers to attend: minimum number of passenger or market share per route to be competitive against other airlines serving same origin and destination connections. In case of opening a new route, it is the optimum number of non served passengers to serve.
- Aircraft utilization: aircraft must be flying the maximum possible time to minimize aircraft cost per seat km (CASK) or aircraft cost per seat mile (CASM) and increase revenue per seat km (RASK) or revenues per seat mile (RASM).
- Aircraft physical characteristics: airlines need to consider what aircraft types can be used to flight each route of its network because not all aircraft have the capacity to fly all routes.
- Size of the fleet.
- Aircraft route load factor: optimum number of passengers to transport per flight.
- Seat Capacity: optimum number of aircraft seats that minimize operation costs and maximize revenues.
- Frequency: optimum number of flights to minimize operation cost and maximizes revenues, profits and NPV.
- Airport capacities: Airports represent a very important constraint because airlines need to negotiate with them how many slots per day airlines can have. It constrains the number of frequencies on routes. Airports need to have the capacity to receive big aircraft and high number of pax flow at their terminals. Airports also represent a time

constraint since congested airports require aircraft to stay more time on the ground what constraint the maximum aircraft utilization and the number of frequencies.

- Quick turnaround times, waiting times in the air and on the grounds are important in the short-haul market because they constrain the total number of frequencies that can be operated by one aircraft, increasing the number of aircraft and the total investment.

3 Airline and aircraft operation costs calculation models

In the past with a non-competition scenario, the need for FSC's to minimize operating cost was not urgent. The raise of operating cost was paid by the passengers. Nowadays, as it has been explained in Chapter 2, airlines no matter their business model have been forced to put attention to the minimization of the airline operating costs to enable low fares and be more competitive. Today airlines business models differ greatly in pricing strategy and cost structure.

In an extremely competitive industry, the estimation of the average airlines operating costs, airport charges and fares between two different cities/airports are very important for airlines to make the decision whether or not to enter or exit routes. Normally, airlines forecast their operating costs and fares using time series data together with econometric models by extrapolating observed patterns of growth into the future [Carmona Benitez and Lodewijks, 2010c]. These statistical methods are useless when airlines consider opening new routes because data of those routes is not available. In that case, the statistical model's parameters can be estimated using real data and then calculate airlines operating costs or fares of the new route based on a similar route under the assumption that the new route will behave alike to other routes with similar characteristics. Developing an airline operating cost mathematical model will allow studying the consequences of the competition between airlines that have different business models and to calculate the airlines operating costs for new routes. Similar, the development of an aircraft operating cost mathematical model will allow calculating route operating cost for different aircraft types.

Database

Each year, the US Department of Transportation Office (DOT) of Aviation Analysis releases a domestic airlines fares consumer report that includes information of approximately 18,000 routes operated by all airlines inside the United States. The reports include non-directional passenger number, revenue, nonstop and track mileage broken down by competitor. Only carriers with more than 10 percent market share on each route are listed [DOT US consumer report, 2005-2008]. This database uses miles (mi) as a unit of distance, the distance data has been transformed to km (1mi=1.609km). Appendix B contains the name and code of the airline that provided data to the DOT US consumer report [2005-2008].

This research studies the data from 2005 to 2008 because the data available during the development of the project was from 2005 to 2008. This database was selected because the information release is very useful to assist in answering the main research question and the four sub questions because it is available for the general public free of charge.

The DOT US consumer report [2005-2008] does not contain fares regarding different service classes and booking information, making it difficult to develop models that consider different fares for the same route. For example, aircraft type, number of seats, frequencies and operating costs per airline per route are also not available. It makes difficult to assess the influence of important parameters that might have a big impact on airline operating costs and fares that could be captured in the regression models, and reduce the data dispersion created by different fares charged by different airlines on similar distance routes. Other empirical data was used from US Bureau of Economic Analysis, US Bureau of Transport Statistics, Research and Innovative Technology Administration (RITA), AviationDB, seatguru.com, inflationdata.com and aircraft manuals from Boeing, Airbus and Embraer [Airbus, Boeing and Embraer manuals] to mitigate these problems. Although the main database used and studied in this thesis has valuable information that allowed answering the main research question and the four sub-questions, it is important to keep these limitations in mind.

The aim of this chapter is to propose a mathematical model that calculates airline operating costs per route per passenger and a mathematical equation that calculates aircraft operating costs per route per aircraft type. In Section 3.1, the airlines operating cost are presented based on econometric and engineering approaches. An airline operating cost model (AOC) and a mathematical equation (AGE) are developed in Section 3.2. The aircraft operation cost equation will form part of the optimization model that will be proposed in Chapter 6. The model maximizes an airline network net present value selecting those routes that represent an opportunity to open new services. In Section 3.3, the mathematical equation (AGE) is compared versus the Breguet Range equation. In Section 3.4, an analysis of the main consequences of the competition between different airline business models FSC vs. LCC is presented by using the AOC model. Finally, a discussion on the different airline operating costs models is presented in Section 3.5 as a conclusion to this chapter.

3.1 Airline and aircraft operation costs

A number of studies documenting airline operating costs and airfare pricing can be found in the literature on air transport management and economics.

Three main approaches for airline cost calculation can be distinguished [Betancor et al, 2005]:

1. *The econometric approach* using statistical methods such as multi-regression analysis to find dependent variables that are highly correlated with an independent variable. The independent variable is determined by two components: a systematic component captured by the multi-regression equation and a random component that is unknown represented as the error term. The error component is part of the model that does not explain or capture the independent variable response.
2. *The engineering approach* tries to define the cost function based on engineering relationships, and relate independent variables to the dependent cost variable by adding a cost value to each variable trying to calculate the right cost. The advantage is that the total costs can be added to complex models for optimization purpose.

3. *The cost allocation approach* takes fixed and variable elements into account and allocates them to the right output. This approach needs to allocate the operating costs into different output measures such as aircraft related costs (i.e. maintenance and repairs), time related costs (i.e. crew and catering staffs) and distances related costs (i.e. fuel, oil, tyres). Airlines costs can also be divided into non-operating costs and operating costs. Non-operating costs are also known as non-operating expenses. These kinds of expenses are related to interest such as charges for borrowing money, profit/losses from currency exchange, government subsidies and profit/losses from assets retirement. On the other hand, operating costs (AOC) are those related to the operation of the airline and can be classified into direct operating costs (DOC) and indirect operating costs (IOC). DOC costs are those that can be allocated to the aircraft operating costs whilst IOC costs are those that are normally caused by running the airline's business (Figure 3.1). Since the purpose of this chapter is to propose a mathematical model that calculates airline and aircraft operating costs rather than calculate cost allocated into different output groups, this method is not considered.

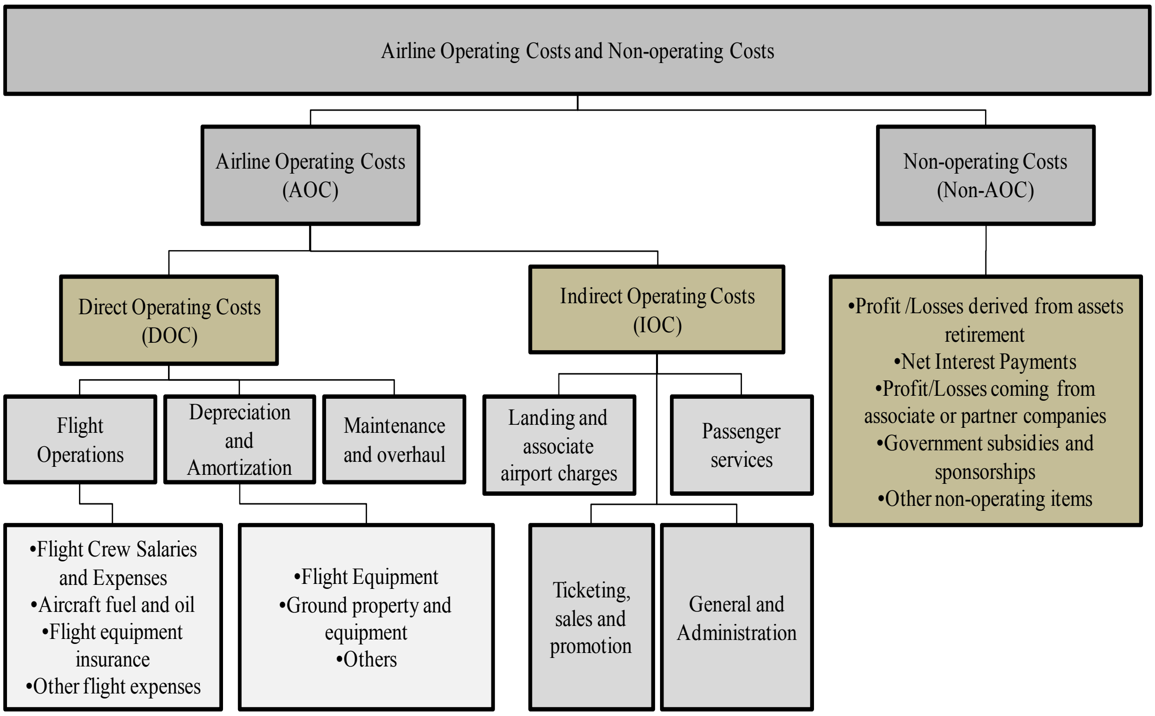


Figure 3.1 Airline Operating Costs (AOC) and non-operating Costs (Non-AOC)

When talking about costs it is important to distinguish between the unit and marginal cost. Unit cost is calculated by the total cost per flight divided by the number of seats offered on the flight. It can also be calculated as the total airline costs divided by the total number of seats offered by the airline in its whole network.

3.1.1 Econometric Approach

In literature different mathematical models are presented using different parameters mainly developed to estimate airlines fares rather than airline operation costs. Caves, Christensen and Tretheway [1984], Oum and Yu [1998], and Gillen, Oum and Tretheway [1997] studied the competitive cost between international airlines using a Cobb Douglas production function (Equation 3.1). A Cobb Douglass production function is meanly used in economics. It explains or assesses the relationship between input and output of production parameters. The production output is determined by the amount of labor involved, the amount of capital and energy used. The transcendental logarithmic function, better known as translog function, is the generalization of the Cobb Douglass cost function. The purpose of the translog cost function is to identify a specific functional form for a cost function that represents all of the assumptions and results of the minimization cost model. For example, the translog cost function has been used to study transportation processes as an output, such as airline passenger-km served, affected by inputs, such as capital, labor and energy. Equation 3.1 gives the general form of T:

$$T = g(K, L, E) = A_0\, K^{\beta_0}\, L^{\alpha_0}\, E^{\gamma_0} \qquad (3.1)$$

Where:

T	= transportation output such as passenger per km	[i.e. pax/km]
K	= capital such as monetary worth of all machinery, building and equipment	[i.e. usd]
L	= labor such as total number of person hours worked in a year	[i.e. hours]
E	= energy such as total amount of energy used in a year	[i.e. watts]
α_0, β_0, γ_0	= outputs elasticity coefficients of capital, labor and energy respectively.	[-]
A_0	= constant value	[-]

According to Zellner, Kmenta and Dreze [1966] the Cobb Douglas production function coefficients can be estimated by the least square method (OLS) providing reliable estimators of the function parameters or coefficients α_0, β_0, γ_0.

Caves, Christensen and Tretheway [1984] research purpose was to analyze the competition consequences between small and large airlines in a non regulated scenario. The main point was to investigate whether small carriers have a disadvantage against large airlines because of economy of the scales. In this case, economy of scales explains that a large airline company will have cost advantages against a smaller carrier because the average cost per passenger km is lower. To achieve their goals, they used a Cobb Douglas cost function. They separated the output variable into various output variables which are main airline characteristics such as average route distance, route load factor and average seating capacity that can be exogenously determined. Their model also included the number of nodes served, a firm effect coefficient, input prices, labor, fuel, materials and dummy variables also known as indirect variables that are qualitative data manipulated to be quantitative data. The results of their model show that if there exist sustainable prices that can cover the cost, a so-called welfare optimum relation between fares and costs can be found without regulation. It means that airfares in low density routes are higher.

Gillen, Oum and Tretheway [1990] also used a Cobb Douglas cost function with the objective to assess the effects of specific regulatory and government ownership policies. They also used their model to compare the US and the Canadian markets finding that even though the regulatory and environmental conditions are different between both countries their markets were actually similar. They concluded that smaller airlines have higher unit costs than larger carriers. They also concluded that a small carrier should not have any cost disadvantage because they will achieve passenger flow density within its small network in similar way to a larger carrier with a bigger network.

Oum and Yu [1998] modified the Gillen, Oum and Tretheway [1990] function. They multiply the weight load factor by the capital stock and add different parameters to the Cobb Douglas function such as the revenue shares of freight and mail, non-scheduled services, and an efficiency index. By estimating the multi-regression coefficients the model calculates that labor, fuel and material account for 32%, 15% and 53% of the variable cost respectively. At the same time, distance length and load factor show negative coefficients meaning that variable costs decrease when routes are longer and with higher occupation.

Contrary to Caves, Christensen and Tretheway [1984], Oum and Yu [1998], and Gillen, Oum and Tretheway [1997], Swan [2002] and Swan and Adler [2006] developed models from an engineering point of view instead of an econometric approach.

3.1.2 Engineering approach

Swan [2002] studied the hypothesis that the airline industry is carrying more passenger traffic on their networks when operating larger capacity aircraft, by increasing the number of frequencies on their routes rather than opening new route services. To accept or reject this hypothesis, Swan [2002] compared the marginal cost of seats on a connection flight to the average cost of seats on a direct flight. To do so, he developed a simple planar cost form function model that calculated route costs depending on route distance range and aircraft numbers of seats taking into account the cost for a ground connection and the average cost per seat for the same trip flying direct:

$$AOC_{u_r} = (D_r + O_0) \times (S_x + O_1) \times O_2 \qquad (3.2)$$

Where:

AOC_u	= Aircraft operation cost per pax	[usd/pax]
D_r	= distance or range	[km]
r	= route link	[-]
S_x	= aircraft number of seats	[seats]
x	= aircraft type	[-]
O_0	= constant distance	[km]
O_1	= constant number of seats	[seats]
O_2	= model cost coefficient	[usd/km/seat]

Swan [2002] used the model to compare the costs of connections considering only the cost of using larger airplanes to carry the demand to the cost of a direct flight including the full cost of the additional small airplane. Contrary to the hypothesis, they found that the airline industry growth has been accompanied by using small aircraft sizes. They explained five reasons why the air passenger transport system has growth by increasing frequencies and not aircraft size:

1. Deregulation of the airline markets increased competition and number of routes, some of these routes with little pax flow. Opening new routes is as strong as increasing frequencies on existing routes because adding more markets minimize airline costs by increasing aircraft utilization and pax flow.
2. Aircraft size reduces operating costs with larger aircraft until a certain number of seats have been reached. Then, it becomes less important.
3. Airports are being connected to a high number of destinations operating small aircraft, rather than connecting with a small number of airports operating large aircraft.
4. Markets that needed over 227 seats are cheaper to operate with direct flights than with connection. It demands more frequencies or flights between origin and destination airports and reduce pax flow per route.
5. Airlines provide a high number of flights per day with small aircraft because passengers have become wealthy demanding high number of frequencies. Then, aircraft load factors and profits decreases if airlines increase the average number of seats.

Airport congestion is the factor that can be the reason for demand large aircraft sizes. It is because airports have limited capacity. However, Swan [2002] found that airplane size has declined slightly at larger airports. In reality, there is a mix between aircraft sizes. Congestion has been reduced by serving more direct flights rather than connecting through a hub.

Swan [2002] final result was that the airline industry has moved to direct flights, more frequent, more connections and thus more expensive industry rather than using larger aircraft sizes to transport more pax flow per flight connecting them at a hub airport to increase aircraft load factors as much as possible. Swan [2002] results are highly related to this research because the purpose of this thesis is to assess the feasibility of the air passenger transport industry to select routes that represent an opportunity for opening new services, and design an airline network.

Swan and Adler [2006] used Swan's [2002] model to analyze a different database. This model was used to do disaggregate aircraft operating costs into various cost categories to provide conditions from an engineering point of view and develop a generalized aircraft trip cost function. Their model enabled a direct analysis of the operating cost function without the problems associated with financial reporting practices. They compared Equation 3.2 to a Cobb-Douglas function (Equation 3.3) to evaluate econometric results, based on historical data. The model can be calibrated for either km or mi. Table 3.1 shows their model coefficient values for different haul markets:

$$AOC_{u_r} = g(D_r, S) = A_1 \, D_r^{\alpha_1} \, S^{\beta_1} \qquad (3.3)$$

Where:

A_1 = constant value [usd/km/seat]

α_1, β_1 = coefficients [-]

Table 3.1 Swan and Adler [2006] Cobb Douglas cost function model coefficient values

	A_1	α_1	β_1
Short-haul	2.44	-0.40	-0.25
Long-haul	0.64	-0.35	-0.09

Equation 3.3 shows that aircraft operating costs, aircraft seats and route range have a relation that can be expressed as a translog cost function.

From literature review, it can be concluded that apparently the Swan and Adler [2006] translog cost function (Equation 3.3) can be used to calculate airline operation costs. Although, Equation 3.3 is proven for different aircraft types at short and long-hauls, in Chapter 2, it has been shown that all airlines apply different strategies to minimize operating costs. Each airline has a different number of seats and a variety of aircraft types serving different routes. For these reasons, the coefficient values used in Equation 3.3 (Table 3.1) cannot be used as a general formula, unless it is validated. This leads to the questions: Can Equation 3.3 be used as a model that calculates airline operation costs? If yes, how accurate is Equation 3.3 when calculating airline operation costs at different routes?

3.2 Models design and variables

As it has been explained in Section 3.1, there is a need to calculate airline operating costs to design and analyze an airline route network. In this section, two models will be developed to calculate airline operating costs. The first model is based on a translog cost function that calculates airlines route operating costs (AOC model) per pax per distance by calculating an airline operation cost factor. This model was described earlier in Carmona Benitez and Lodewijks [2010c]. The AOC model can be compared with Equation 3.3. The results reveal whether or not Equation 3.3 can actually calculate the airline operation costs.

It is also necessary to study the aircraft performance payload versus range cruise chart for each aircraft [Airbus, Boeing and Embraer manuals] to evaluate whether different aircraft having the same number of seats have equal operating costs. It is unlikely that two different aircraft will have the same operating cost at similar route distances as it is calculated by using Equation 3.3. For this reason, a second model developed to estimate airlines operating costs by calculating jets fuel consumptions (AGE model). The AGE model is an equation that calculates aircraft operating costs by calculating the fuel consumption based on aircraft characteristics, capacities and constraints.

3.2.1 Airline operation cost model (AOC)

Equation 3.3 suggests that airline operating costs are equal for airlines operating aircraft with same number of seats. This suggest that the competition between airlines operating similar routes would only depend on fares, and strategies to minimize operating costs do no matter, what it is not true according with Chapter 2. This makes important to validate if Equation 3.3 can calculate airlines operating cost for different airlines just by using route distance and aircraft seats as parameters.

Regression analyses have been done on the 2005, 2006, 2007 and 2008 year data [DOT US Department of Transportation, 2005-2008] to evaluate and develop a mathematical model that calculates airline route operating costs per airline using real airline operating costs data. The results are compared with Equation 3.3 calculations. The results will conclude if Equation 3.3 can calculate airline operating costs by distance and aircraft number of seats.

In order to allow comparison of the operating cost per airline, Equation 3.3 must be modified. Realizing that all aircraft of an airline have an average number of seats, and all airlines have an average cost factor, Equation 3.3 is modified to Equation 3.4.

$$AOC_{u_{r,a}} = A_2 D_r^{\alpha_2} f_a^{\beta_{2a}} \qquad (3.4)$$

Where:

f	= costs factors per route per passenger per km range	[usd/km/pax]
A_2	= constant value	[-]
α_2, β_2	= coefficients	[-]
a	= airline	[-]

Equation 3.4 proposes a translog cost function model (AOC model) very similar to Swan and Adler [2006] (Equation 3.3). Equation 3.4 calculates airline operating costs per route based on the route distance, and an airline operating cost factor (f_a) per airline. The cost factor can be estimated by the OLS method [Spiegel, 2000]. It can also be calculated using real airline operating cost data [AviationDB] if it is available.

Equation 3.4 calculations using f_a values estimated by OLS method are validated by correlation analysis with Equation 3.4 calculations using real operating cost data [AviationDB]. Despite the value of the parameter f_a can be calibrated or calculated from real data, Equation 3.4 still being exactly the same equation. The OLS method may calibrate the parameters of Equation 3.4 with different values, but Equation 3.4 calculations are expected to be equal, and the correlation between calculations is expected to be always 1 ($R^2 = 1$). The correlation between the calculations using f_a values estimated by OLS method, and the calculations using real f_a values [AviationDB] validate Equation 3.4 calculations using f_a values estimated by OLS method. Since Equation 3.3 and Equation 3.4 are similar translog cost function models, the OLS method may calibrate the parameters of both equations with different values, but the determination of the coefficients of Equation 3.3 and Equation 3.4 is equal, and the correlation between their calculations is expected to be 1 (R^2 = 1) (Figure 3.2). Thus, the correlation between equations validates Equations 3.3.

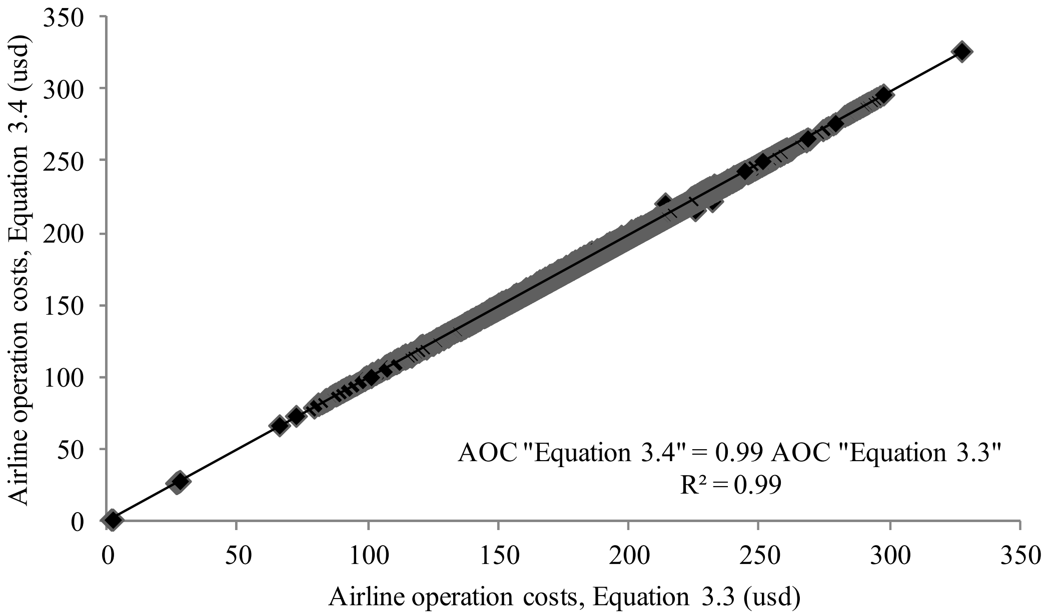


Figure 3.2 AOC model VS Cobb-Douglas [Swan, 2006] model

Table 3.2 shows the model coefficient values for both, the AOC model (Equation 3.4) and Equation 3.3 calibrated for distances in km for 2005 year. Table Appendix D. 1 shows the model coefficient values for the AOC model using real f values from AviationDB.

Table 3.2 AOC and Equation 3.3 models coefficient values for the US domestic market

Model	*Equation 3.4*		*Equation 3.3*		*Model*	*Equation 3.4*		*Equation 3.3*	
Coefficients	A_2	α_2	A_1	α_1	Coefficients	A_2	α_2	A_1	α_1
Values	37.25	0.20	37.13	0.20	Values	37.25	0.20	37.13	0.20
Airline code	f	β_{2a}	S	β_{2a}	Airline code	f	β_{2a}	Seats	β_{2a}
AA	11.62	0.02	171	0.01	FL	2.34	-0.19	125	-0.03
AS	10.22	0.04	149	0.02	PN	2.20	1.28	132	0.50
CO	6.53	0.07	161	0.03	XP	2.09	-6.29	150	-0.93
DH	5.98	-0.11	132	-0.04	QX	1.84	0.65	61	0.11
WN	5.07	-0.21	137	-0.07	U5	1.58	-3.46	168	-0.35
YX	4.73	0.05	102	0.02	AQ	1.54	0.28	120	0.03
HA	4.30	0.24	132	0.07	SY	1.54	0.03	164	0.00
B6	3.46	-0.21	138	-0.06	E9	1.33	0.84	45	0.06
NW	3.80	0.07	175	0.02	TZ	1.23	-2.96	132	-0.13
DL	3.30	0.05	175	0.02	CX	1.10	0.73	132	0.50
YV	3.15	1.73	63	0.50	UA	1.06	1.78	181	0.02
OO	2.92	-4.25	54	-1.05	NK	1.02	0.21	148	0.00
F9	2.67	-0.12	134	-0.02	G4	1.00	0.19	148	0.00
HP	2.35	0.09	132	0.02	US	0.98	2.10	149	-0.01

The coefficients of Equation 3.4 have been estimated by OLS method by minimizing the sum of square percentage error (SSE%) (Equation 3.5) between real fares and airlines operating costs calculated by Equation 3.4.

$$SSE\% = \sum_{r=1}^{R}\left(\frac{AOCu_{r,a} - AOCrealu_{r,a}}{AOCrealu_{r,a}}\right)^2 \quad (3.5)$$

Where:

R = Total number of routes in the study [-]

Another option is to minimize the sum of square error (SSE) (Equation 3.6) rather than the SSE%. Slightly better results have been achieved by the minimization of the SSE%.

$$SSE = \sum_{r=1}^{R}\left(AOCu_{r,a} - AOCrealu_{r,a}\right)^2 \quad (3.6)$$

The main difference between Equation 3.3 and Equation 3.4 is that Equation 3.3 uses the number of seats as input variable, whilst Equation 3.4 estimates the airline cost factor f_a. The average numbers of seats per airline have been calculated (Table Appendix C. 1, Table Appendix C. 2, Table Appendix C. 3 and Table Appendix C. 4) [RITA, 2005] to compare both models. The AOC model does not need to know the real values of the parameters f_a or S_a to calculate airline operating costs. This is presented in Chapter 3.2. The AOC model allows studying how airlines operating cost change when airlines costs increase or decrease; it is the main advantage over Equation 3.3. Finally, the AOC model cannot analyze operating costs according with the number of aircraft seats. This is the main disadvantage over Equation 3.3.

Equation 3.4 can be used to analyze what happen when airlines operating costs increase or decrease only if real airlines operating cost factors (f_a) are known. Equation 3.4 cannot be used to analyze what happen when airlines operating costs increase or decrease if the value of the parameter f_a is calibrated by OLS method. In this case, Equation 3.4 can only calculate airlines operating costs on an airline route.

The AOC model (Equation 3.4) can also be modified to calculate airline operating costs by a cost allocation approach. For example, the airline operating costs can be allocated into direct operating costs (DOC) and indirect operating costs (IOC). Equation 3.7 shows that Equation 3.4 can be modified to calculate DOC and IOC costs per pax km. Table Appendix D. 8 shows Equation 3.7 coefficient values.

$$AOC_{u_{ra}} = A_2\, D_r^{\alpha_2}\left(f_{DOCa}^{\beta_{2DOCa}} + f_{IOCa}^{\beta_{2IOCa}}\right) = A\, D_r^{\alpha_2} f_{DOCa}^{\beta_{2DOCa}} + A\, D_r^{\alpha_2} f_{IOCa}^{\beta_{2IOCa}} \quad (3.7)$$

Where:

f_{DOCa} = DOC airlines operating costs factors per route per pax per km [AviationDB] [usd/km/pax]

f_{IOCa} = IOC airlines operating costs factors per route per pax per km [AviationDB] [usd/km/pax]

$\beta_{2\,DOCa}$ = direct operating costs coefficients [-]

$\beta_{2\,IOCa}$ = indirect operating costs coefficients [-]

In the same way, each type of airline operating costs can be calculated by modifying Equation 3.4, i.e. Equation 3.8. This is not a cost allocation approach because Equation 3.8 calculates each specific airline operating cost. The total airline operating cost is equal to the sum of all different operating costs. Equation 3.9 calculates a specific airline operating costs. Each f_{OCFa} can be calculated by OLS method or using real data [AviationDB]. Table Appendix D. 9 shows Equation 3.9 operating costs calculations. Table Appendix D. 10 shows Equation 3.8 coefficient values.

$$OCF_{r,a} = A_2 \, D_r^{\alpha_2} f_{OCF,a}^{\beta_{2OCF,a}} \quad (3.8)$$

Where:

$$f_{OCF,a} = \frac{\sum_{OCF=1}^{OCF} OCF_a}{TMF_a} \quad (3.9)$$

$F_{OCF,a}$ = Airlines operating costs factors OCF per route per pax per km [AviationDB] [usd/km/pax]
OCF = airline operation costs type OCF, OCF can be any cost in Figure 3.1 [usd/pax]
TMF = Total airline km flown during one day [AviationDB] [usd/km]

Equation 3.8 allows analyzing how airlines operating costs change when a specific cost factor increase or decrease. It helps estimating and studying changes in a particular operating costs.

The main conclusion is that a generalized form of the Cobb-Douglass function tailored for a specific purpose works really well.

3.2.2 Aircraft operating cost model (POC)

After studying different aircraft performance payload versus range cruise chart for each aircraft it can be concluded that Airbus, Boeing and Embraer aircraft operating costs are not equal [Airbus, Boeing and Embraer manuals] (Appendix E). For example, an A321 and a B737-700 with exactly the same number of seats do not have the same jet fuel consumption cost, that of course also depends on the engine installed, at 4,630km (2,877mi = 2,500nm) flight distance (Figure 3.3).

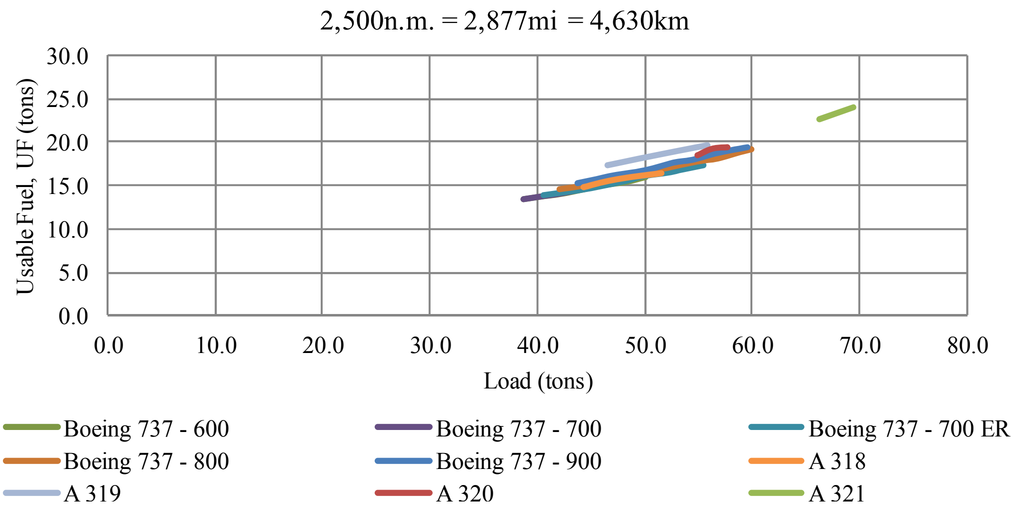


Figure 3.3 Aircraft payload vs. jet fuel consumption volume at 4,630km

Table 3.3 Jet fuel cost percentage from the total operating costs and average jet fuel price [UA Annual Report, 2009]

Year	*Jet fuel costs percentage in respect to the total operating costs (%)*	*Average Jet Fuel Price (JFP) (usd per litter)*
2005	26.7	0.47
2006	29.4	0.54
2007	30.0	0.58
2008	38.5	0.86
2009	26.3	0.52

Aircraft operating costs cannot be calculated using Equation 3.3 because it does not take the aircraft specifics into account. Airlines operating cost factors calculated using average airlines operating costs (Equation 3.7 and Equation 3.8) do not recognize different aircraft operating costs and load capacities. They calculate airline operation costs no matter the aircraft type because they are based on the average number of seats of all planes of an airline. This means that, with these equations, it is not possible to optimize in terms of selecting the best aircraft for a specific route.

Fuel consumption strongly influences airline operating costs and fares. It is the main parameter determining aircraft and airline operating costs. From 2005 to 2008, this factor represented more than 24% from the total US domestic airline cost market. Figure 3.4 confirms that aircraft fuel represent the major part of airlines operating costs by comparing the total US domestic airlines costs, Southwest airlines (WN) and American Airlines (AA) in 2005. Both airlines, representing different business models, LCC and FSC respectively, expended more in jet fuel than any other cost. United Airlines (UA) spent around 26% (Table 3.3) similar to AA and WN. All airlines together spent an average of 24% during 2005.

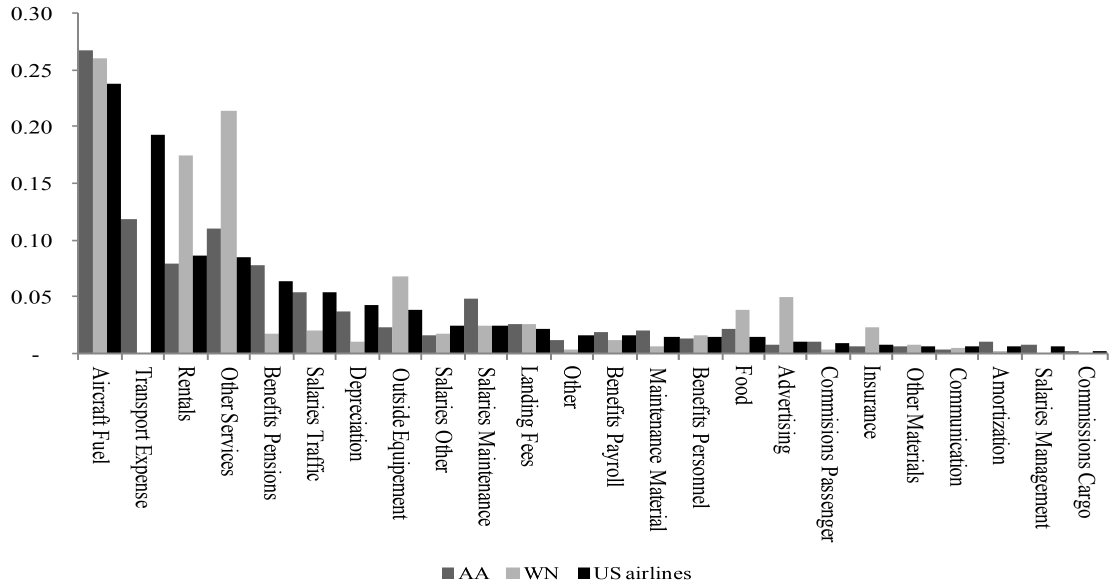


Figure 3.4 Total US domestic airlines costs, Southwest Airlines (WN) and American Airlines (AA) costs 2005 [AviationDB]

The fuel consumption of an aircraft can be calculated based on the analyses of aircraft payload-range diagrams found in their manuals [Airbus, Boeing, Embraer manuals]. For example, Figure 3.5 shows a B737-800 aircraft, arranged with two general electric engines (CFM56-7), fuel consumption chart. The maximum range of an aircraft varies depending on the payload it carriers. For example, the B787-800 (CFMI CFM56-7 engines) maximum range with zero payload and maximum fuel capacity is 5,500nm[9] (10,186km or 6,329.4mi). The maximum range carrying 62.8 tons of loads is 2,000nm (3,704km or 2,301.6mi) (Figure 3.5). The minimum flying distance depends on the difference between the take-off weight and landing weight and the engines specific fuel consumption (SFC). Therefore, in this thesis the aircraft generic fuel consumption equation (AGE) (Equation 3.10) has been used based on the technology-cost relationship between two main parameters that determine aircraft jet fuel consumption: load and range. Appendix E shows different aircraft payload vs. jet fuel consumption analyses at different ranges developed based on each aircraft payload vs. range cruise (i.e. Figure 3.5) [Airbus, Boeing and Embraer manuals]. Figure 3.3 is part of the analyses.

[9] 1nm = 1.8520km = 1.1508mi

$$UF_{x,r} = (B_0 + B_1 D_r)\, Load_{x,r} + (C_0 + C_1 D_r + C_2 D_r^2) \quad (3.10)$$

Where:

UF_r	= Usable fuel or quantity of fuel needed for aircraft propulsion to fly D_r, it represents the aircraft jet fuel volume consumption to fly a route with distance D_r	[tons]
$Load_x$	= aircraft load	[tons]
x	= Aircraft type x	[-]
r	= route from airport origin ORI to airport DES	[-]
B_0	= constant value	[-]
B_1	= constant values	[km^{-1}]
C_0	= constant value	[tons]
C_1, C_2	= constant values	[tons/km]

The coefficient values of Equation 3.10 have been determined by the OLS method using the payload vs. jet fuel consumption analyses per each Airbus, Boeing and Embraer aircraft at different ranges (Appendix E).

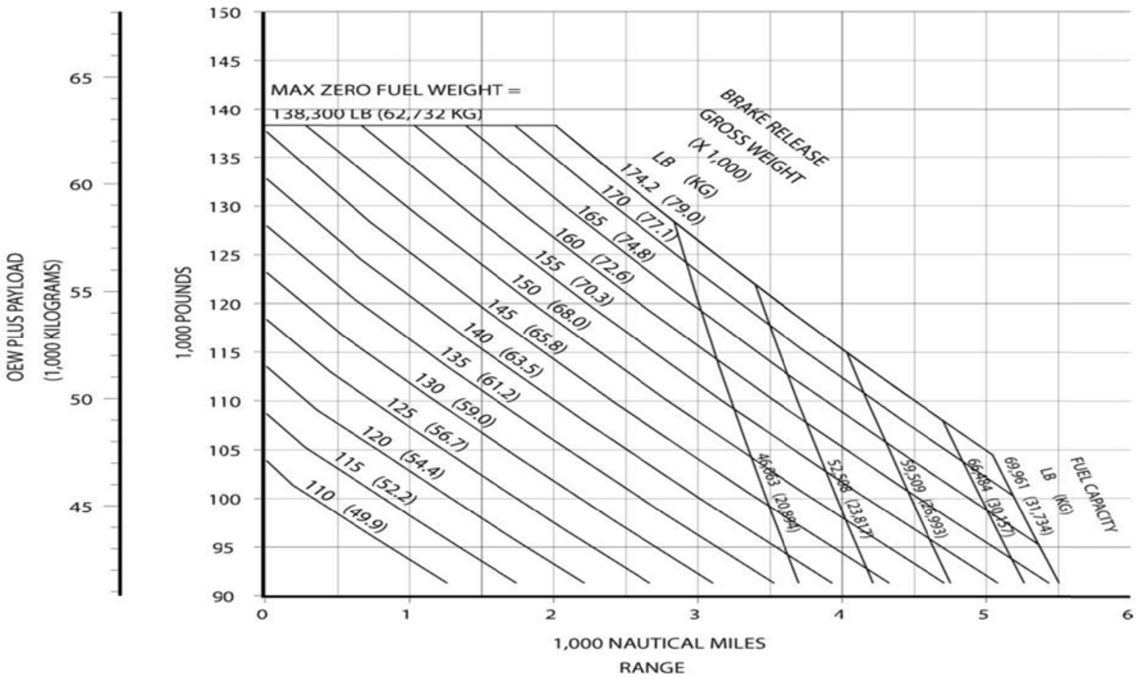


Figure 3.5 Airplane performance payloads vs. range cruise chart [B737 manual, 2005]

In our example, a B737-800 aircraft arranged with two engines CFM56-7 will consume almost the same amount of fuel on routes with similar ranges with some differences caused by climate conditions such as wind flows and temperature. The fuel consumption parameter is a useful measure that can be directly related to the aircraft operating costs. An aircraft route operating cost can be estimated by multiplying the AGE model (Equation 3.10) with the jet fuel average price (JFP), and divided by the jet fuel cost of the AOC percentage (%JFC). Thus, the aircraft operating cost model (POC) (Equation 3.11) calculates aircraft costs per flight based on aircraft jet fuel consumption per flight distance at current jet fuel price.

$$AOC_{x,r} = \frac{[(B_0+B_1D_r)\, Load_{x,r} + (C_0+C_1D_r+C_2D_r^2)] \times JFP_t}{\%JFC_t} \quad (3.11)$$

Where:

JFP	= Jet fuel price	[usd/l]
%JFC	= Jet fuel cost percentage of total AOC	[-]
r	= route from airport ORI to destination DES	[-]
t	= time in years, months, day	[-]

Aircraft jet fuel consumption data have been deducted from the payload-range diagrams. The coefficient values of Equation 3.10 are determined using the jet fuel consumption data. The data is expressed in terms of the relationship between load and jet fuel volume. The coefficient values of Equation 3.10 are determined by minimizing the SSE% between jets fuel consumption data and the AGE model calculations. Figure 3.3 shows an example of a jets fuel volumes vs. loads chart at 2,500nm (4,630km or 2,877mi) range.

The AGE model (Equation 3.10) overall goodness-of-fit analyses (Table 3.4) indicate that Equation 3.10 is highly accurate in calculating the total jet fuel volume needed to fly a certain route link by a certain aircraft. The results between the aircraft total jet fuel volume calculated by the AGE model and the jet fuel consumption data are correlated over 99% for all Boeing, Airbus and Embraer aircraft (Table 3.4 and Figure 3.6).

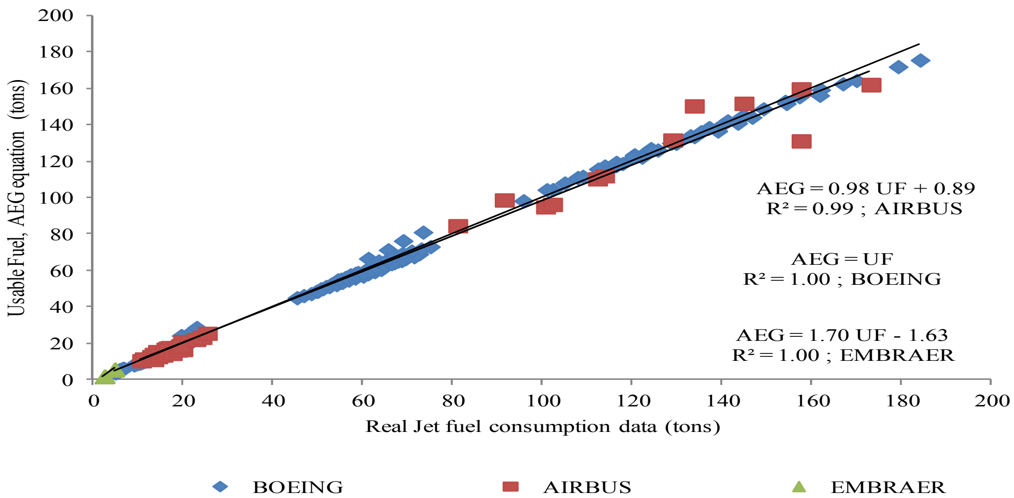


Figure 3.6 Jet fuel consumption modeling results with AGE equation

Table 3.4 AGE equation coefficients values and correlation results

	B_0	B_1	C_0	C_1	C_2	*Total data points*	*SSE%*	R^2
Boeing	8.00E-02	3.28E-05	-6.50E-01	7.94E-04	8.69E-08	305	0.57	1.00
Airbus	2.70E-01	3.10E-05	-3.57	-1.60E-05	4.43E-08	50	0.29	0.99
Embraer	2.49E-02	2.99E-05	9.89E-01	4.74E-04	9.64E-08	37	0.02	1.00

The SSE% results mean that the overall results lay in between [-17%, 14%] range for Airbus aircraft, [-11%, 20%] for Boeing aircraft and [-5%, 5%] Embraer aircraft (Figure 3.7). In the case of Boeing aircraft, from a total of 305 data points, 90% of the calculations have less than ±5% SSE% meaning very little dispersion whilst for the case of Embraer, from a total of 37 data points, 100% of the calculations have less than ±4% SSE%. More dispersion has been found for Airbus aircraft where just 38% of the calculations have less than ±5% SSE% (Figure 3.7).

Figure 3.6 and Figure 3.7 confirm that the AGE model is more accurate for Boeing and Embraer than Airbus. Airbus data points are more disperse than Boeing and Embraer points. This is because Boeing has a higher number of data points under study than Airbus and Embraer adding a high number of SSE%. Boeing payload-range diagrams are more detail than Airbus payload-range diagrams. Therefore, Equation 3.10 coefficient values are more precise for Boeing than for Airbus aircraft. As an example, Table 3.5, Figure 3.8 and Figure 3.9 compare the AGE model calculations for two medium sizes (B737-800 and A321) and one large aircraft sizes (B777-200LR) with the aircraft payload range diagrams [Boeing and Airbus manuals] at different loads.

Table 3.5 Fuel consumption modeling with AGE equation model

Aircraft	*Data points*	*% inside ±10%*	*% inside ±5%*	*R*	*R^2*	*SSE*	*SSE%*
B737-800	103	86	100	1.00	0.99	70.64	0.21
A321	52	58	77	1.00	1.00	274.90	1.44
B777-200LR	102	97	99	1.00	1.00	2,403.80	0.69

The fuel consumption calculations with the AGE equation model are correlated over 99% for all the examples shown by Table 3.5. The SSE% results indicate that 86%, 58%, 19% and 97% calculations lay into ±10% SSE% range, and 100%, 77%, 89% and 99% lay into ±20% SSE% range for B737-800, A321, and B777-200LR respectively.

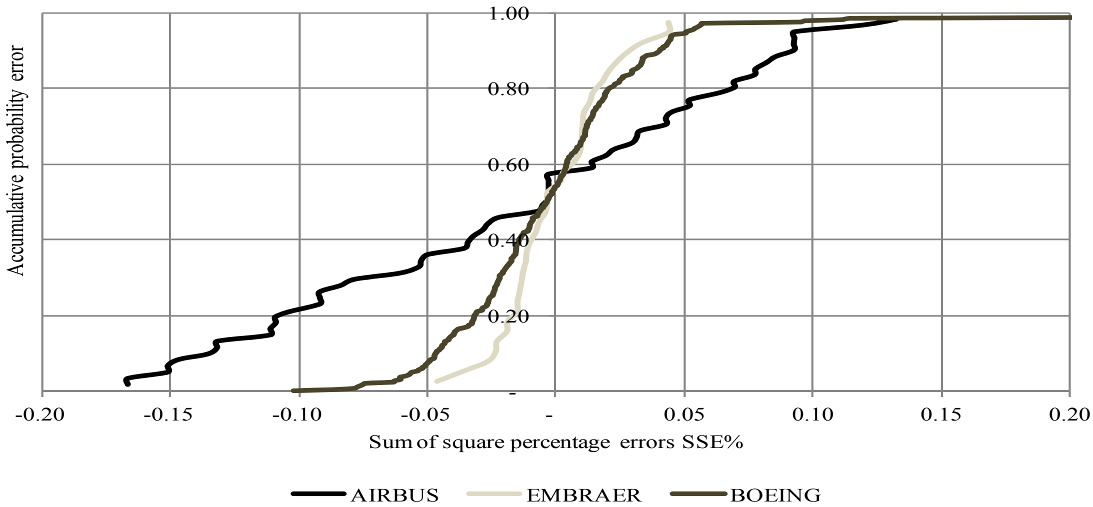


Figure 3.7 Jet fuel consumption SSE% distributions, AGE equation

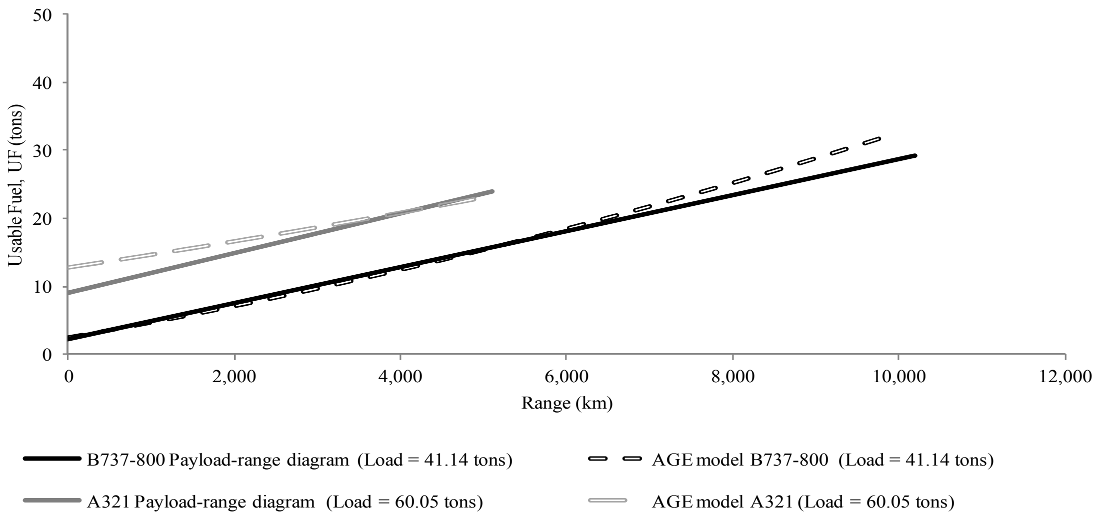


Figure 3.8 Fuel consumption modeling with AGE equation model (B737-800 and A321)

The AGE equation can be used as a general equation to calculate jet fuel consumption for any aircraft size per aircraft manufacturer (Figure 3.10). It just needs to be recalibrated for Airbus if more detail payload-range diagrams are available.

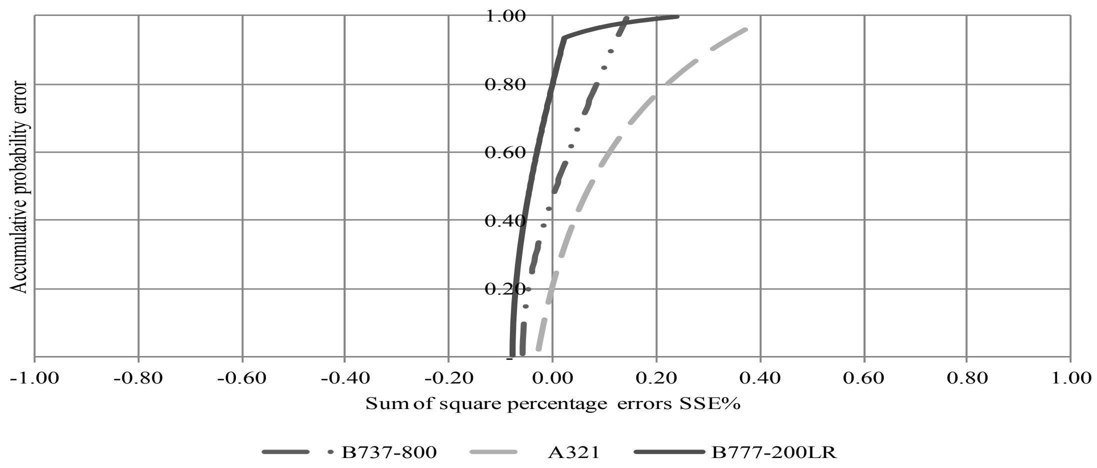


Figure 3.9 Fuel consumption modeling SSE% with AGE equation model (B737-800, A321, and B777-200LR)

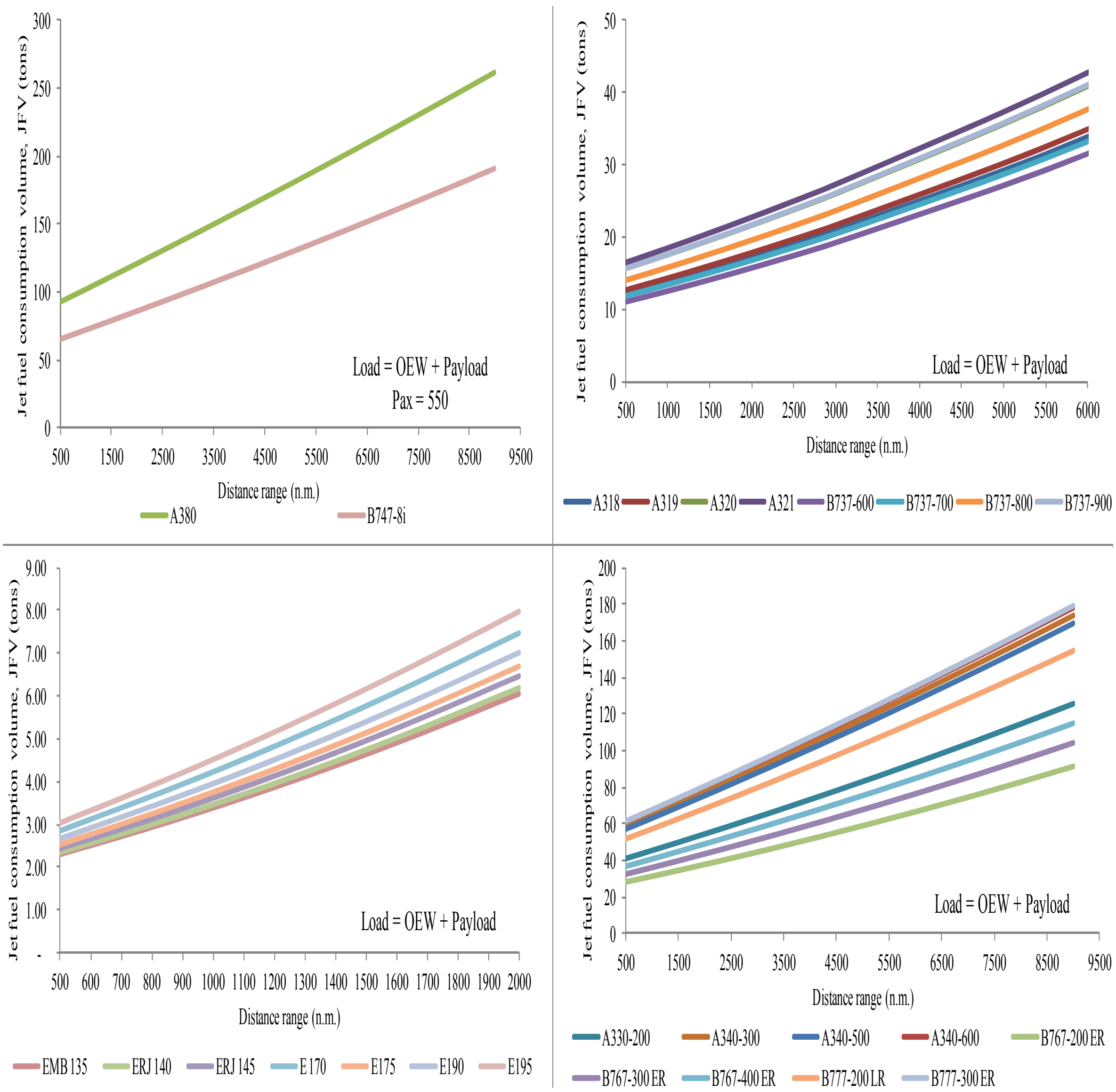


Figure 3.10 Fuel consumption modeling with AGE equation model, all aircraft

3.3 AGE equation model VS Breguet Range equation model

The AGE model allows an accurate calculation of aircraft fuel consumption, and it has been calibrated for three major aircraft manufacturers (Airbus, Boeing and Airbus). Its main disadvantage is that it does not capture all efficiencies that influence an aircraft fuel consumption affecting aircraft operating costs, such as structural weight, aerodynamics and engines specific fuel consumption, per flight. If a specific aircraft type needs to be analyzed in more detail, the Breguet range equitation (BRE) (Equation 3.12) is useful in describing the mechanics of any aircraft in flight [Lee, 1998].

$$\mathrm{Range_r} = \left(\frac{\mathrm{V_{C,x}} \times \left(\frac{\mathrm{Lift_x}}{\mathrm{Drag_x}}\right)}{\mathrm{g} \times \mathrm{SFC_e}}\right) \ln\left(\frac{\mathrm{W_{TO,x,r}}}{\mathrm{W_{DES,x,r}}}\right) \quad (3.12)$$

Where:

$$\mathrm{A_3} = \left(\frac{\mathrm{V_{C,x}} \left(\frac{\mathrm{Lift_x}}{\mathrm{Drag_x}}\right)}{\mathrm{g\ SFC_e}}\right) \quad (3.13)$$

Range	= possible aircraft flying distance	[km]
e	= engine type	[-]
Lift	= aircraft lift force	[N]
Drag	= aircraft drag force	[N]
$V_{C,x}$	= cruise velocity	[km/hr]
g	= gravitational constant	[km/hr^2]
SFC	= engine specific fuel consumption	[g/kN/sec]

and

$$\mathrm{W_{TO\ x,r,t}} = \mathrm{Load_{x,r,t}} + \mathrm{UFe_{x,r,t}} \quad (3.14a)$$

$$\mathrm{W_{DES,x,r,t}} = \mathrm{W_{TO,x,r,t}} - \mathrm{UF_{x,r}} \quad (3.14b)$$

Where:

W	= Aircraft weight before takeoff (TO) or landing (DES)	[tons]
OEW	= Aircraft operation empty weight	[tons]
$UF_{x,r}$	= jet fuel volume to fly a route distance D_r	[tones]
$UFe_{x,r}$	= jet fuel volume to fly a route link distance to closest emergency airport	[tones]

The final total aircraft load is equal to the OEW plus the payload:

$$\mathrm{Load_x} = \mathrm{Payload_x} + \mathrm{OEW_x} \quad (3.14c)$$

$$\mathrm{Payload_{x,r,t}} = \mathrm{S_x}\left(\frac{\mathrm{WPax+NBags\ WBags}}{1000}\right)\mathrm{LF_{x,r,t}} + \mathrm{Cargo_{x,r,t}} \quad (3.14d)$$

Where:

Payload	= Aircraft payload before landing	[tons]
WPax	= 89 kg per pax [Peeters, Middel and Hoolhorst, 2005]	[kgs]
NBags	= Total number of bags available per pax (LCC's = 1, FSC's = 2)	[-]
WBags	= 21 kg per bag	[-]
LF	= Pax load factor	[-]

The engine specific fuel consumption is defined by the mass fuel flow divided by the engine thrust force (ETF):

$$\mathrm{SFC} = \frac{\mathrm{m_f}}{\mathrm{ETF_e}} \quad (3.15)$$

Where:

m_f	= mass fuel flow	[g/sec]
ETF_e	= engines thrust force	[N]

Equation 3.16 calculates the lift/drag force ratio [Filippone, 2000] as a function of the aircraft velocity in Mach. Equation 3.17 calculates the lift/drag ratio as a function of aircraft engine

thrust required for steady level and the aircraft angle of attack [Phillips, 2004]. It is the angle between the aircraft body reference line and the oncoming flow:

$$\frac{Lift_x}{Drag_x} = 4(1 + \frac{3}{M_x}) \quad (3.16)$$

Where:

M_x = Mach number for aircraft type x [-]

$$\frac{Lift_x}{Drag_x} = \frac{ETF_{STL} \cos \alpha_{AT}}{(W_x\, g) - ETF_{STL} \sin \alpha_{AT}} \quad (3.17)$$

Where:

W_α = aircraft average weight [tones]
ETF_{STL} = Engine Thrust for steady level (STL) [N]
g = gravitational acceleration [m/s^2]
α_{AT} = Aircraft angle of attack [-]

Equation 3.12 takes into account propulsion, aerodynamics and structural characteristics. It considers three main parameters: engines specific fuel consumption (SFC), lift-to-drag ratio (Lift/Drag) and structural weights (W). The Breguet range equation has been used to study aircraft CO_2 emissions and aircraft energy usage in terms on fuel burn or energy per available seat km (ASK). According to Lee [1998] and Lee et al. [2001] the model can also be modified for different purposes. For example, capacity utilization analysis by inclusion of the load factor (LF) or fraction of aircraft seats filled, and aircraft performance or aircraft operating costs. Lee [1998] used the Breguet range equation to study the relationship between aircraft performance and costs. His aim was to study aircraft emissions. Thus, the fuel consumption of an aircraft can be estimated using the AGE model (Equation 3.10) or by the Breguet model (Equation 3.12).

The aircraft fuel consumption parameters denote the amount of fuel consumed to move a certain amount of payload over a certain distance. Thus, the initial weight is equal to the OEW (operating empty weight) plus the maximum payload capacity (number of passengers, passenger's bag and cargo) and the required amount of fuel to fly from origin to destination. The final weight is equal to the initial weight minus the fuel burned up during the flight.

Re writing Equation 3.12:

$$D_r = A_3 \ln\left(\frac{UF_{x,r}+Load_{x,r}}{Load_{x,r}}\right) = A_3 \ln\left(1 + \frac{UF_{x,r}}{Load_{x,r}}\right) = \left(\frac{V_{C,x}\left(\frac{Lift_x}{Drag_x}\right)}{g\, SFC_e}\right) \ln\left(1 + \frac{UF_{x,r}}{Load_{x,r}}\right) \quad (3.18)$$

$$UF_{x,r} = \left(e^{\frac{D_r}{A_3}} - 1\right) \times Load_{x,r} \quad (3.19)$$

Knowing that:

$$e^d = 1 + \frac{D_r}{1!} + \frac{{D_r}^2}{2!} + \frac{{D_r}^3}{3!} \quad (3.20)$$

$$UF_{x,r} = \left(\frac{D_r}{A_3} + \frac{1}{2}\left(\frac{D_r}{A_3}\right)^2 + \frac{1}{6}\left(\frac{D_r}{A_3}\right)^3\right) Load_{x,r} \quad (3.21)$$

Equation 3.19 can be simplified to:

$$UF_{x,r} = \left((A_3)^{-1} D_r + \frac{1}{2}(A_3)^{-2} D_r^2 + \frac{1}{6}(A_3)^{-3} D_r^3\right) Load_{x,r} \quad (3.22)$$

According to Waitz [2003] the BRE model is quite accurate for routes longer than 1,500km. In shorter flights, the acceleration/climbing and deceleration/descending phase should be taken into account. The Breguet model equation can be modified into a multi-regression model (BMR) with a constant fraction B_3 (Equation 3.23). It takes into account climbing and descending.

$$UF_{x,r} = (B_3 + (A_3)^{-1} D_r + 0.5(A_3)^{-2} D_r^2 + (1/6)(A_3)^{-2} D_r^3) Load_{x,r} \quad (3.23)$$

The aircraft fuel volume for a specific route range can be determined for a steady state cruise. Equation 3.23 needs to be calibrated for each aircraft-engine configuration using the aircraft jet fuel consumption and payload data available at each specific aircraft manual [Airbus, Boeing and Embraer manuals]. Since the BRE model only applies for constant fly velocities (v), lift-to-drag ratio and SFC, these assumptions are only valid during cruise flights [Waitz, 2003]. The SFC value changes according to the range and payload. Thus, each aircraft flight has a different SFC. If Equation 3.12 or Equation 3.22 are used to calculate the fuel consumption at different distances without calculating the SFC per flight, the calculations are not accurate. If instead of using the Breguet equation model (Equation 3.12 or Equation 3.22) the BMR is used (Equation 3.23), the model can calculate jet fuel consumptions without the necessity of knowing the SFC highly accurate by calibrating the coefficient values $A_{3,est.}$ and B_3 (Table 3.6) by OLS method using the payload vs. jet fuel consumption analyses per each Airbus, Boeing and Embraer aircraft per engine type at different ranges.

Table 3.6 show BRE and BMR models coefficient values. Because larger size Airbus aircraft payload range diagrams just show the maximum range at the higher possible load and the maximum range without payload, it is not impossible to calibrate the BMR coefficients, A_3 and B_3, model for different ranges carrying the same load.

Table 3.6 BRE and BME models coefficient values

Aircraft	*Engine*[10]	*Load (Thrust)*	*ETF (KN)*	*V (km/hr)*	*Lift / Drag*	*m_f (kg/s)*	*SFC (g/kN/s)*	*A_3 (Eq.3.12)*	*$A_{3,\ est.}$ (Eq.3.23)*	*B_3*
B737-800	CFM56-7	41.14	121.44	838	19.29	359.25	15.08	30,345	18,582	0.06
A321	V2500-A5	60.05	120.00	860	18.63	389.20	14.37	31,582	24,743	0.16
A321	CFM56-5B	60.05	148.00	860	18.63	439.08	15.71	28,889	----	----
A340-600	RRTRENT 500	176.36	249.00	907	17.95	860.46	14.14	32,608	----	----
A380	RRTRENT 900	276.80	311.00	960	17.48	1,204.29	13.06	36,399	----	----

Table 3.7 Fuel consumption modeling with BRE model and BMR model

Model	*Aircraft*	*Data points*	*% inside ±10%*	*% inside ±5%*	*R*	*R^2*	*SSE*	*SSE%*
BRE	B737-800	103	0	0	1.00	1.00	2,969	21.18
BRE	A321	52	0	0	1.00	1.00	5,575	6.50
BMR	B737-800	103	100	76	1.00	1.00	34.02	0.14
BMR	A321	52	100	88	1.00	1.00	24.14	0.04
BMR	B747-8i	119	98	53	1.00	1.00	4,297	0.33

Table 3.7 and Figure 3.11 show the SSE, SSE% and correlation analyses comparing the BRE, BMR and AGE models. The SFC values have been calculated using Equation 3.13, Equation 3.14, Equation 3.15, and Equation 3.16 or Equation 3.17. The SFC values have been compared with the engines performance values [GE Aviation] [Rolls-Royce] [Pratt-Whitney] to make sure they coincide. After calculating the SFC coefficient value, the results show that the BRE is not accurate to model aircraft jet fuel consumptions because it does not consider

[10] [GE Aviation] [Rolls-Royce] [Pratt-Whitney]

claiming and descending. A constant value B_3 must be added to the BRE model. The best model, to calculate aircraft jet fuel consumption per distance range is the BMR model.

All the BRE model calculations are outside ±10% SSE% range. Contrary all the BMR model calculations are inside ±10% SSE% range. The percentage of calculations inside ±5% SSE% is 86% and 88% for the B737-800 and A321 respectively.

The results confirm that the BRE needs to consider a B_3 constant value to calculate aircraft fuel consumption. The results also validate the BMR model and confirm that the BMR model allows finding the coefficient values that better approximate the jet fuel calculations to the pay-load range diagram without the necessity of calculate each parameter for different distance ranges.

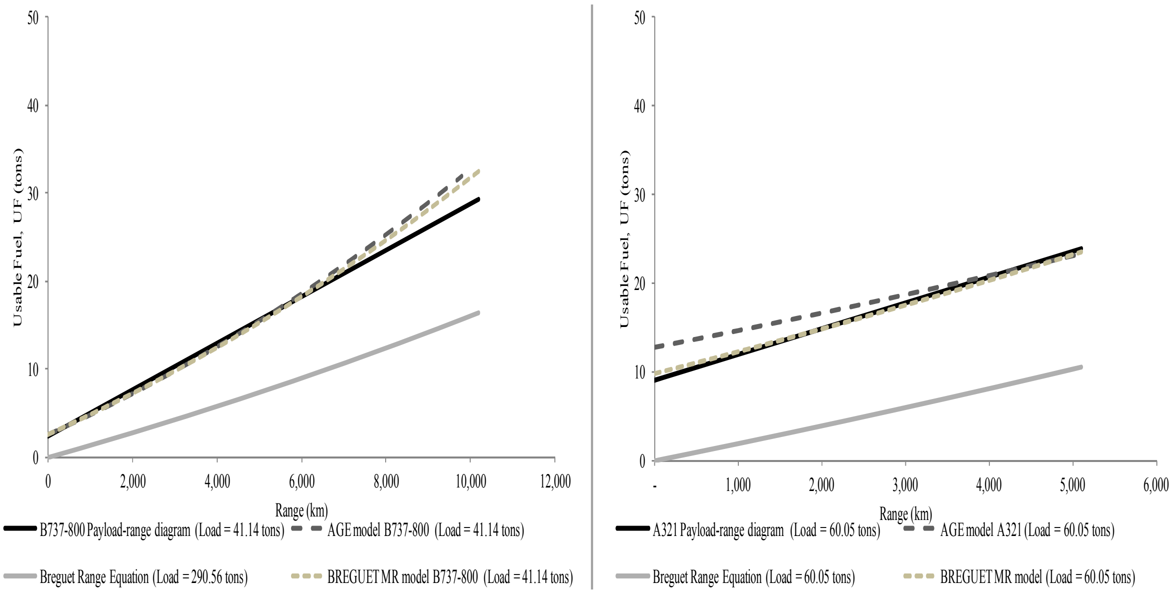


Figure 3.11 Fuel consumption models comparison

The BMR model takes into account structural, aerodynamics and engine efficiencies [Peeters, Middel and Hoolhorst, 2005]. That is the main advantage of the BMR model (Equation 3.23) over the AGE model. The BMR model has to be calibrated for each aircraft configuration. It cannot be used as a general model. This is its major disadvantage compared to the AGE model. The AGE model is only a function of load and distance, different OEW efficiencies per aircraft type can only be explained with differences in OEW. Aircraft with low OEW per passenger have a high structural efficiency and thus perform better. Other characteristics are captured in the model parameter values such as aerodynamic and engine efficiencies, which in the Equation 3.10 do not change with aircraft type. This is probably because engine, aerodynamics, structural efficiencies and aircraft cruising speed, all have similar magnitude and are related to the aircraft manufacturer designs. Because the AGE model does not need to be calibrated per aircraft type and engines, the AGE equation is the preferred model to calculate jets fuel consumption. However, if a specific aircraft type needs to be analyzed the BMR models represent a better approach.

3.4 Analyses of the low-cost and full service carriers air transportation system using the AOC model

The aim of this section is to analyze the main consequences of the competition between different airlines business models (FSC vs. LCC) from an operating cost point of view. This analysis is based on Carmona Benitez and Lodewijks [2010a]. Appendix D shows the AOC model coefficient values for all different competition analysis presented in this section.

Figure 3.12 shows a comparison between airlines operating costs estimated using the AOC model (Equation 3.4) at 1.609km (1mi) and 9,654km (6,000mi) distance. The results indicate that LCC operating costs can be higher than FSCs. Horizon Air (QX), Hawaiian Airlines (HA) and Boston-Maine Airways (E9) are the most expensive low-cost carriers with an operation cost over FSC's.

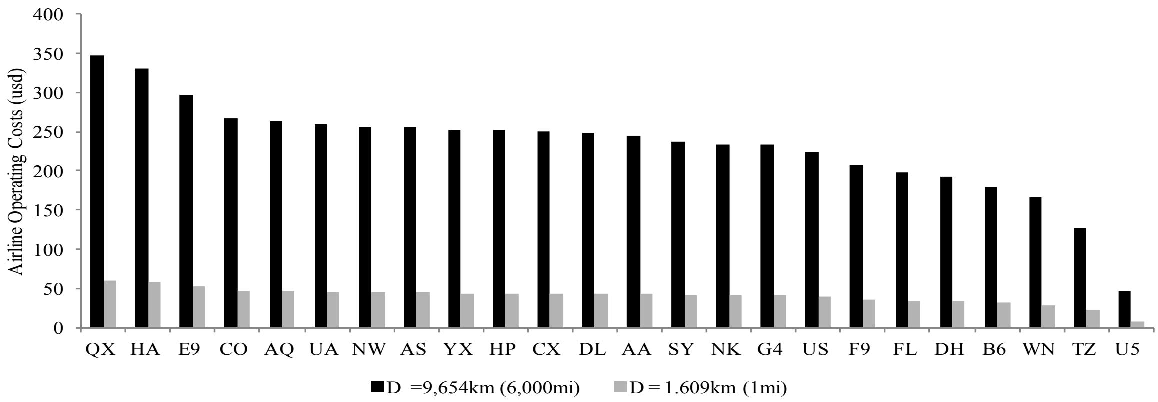


Figure 3.12 2005 Operating costs calculated with AOC model at 1.609km and 9,654km

The correlation between operating costs estimated using the AOC model (Equation 3.4) and real fares from the US Domestic Airline Fares Consumer Report database 2005 are shown in Table 3.8 and Figure 3.13. The values of R^2 present the relation between airlines operating costs and airline fares per route. These correlations show how much of airlines routes fares are determined by airlines operating costs. Table 3.9 shows the correlation constant values A_2, α_2, and β_2's for the LCC and the FSC markets respectively. The number of routes with losses, profits and profits over 20% the airline operating costs are also shown in Table 3.8.

Table 3.8 Business models correlation results with AOC model, 2005

Year 2005	*Complete market data*	*FSC market data*	*LCC market data*
R	0.58	0.58	0.87
R^2	0.34	0.40	0.76
Total routes	17,583	15,521	2,062
Routes with losts	39%	39%	40%
Routes with profits	61%	61%	60%
Routes with profits over 20% AOC	26%	27%	20%

Equation 3.4 estimates a correlation between fares and airline operating costs in 58% for the complete market. Whilst 58% of the FSC routes fares are close between each other, the rest shows higher dispersion. Equation 3.4 estimates a correlation between fares and airline operating costs in 87% showing little dispersion between LCC's fares. The results suggest that FSC's earned or lose more money than LCC's because their routes show higher dispersion than LCC's. Contrary, LCC's have few profits or few losses per passenger ticket.

Table 3.9 AOC model coefficient values FSC and LCC market separately, 2005

FSC	*2005*	*15,521 routes*			*LCC*	*2005*	*2,062 routes*		
A_2	33.73				α_2	0.27			
Carrier	*[AviationDB]*	β_2	*f'a*	β_2	*Carrier*	*[AviationDB]*	β_2	*f'a*	β_2
DL	24.57	0.03	0.63	- 0.23	WN	10.81	- 0.26	0.41	0.68
UA	21.63	0.06	0.69	- 0.46	FL	11.30	- 0.21	0.16	0.28
AA	18.76	0.03	0.85	- 0.60	F9	13.30	- 0.16	0.36	0.41
NW	41.50	0.04	0.88	- 1.17	B6	10.83	- 0.24	0.37	0.58
US	22.36	0.01	0.81	- 0.13	TZ	29.90	- 0.17	0.00	0.06
CO	24.11	0.06	0.78	- 0.80	NK	14.89	- 0.25	0.05	0.23
HP	16.62	0.04	0.69	- 0.31	SY	12.17	- 0.25	0.02	0.17
AS	34.21	0.02	0.71	- 0.23	XP	21.78	- 0.13	0.19	0.23
YX	23.40	0.01	0.82	- 0.18	DH			0.14	0.27
AQ	30.61	0.00	0.73	- 0.01					
G4	11.50	- 0.15	0.49	0.51					
U5	13.35	- 0.15	0.44	0.47					
QX	10.09	- 0.11	0.41	0.29					
OO	6.80	0.25	0.41	- 0.55					

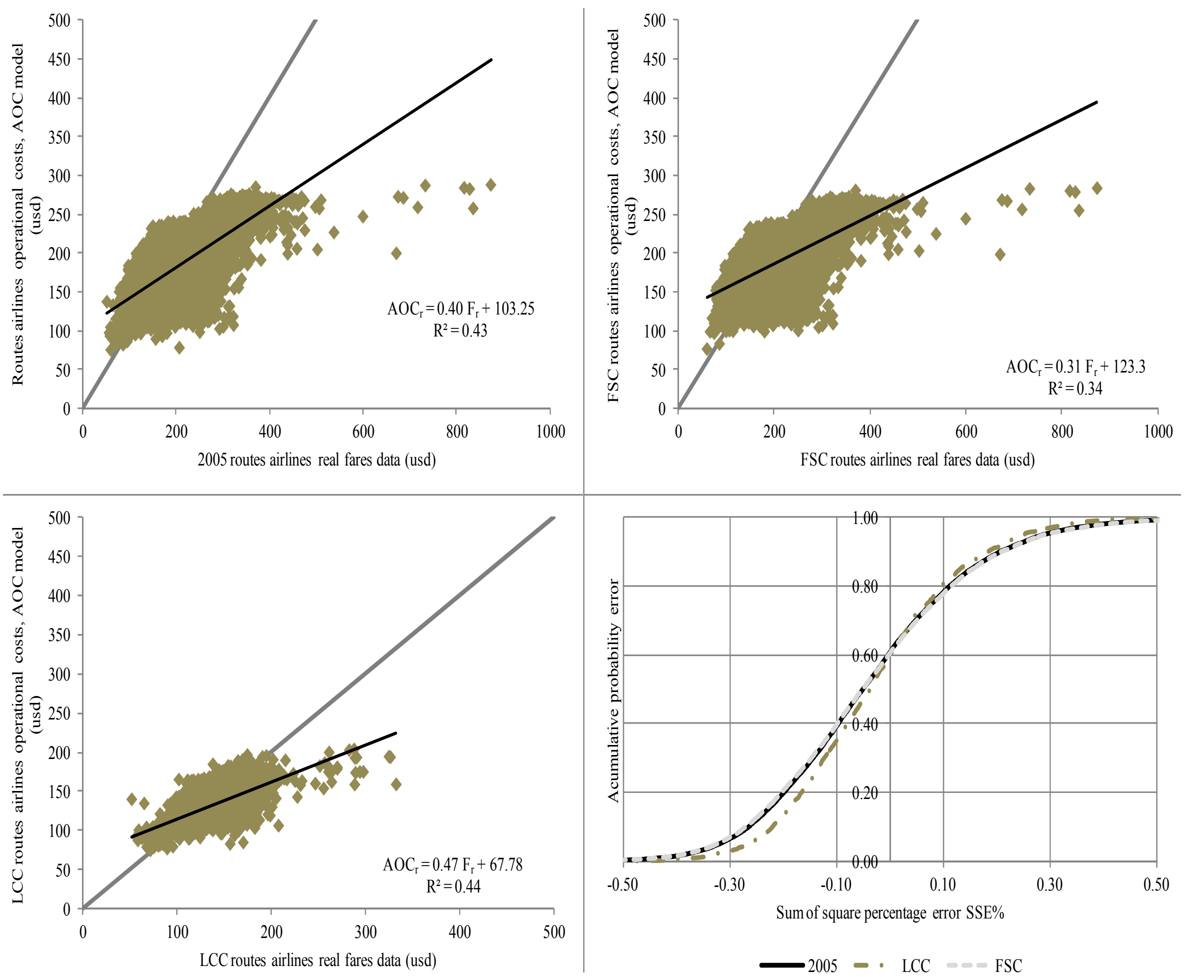


Figure 3.13 SSE% and correlation analyses 2005 between routes airlines operating costs and route airlines real fares data

In both markets, approximately 40% of the routes are losing money according to the sum of square error (SSE%) (Figure 3.13). These routes have higher operating cost than average ticket price. This does not mean that airlines are losing money on these routes. As it has been explained in Chapter 2 and Figure 3.1 (non-operating costs) airlines routes can be subsided by governments, hotel companies, etc. Those routes were airlines are making money represent 60%. Routes with over 20% profits represent 27% and 20% for the FSC and LCC markets respectively. This indicate that more dispersion will be found for the FSC market than for LCC market when trying to develop a model to estimates airline route fares (Chapter 4).

The AOC model has demonstrated that some of the main parameters provoking fares dispersion are distance range, airlines operating costs factors, airline business model type (FSC or LCC), airport/cities and cities economic type such as tourism (route subsidizing) appears to be significant to develop a model to estimate airlines routes fares (Chapter 4).

3.4.1 Airlines business models competition analysis using the AOC model

Depending on the type of airline providing service between two airports a competition analysis between airline business models can make (Figure 3.14). The database has been divided into three different competition cases scenarios according to the type of airlines serving each route: routes dominated by full service carriers (FSC-FSC), routes in competition (FSC-LCC) and routes completely dominated by low-cost carriers (LCC-LCC). The AOC model coefficient values are shown in Table Appendix D. 2, Table Appendix D. 3, and Table Appendix D. 4 respectively.

Table 3.10 shows the correlations between the AOC model and real fares for the three competition cases. The resulted of R^2's show how much of the airlines routes fares are determined by airlines operating costs parameters. The results show that routes dominated by low-cost carriers have, in percentage, more non-profitable routes than the other two cases. Routes dominated by full service carriers have over 40% non-profitable routes. A possible explanation could be that FSC airlines try to keep out LCC's from entering these routes by lowering fares under their operating costs. Finally, the competition between FSC and LCC has, in percentage, less non-profitable routes and more routes with profits over 20% of the operating costs. In this competition case scenario, 31% of the FSC routes are non-profitable whilst 22% of the LCC routes are non-profitable. For the FSC and LCC business models, 69% and 78% are profitable routes respectively. From all the FSC and LCC routes under competition, 34% and 40% achieves a margin of at least 20% profits.

Table 3.10 Airlines competition markets correlation results with AOC model, 2005

Year 2005	*FSC-FSC*	*FSC-LCC*		*LCC-LCC*
R	0.64	0.66		0.86
R^2	0.41	0.43		0.74
Airline business models	*FSC-FSC*	*FSC*	*LCC*	*LCC-LCC*
Total routes	3,261	12,260	2,000	62
Routes with lost	40%	31%	22%	44%
Routes with profits	60%	69%	78%	65%
Routes with profits over 20% AOC	840	4,169	800	5

Figure 3.14 shows higher costs for the FSC-LCC and FSC-FSC competition cases than the LCC-LCC competition case. It is because there are no longer routes than 4,334km (2,693mi) in the LCC-LCC competition case. The operating costs increase as distance increases but the unit cost per km decrease. Finally, the SSE% analyses show that less dispersion exist when LCC's are competing between each other. Thus, LCC's airlines profits are very low per passenger ticket sold.

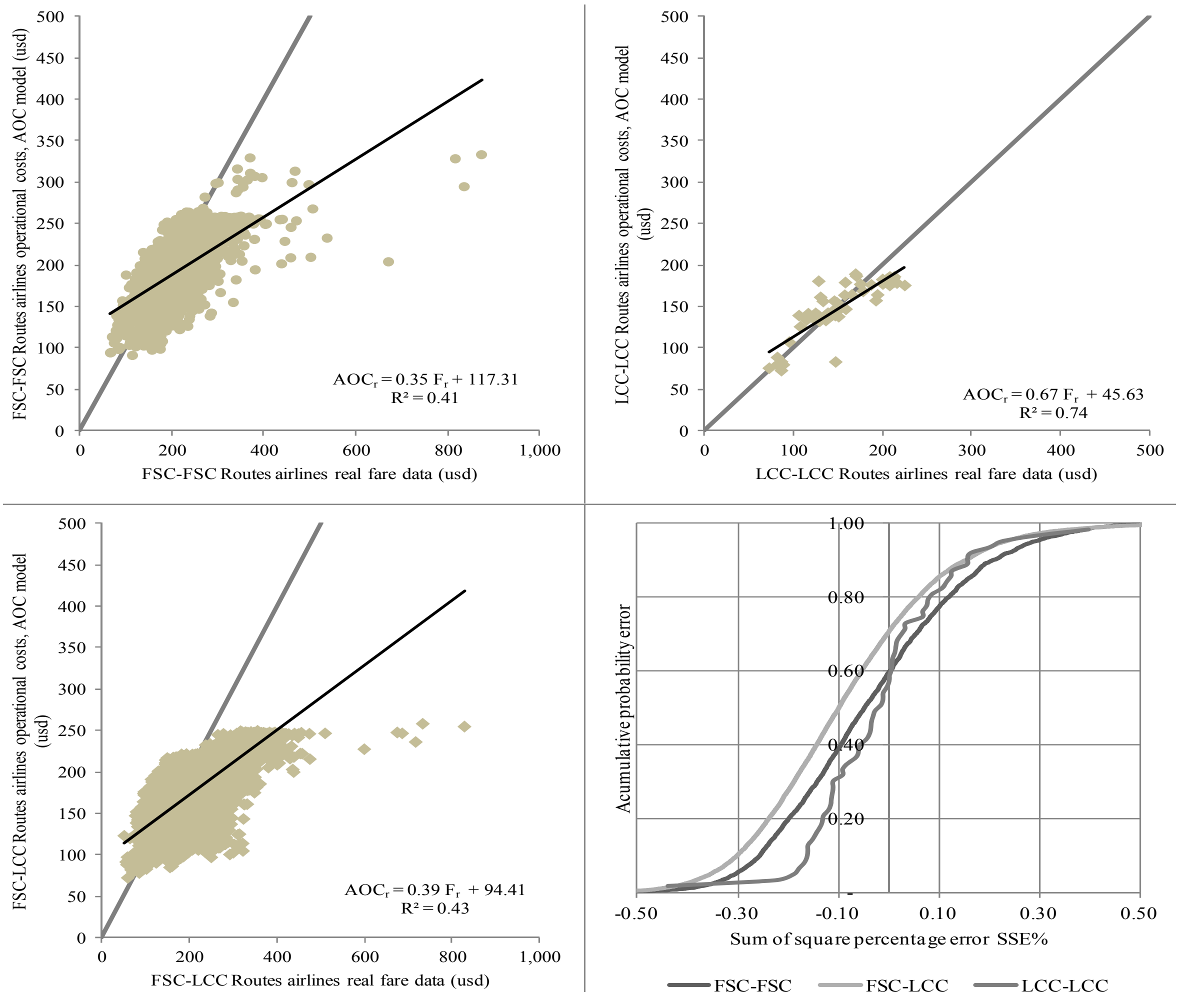


Figure 3.14 Airlines competition markets correlation results with AOC model, 2005

3.5 Discussion

It is necessary to find and analyze the principal parameters determining routes operating costs to develop a mathematical model for the airline operating cost calculation. In this chapter, different airline operating cost models were presented, and two models were developed based on econometric and engineering approaches. Both models have been compared with real data. They have been found to be satisfactory accurate to calculate airline and aircraft operating costs. The AGE model is the most suitable model for the purpose of this research because it differentiates between aircraft operating costs. The AGE model can be used to generate operating costs data for a fleet assignment problem without requiring any extra information.

A translog function (AOC model) has been used for other researches, as well. Here, this equation has been confirmed to be an accurate mathematical function to calculate airline operating costs per route per passenger distance. The main parameters used by the proposed translog function are distance range, average airlines operating cost factors and a constant coefficient. The number of seats is also a parameter that can be used not just for aircraft operating costs calculation at different hubs, as Swan and Adler [2006] used it, but also to calculate airline operating costs. One of the most important advantages of the AOC model is the possibility to calculate different operating costs per route per pax allowing studying each operating cost effect on fares. The disadvantage is that it does not consider that different aircraft types have different costs.

The AGE model is based on load and range. It is sufficiently accurate model to calculate the total jet fuel volume needed to fly a certain route link by any aircraft type. The fuel consumption parameter is a useful measure that can be directly related to the aircraft operating costs. An aircraft route operating cost can be estimated by multiplying the AGE model (Equation 3.10) to the jet fuel average price, and divided by the jet fuel cost percentage (%JFC). This model is called aircraft or plane operating cost model.

While discussing the results, it was evident that Equation 3.3 and the AOC model (Equation 3.4) can estimate route airline operating costs per passenger distance. Contrary the AGE model can calculate route aircraft operating costs per flight per aircraft. The AOC model represents some advantages analyzing airlines market behavior such as airlines business models competition. The AGE or BMR models, however, represent more suitable models for designing an optimization model that determines routes to open new services and design an airline network. One reason is that the AOC model cannot be used for a new airline unless it is assumed that this will show similar operating costs than a similar carrier. This is not very likely. One of the results of the analysis in this chapter shows that in fact some LCC's are as expensive as FSC's. Another reason is the fact that the AOC model does not distinguish between aircraft types. It has been proven that different aircraft have different costs depending on: load, distance range, engines specific fuel consumption efficiencies, lift-to-drag ratio (aerodynamics) and structural weight. This makes the engineering models more appropriate to be added into an optimization model than the econometric models. Different aircraft engine configurations affect operating costs. The AOC does not take this parameter into account.

The AGE model disadvantages compared to the Breguet range equation (BRE) can be accounted for the AGE model by modifying the BRE model as a multi-regression model (BMR). The BMR model has the capacity to capture all efficiencies that influence aircraft fuel consumption such as structural weight, aerodynamics and engines specific fuel consumption. The major advantage of the AGE model over the BMR model is that the BMR model has to be calibrated for each different aircraft type and cannot be used as a general model. Because the AGE model needs not to be calibrated per aircraft type, the AGE model represents a general equation to calculate jets fuel consumption for different aircraft type. Still, if a specific aircraft type needs to be analyzed the BMR model leads to a better result.

The aircraft operation cost model (POC) calculates the aircraft operating cost that are spent by an airline per aircraft type per operation. This includes airport charges that are transferred to passengers for using the airport. This model is not able to calculate passenger airport fees, but these fees are already considered in the total aircraft operating costs. Thus, it can be concluded that the calculation of airport fees are not needed because they are already calculated in the aircraft operating costs.

Finally, the consequences of the competition between different airline business models are analyzed by the AOC model. The competition analysis showed that routes dominated by LCC's have in percentage, more non-profitable routes than routes dominated by FSC's. The competition between different airlines business models (FSC-LCC) has, in percentage, less non-profitable routes and more routes with profits over 20% of the operating costs. The LCC-LCC competition case analysis shows that the competition between LCC's causes very low profits per passenger ticket. These results allow understanding the behavior of the market and how airlines calculate their route fares in markets with and without competition. The competition between airlines business models must be considered when developing a model that calculates routes fares.

4 Models for competitive airline route average pricing

The ticket price is the most important parameter influencing revenues. Setting a ticket price is the first step of selling any product [Dolgui and Proth, 2010]. Since the deregulation and liberalization (privatization) of the air transportation industry in the 1970's [Aldamari and Fagan, 2005], the competition between airlines has increased and domestic yields have decreased [Guillen and Lall, 2004]. This has made airlines fares an important factor to enable domination of routes, increasing market share and passenger (pax) volume.

It is not easy for an airline to enter into new routes or to open new markets. It is even more complicated to gain a significant piece of the market share, keep it and then survive in a very competitive industry. Determining the route fare is an important managerial tool. Airlines can use fares to identify routes that are an opportunity to open new services. Normally, companies fix prices applying different methods: cost-plus, price testing, estimation made by experts, market analysis and conjoint measurement (surveys) [Dolgui and Proth, 2010].

Based on the advantages and disadvantages of each pricing method (Table 4.1), market analysis is selected as the pricing method for this research. Market analysis allows developing mathematical models by the analysis of the US domestic airlines fares consumer report database [DOT US Consumer Report, 2005-2008]. Its main advantage is that it considers the behaviour of the market. Contrary, cost-plus and price testing do not and conjoint measurement requires paying for survey campaigns.

The aims of this chapter are: firstly, to study existing airlines fare calculation models presented in Section 4.1. Secondly, to explain why airline fares have been and will be the main factor to open new routes enhancing passenger flow (Section 4.2). Thirdly, to develop a mathematical model that calculates airline route fares (FEM) (Section 4.3). Fourthly, to set-up a method to identify routes that represent an opportunity to open new services based on the calculation of the most competitive fare (CFEM) (Section 4.4). Fifthly, a forecasting method is applied to estimate fares values in future years (Section 4.5). Finally, a discussion on the different fare estimation models and the CFEM method is presented in Section 4.6 as a conclusion to this chapter.

Table 4.1 Summary of fix price methods Pros and Cons [Dolgui and Proth, 2010] [Dobson and Kalish, 1993]

Fix pricing methods	*Pros*	*Cons*
Cost-plus method	Price is easy to calculate by using this method. The profit is a percentage of the cost. It apparently guarantees margins. It only requires knowing costs. Thus, market tends to be stable.	Does not take into account customers perception and levels of demand between related products. Ignores competition and the opportunity cost of selecting the best price.
Price testing	Helps to determine price and the market niche. The price is calculated by changing the price of the product relatively easy.	Clients cannot be recognized. Customer's characteristics cannot be used as an advantage.
Estimation made by experts	This method is used to price a new product by asking the opinion of several experts.	Customers are not taken into account. It increases the probability of pricing wrongly according with how the market valorisation of the product.
Market analysis	Based on the statistical analysis of the product historical data. It can be defined by a mathematical function model. New products can be priced by similarity with related existing ones.	The analysis assumes that products behave as in previous years, months, seasons, etc. Pricing a new product assumes that its market behave like a similar existing product. This might or might not happen but there are no other options since data is not available.
Conjoint measurement	Based on interviewing different costumers. It determines how customers value different parameters of a product. This method can use regression or optimization methods. For example, Dobson and Kalish [1993] design and price a product line using cost data.	It is a costly method. It requires paying for surveying campaigns to generate enough data per specific product. In the case of an airline, a survey has to be performed per route.

4.1 Airfare determination

The air transport business has a very dynamic and complex pricing system. A number of studies documenting the subject of airfare pricing exist and are discussed through this section. Most of them developing and analyzing different pricing determinants to study different topics such as LCC's effects, price dispersion, airports airfare role, monopoly, pricing discrimination, financial distress, competition, predatory, bankruptcy and pricing strategy (i.e. price war, revenue management). In these topics, different models have been developed to calculate airlines routes fares to study the competition between airlines facing different scenarios (i.e bankruptcy), but none of them calculates the average route fare with the purpose to identify and open new services.

In order to develop a model that calculates an airline average route fare, a study on existing airfare pricing models has been carried out. The intention of this study was to find possible airfare determinants that can be used as independent variables (IV's) for airfare calculations. This is a relevant issue, since fare dispersion is quite significant in the airline industry [Alderighi, 2010]. Another reason was to identify the major consequences and reactions that could happen on the market when an airline enters new routes operated by other airlines such as price war and predatory conditions that can lead airlines to bankruptcy. This knowledge might be helpful to make sure that the selected routes avoid these kind of scenarios.

According with Morrison and Winston's [1995] approximately 50% of the variation in airfares in the US might be due to routes travel distances, routes passenger demand, and the competition between airlines and airports operating the same routes.

Vowles [2000] developed an econometric model to study different airfare pricing determinants concluding that Southwest Airlines (WN) is a significant determinant of fares besides the distance. Vowles [2006] also studied pricing in hub to hub markets using different determinants such as a definition of different route types, low fare carriers, competition in hub to hub markets and a classification between tourism and non tourism cities. His results show that low fare carriers have a high influence in airfares determinants in the US.

Windle and Dresner [1995; 1999] looked at the role of the low fare carrier's entrance into air transportation markets. Their results show that the presence of LCC's in the air transport markets was significant, while market concentration was not [Windle and Dresner, 1995]. They also studied the reaction of Delta Airlines (DL) to the entrance of ValueJet (J7) on some routes. Their results show that fares on routes where both airlines compete went down, but Delta did not increase fares on other routes without competition to compensate revenues [Windle and Dresner, 1999].

Pels and Rietveld [2004] developed models to estimate fares for different airlines. First, they found that FSC's do not follow the fare movements of LCC's. Second, some carrier appears to lower fares when competitors raise fares. Third, all airlines increase fares as the departure date gets closer.

Fuellhart [2003] found similar results as Vowles [2000]. The presence of significant low fare competition can have important effects on the airfares paid by passengers. According with Fuellhart [2003] the influence of low fare competition from a specific airport can have important effects on routes fares in other airports in the same region. Goetz and Sutton [1997] reported that fares from hub airports without a significant presence of LCC's are higher than other hubs with substantial LCC's service.

Borestein and Rose [1994] found that the difference between airline cost, competition and willingness of consumers to change to another carrier are main factors that cause route fares dispersion. City and airport's location between airports seems to be significant, especially together with measures of market concentration and low-fare competition [Fuellhart, 2003].

Chi and Koo [2009] performed a multi-regression analysis to study the pricing behavior and strategies of the US domestic carriers. Their model parameters are airports capacity, aircraft utilization, route frequency, distance and average segment distance, round trip, tourist areas, ticket restrictions, population and income, hub airports, slot controlled airports, market share, LCC, multiple airports located nearby, carrier effects, seasonal effect and a variable representing each carrier under study also used by Carmona Benitez and Lodewijks [2010a].

Borenstein [1989] and Oum [1996] studied the cases of airlines monopolies at airport hubs. The results show that consumers pay a higher fare and concluded that hubs are detrimental to low fares for consumers because there is no competition between airlines. Borenstein [1989] found that an airline with a dominant position in an airport charges higher fares than in other airports operated by the airline.

Van Dender [2007] investigated the effects on fares that carriers charge to passengers and on costs that airport charge to airlines and to passengers. His results suggest that airport charges to airlines highly affect airline fares and that competition between airports exist and affect fares. Airport charges can be used to protect passenger markets and avoid congestion. For example, congested airports can increase airlines fees making airlines increase fares and keep business passengers and avoid leisure passengers who had less value of time congesting the airport and vice versa [Czerny and Zhang, 2011].

Basso and Zhang [2007] proposed the traditional approach for airport pricing. This method uses an equilibrium model where demand for airport services depends on airport fees and on congestion costs of passengers and airlines. It assumes that airline competition is perfect, and delay costs are totally charged onto passengers. The method has been analytically proved by Basso and Zhang [2008] finding that it is only valid if carriers have no market power.

Important conclusions to consider are the remarks made by Gorin and Belobaba [2008]. Their simulation results showed that when one airline enters a route with low fares, the other airlines flying the route will lower fares only if the new airline enters the market with low capacity[11]. This can be an indication of an aggressive reaction and a potential predatory pricing response against the airline entering the market. Contrary, if the new carrier enters the market with a reasonably high capacity, the response to entry allows the other airlines to maintain higher average fares. This is because the airline entering the route is competitive. A decrease on fares comes with a reduction on revenues possibly falling into a price war.

A price war happens when one airline lower route fares below the fares of other carriers flying a route in a non-cooperative behaviour among them [Busse, 2002]. A new airline entering a new route can cause a price war by selling at lower prices [Klemperer, 1989]. Price war is used to either reduce the competition or to increase market share because as prices get lower route load factor increase. The aim is to attract passengers. It can cause enormous losses in terms of margins, customer equity and improvement [Heil and Helsen, 2001]. Price wars are more probable to occur during economic downturns [Zhang and Round, 2011], in periods and on routes with low demand when airlines try to increase load factors and minimize fixed costs [Busse, 2002]. However, price wars are extremely difficult to prove. Many conditions have to exist such as airlines reputation (bankrupt), airlines financial conditions and fluctuations influencing the supply and demand [Morrison and Winston, 1996]. According to Heil and Helsen [2001] market conditions that can explain the emergence and force of price wars are the excess capacity supplied, new entry, market growth and market concentration.

A new airline can evade a price war by avoiding entering routes where capacity exceed the demand, entering markets with negative economic growth and routes where an airline is in bad financial conditions approaching bankruptcy because the other airlines serving the same route as the bankrupt airline will tend to lower fares.

Hofer and Eroglu [2010] investigate the effects of economies of scope in airlines pricing behavior. In this case, economies of scope refer to the reduction on average costs related to the increasing of revenues by transporting cargo volume. The result indicates transporting cargo lower fares. However, a negative effect of cargo on fares happens when airlines have low route market shares. The impact of carrying cargo is higher for long-haul routes than for short-haul routes. The impact is also higher in tourist markets than in business markets.

A logarithmic equation to estimate airline fares and to study the impact of bankruptcy on airline average costs was developed by Barla and Koo [1999]. Their model parameters are route distances, passenger type (business or leisure), variation in price, average operating cost

[11] In the airline transportation industry, capacity refers to the total number of seats offered by an airline on a route or in its total network.

per pax mile, lowest operating cost per pax mile, market share, the Herfindahl index[12] (HHI) is used to measure dispersion, airline number of destinations, a variable that indicates when an airline is on bankruptcy status and a variable that indicates when one airline operating a route is on bankruptcy status. The main results indicate that a carrier under bankruptcy status does not lower fares but the competing carriers will lower fares much more than the weak carrier.

It is important to make clear that airlines do not just lower prices when another carrier is under financial distress, bankruptcy or entering the market. Optimal ways to gain loyalty of new passengers is by lowering prices today and keep them low.

Obeng [2008] developed a model to study airline fares in a medium size market using on-line daily information on fares, aircraft, flights and trip characteristics. Their results show large differences in fares among the airlines, large variation on daily fares offered, and fare differentiation. Seasonal and price behavior of airlines looking at price dispersion of fares have been studied by Garrigos-Simon, Narangajavana and Gil-Pechuan [2010] using jet fuel, money exchange rates and days before departure as IV's. Giaume and Guillou [2004] developed a model to study multiple pricing offered in intra-European routes. The results showed that concentration and price discrimination are negatively related.

From literature, three main airline strategies are noticed: minimize airline operating costs, maximize market share and adjust fares according to the market changes to increase competitiveness.

Changing a route fare is easier and faster to implement than developing a new process to reduce operating costs or increase market share. The fare is a parameter that can be controlled to increase competitiveness in the easiest and fastest way by being adjusted to the state of the market. This is better known as revenue management (yield management). The aim of a revenue management pricing strategy is to maximize revenues, by focusing on exploiting demand [Dolgui and Proth, 2010].

The FSC pricing structure (price discrimination/market segmentation) is complex. This pricing strategy consists of charging different fares to the right customer at the right time. Airlines try to maximize revenue on each individual flight link or route [Zeni, 2001] [Daudel and Vialle, 1994]. Airlines must forecast the demand of each different fare classes by using flight departures historical booking data [Zeni, 2001]. The forecast is used as input data. Then, airlines use it to calculate the optimum number of seats available for the different fare classes by optimization. The aim of this type of pricing system is to set booking limits. First, the demand of different services classes is forecasted. Second, a certain number of seats are being sold to the low fare pax market by studying the characteristics of each flight in terms of how many seats should be allocated for each different fare class [Cross, 1997]. This will result in the optimum combination of fares depending on the conditions of each different passenger [Aldereghi et al., 2004]. Then, if the forecast for business pax is low, few seats will be designated for this class and more seats will be sold to the leisure market and vice versa [Zeni, 2001]. Contrary, LCC's use another kind of revenue management as a pricing system called dynamic pricing. They look at the percentage number of seats sold. A first number of tickets are sold offering heavy discounts for tickets booked long in advance. After certain percentage

[12] Herfindahl index (HHI) measures market concentration. The index is calculated by squaring the market share of each airline competing in the market, in this case the market share of each airline operating each route, and then summing the resulting number. The closer the HHI is to 10,000 the closer the market, in this case the route, is to monopolistic conditions. It also measures the market power of an airline on its routes.

of seats has been sold, a next portion of seats are sold with a more expensive fare and so on [Bruggen, 2007]. This system generates a new air passenger demand of passengers that would not have flown without low fares [Ehmer, 2008].

Table 4.2 summarizes the parameters found in literature which can be used as pricing determinants to develop mathematical models that can calculate airlines route fares.

Table 4.2 Summary of literature pricing determinants

Parameter	*Reference*	*Parameter*	*Reference*
Distance	Morrison and Winston [1995]; Vowles [2000]; Vowles [2006]; Carmona Benitez and Lodewijks [2010a]; Barla and Koo [1999]	Number of passenger demand	Morrison and Winston [1995]
Route classify in different types	Vowles [2006]	Passenger type	Barla and Koo [1999]
		Transport of cargo	Hofer and Eroglu [2010]
Airlines competition	Morrison and Winston [1995]; Windle and Dresner [1996]; Windle and Dresner [1999]; Pels and Rietveld [2004]; Fuellhart [2003]; Carmona Benitez and Lodewijks [2010a]; Borestein and Rose [1994]	Airports competition	Morrison and Winston [1995];Vowles [2006]; Chi and Koo [2009]; Carmona Benitez and Lodewijks [2010a]
Presence of an LCC	Vowles [2000]; Vowles [2006]; Borestein and Rose [1994]; Chi and Koo [2009]	Hub airport	Vowles [2000]; Vowles [2006]
Presence of Southwest Airlines	Vowles [2000]; Vowles [2006]	Airports and airports classify by pax per year	Goetz and Sutton [1997]; Chi and Koo [2009]
Airline costs Lowest Operating cost	Borestein and Rose [1994]; Barla and Koo [1999] Barla and Koo [1999]	Cities and airports geographical location	Borestein and Rose [1994]
Airline type and business type	Chi and Koo [2009]; Pels and Rietveld [2004]; Fuellhart [2003]	Market concentration	Fuellhart [2003]
Airlines business models competition	Borenstein [2989]; Oum [1996]	Airport congestion	Van Dender [2007]; Czerny and Zhang [2011]
Airline route frequency	Chi and Koo [2009]	Airports capacities	Chi and Koo [2009]
Round trip		Available slots	
Ticket restrictions		Airport fees	Van Dender [2007]
Willingness of consumers to change airline	Borestein and Rose [1994]	Countries economic conditions (i.e. downturns)	Heil and Helsen [2001]
Airlines market share	Chi and Koo [2009]; Barla and Koo [1999]	Population	Chi and Koo [2009]
		Income	
Airline capacity	Gorin and Belobaba [2008]	Seasonal Effect	K. Obeng [2008]; Garrigos-Simon, Narangajavana, Gil-Pechuan [2010]
Airlines economic	Busse [2002]; Kemper [1988]; Kemper [1989]; Morrison and Winston [1996]	Source of economic "Tourism"	Vowles [2000]; Vowles [2006]; Chi and Koo [2009]
Aircraft utilization	Chi and Koo [2009]	Herfindahl index	Barla and Koo [1999]
		Money exchange rate	Garrigos-Simon, Narangajavana, Gil-Pechuan [2010]

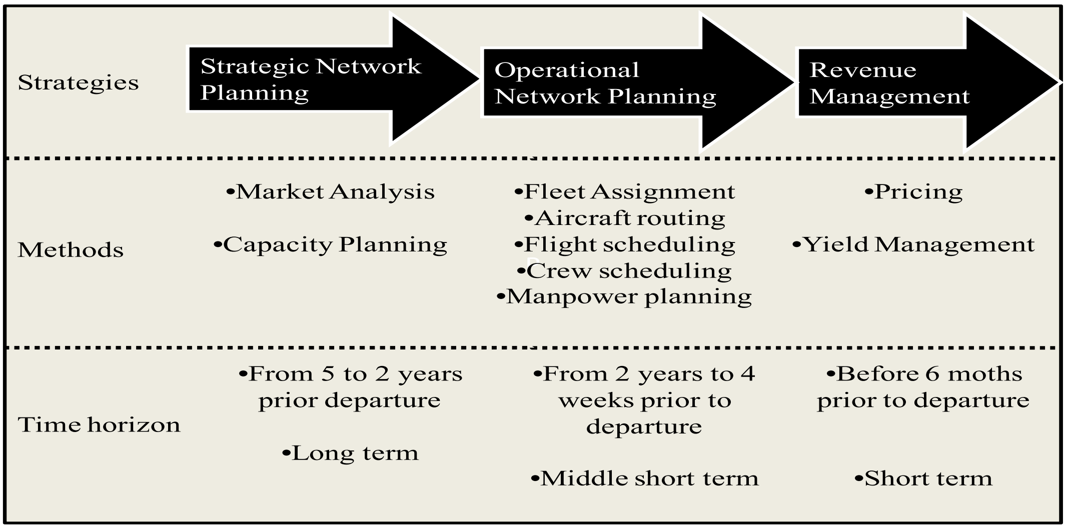


Figure 4.1 Network management processes [Niehaus, Ruehle and Knigge, 2009]

According with Niehaus, Ruehle and Knigge [2009] revenue management is the last stage of the network management and starts at least six months prior departure. It comes after strategic network planning and operational network planning (Figure 4.1). Network management starts analyzing 5 to 2 years prior opening services. Market analysis methods are performed to take decisions and to evaluate the profitability of a network. Operational network planning is a medium to short-term planning, from 2 to 4 years prior to departure. In this stage, models for fleet assignment, aircraft routing, flight scheduling, crew scheduling and manpower planning are developed [Bazargan, 2010]. Because the aim of this research is to identify routes to design a network that represent opportunities for airlines to invest, flight scheduling, crew scheduling, manpower planning and revenue management are out of the scope of this thesis because they come after opportunistic routes have been identified.

4.2 The main factor to open new routes

Since the appearance of LCC's, the competition between airlines has increased [Guillen and Lall, 2004]. Routes with the presence of LCC's have lower average fares than routes dominated by FSC's. This explains why airlines fares are an important factor to dominate routes, increase airline market share and number of passengers. Perhaps the most important strategy applied by LCC's has been the introduction of cheap one way fares. It has undermined the price discrimination power of the FSC's [Tretheway, 2004].

To develop a mathematical model that intents to identify new airline routes that represent a possibility to open new services, the main parameter that has helped US LCC's to growth so fast and attract more passengers, even during difficult economic conditions has to be identified. The real force behind the increase of LCC's pax flow is the level of fares LCC's charge in comparison with FSC's. Since LCC's appeared, the airlines efforts to lower cost have increased, including discontinuing unprofitable routes and service innovations described in Chapter 2. Even when FSC's have developed different strategies to cut operational cost, these have not been enough to compete against LCC's.

Figure 4.2 shows the pax increase/decrease and profits/losses for different US carriers from years 2000 to 2009.

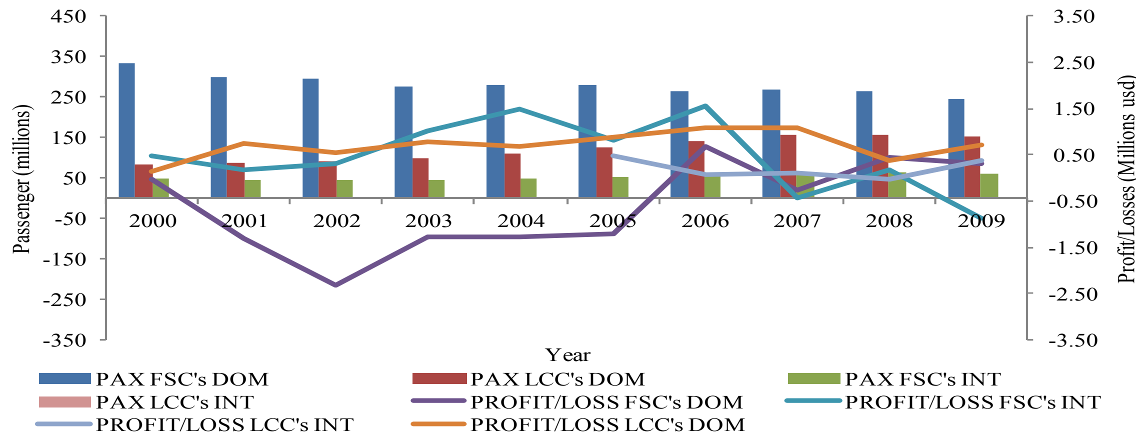


Figure 4.2 FSC and LCC total number of domestic (DOM) and international (INT) passenger flow and percentage profits/losses [RITA, 2000-2009]

The competition between FSC's and LCC's has had a direct effect on airline fares and has lead LCC's to an impressive growth. For instance, the US air pax flow grew from years 2001 to 2008. It dropped from 2008 to 2009 [RITA, 2000-2009][13]. From these numbers, LCC's pax flow grew 86% from year 2001 to 2009. In the same period, FSC's pax flow dropped 20%. In the US domestic market, LCC's pax flow grew 83%. Contrary, FSC's dropped 27%. In the US international market, LCC's pax flow grew 2.37 million pax. FSC's pax flow grew 24%.

The relative growth of pax traveling in LCC markets does not measure the complete impact of LCC services. The consequences have been a strong increase of pax in LCC routes and a decrease in the number of pax flying with FSC's. The US air passenger transportation industry has grown despite the decline in the FSC's number of pax. LCC's are increasing pax flow by winning more routes, year by year (Figure 4.2), with more accessible fares.

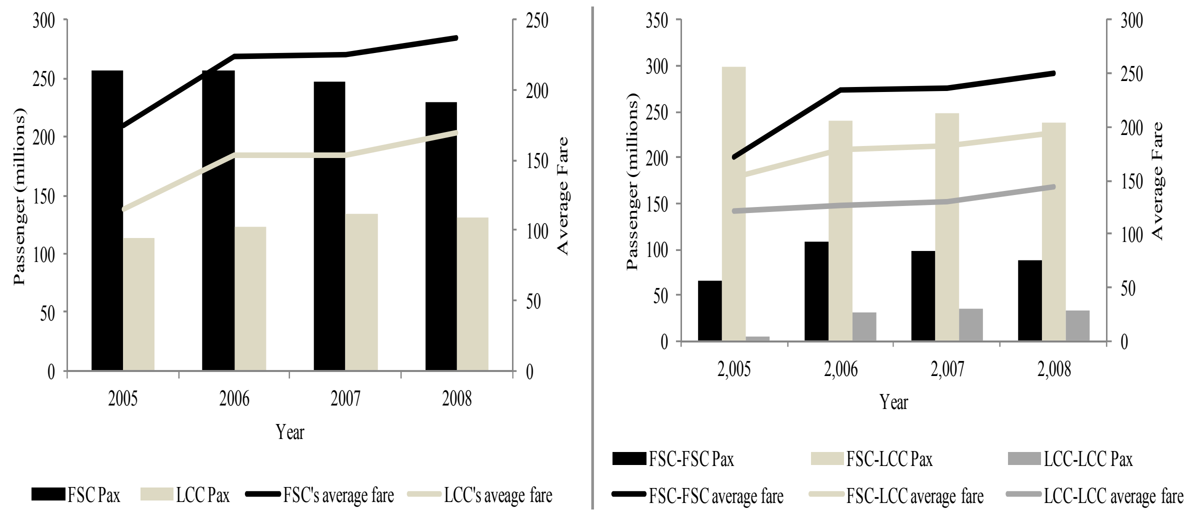


Figure 4.3 Business models and competition market analysis, pax flow and average fares [DOT US Consumer Report, 2005-2008]

Figure 4.3 shows the pax flow and average fare percentages change, calculated as an average weighted fare by using Equation 4.1, from years 2005 to 2008. During this period of time,

[13] The FSC's pax data come from AA, UA, US, DL and CO. The LCC's pax data come from WN, B6, FL and F9 [RITA, 2001 – 2009].

FSC's US domestic market pax flow lost 12.5% pax. LCC's pax flow gained 12.9%. The FSC's average fare increased 27%. LCC's average fares increased 32%.

$$F_{Comp} = \frac{\sum_{r=1}^{RComp}(Q_{r,Comp} \times F_{r,Comp})}{\sum_{r=1}^{RComp}(Q_{r,Comp})} \quad (4.1)$$

Where:

F_{Comp}	= airline route competition type Comp average fare	[usd]
F_r	= Route r average fare	[usd]
Q_r	= Route r number of passengers	[pax]
r	= route	[-]
Comp	= airline competition type (FSC, LCC, FSC-FSC, FSC-LCC, LCC-LCC)	[-]
RComp	= Airlines competition type Comp, total number of routes	[-]

On routes without LCC's operations pax flow decreased 32.2%. Routes under competition, FSC's against LCC's, pax flow decreased too. FSC's pax flow decreased 13.9% and LCC's 11.3%. On routes operated only by LCC's, pax flow increased 619.8% (Figure 4.3).

The average fares on routes operated just by FSC's increased 43.4%. Contrary on routes operated only by LCC's average fare increased 19.3%. On routes under competition between FSC's and LCC's average fare increased 26.4%. Figure 4.3 confirms that low fares enhance pax flow since the market charging the lowest fares (LCC-LCC) is the only one that showed an increased on pax flow from years 2005 to 2008.

Figure 4.4 analyses the increase/decrease of pax flow and average routes fares on different pax flow density markets from years 2005 to 2008. FSC's increased pax flow only on routes with very high density, 0.7 million pax. Contrary, LCC's increased pax flow on all density markets but especially in markets with less than 100 pax per day. Contrary, FSC's pax flow decreased in markets with less than 100 pax per day.

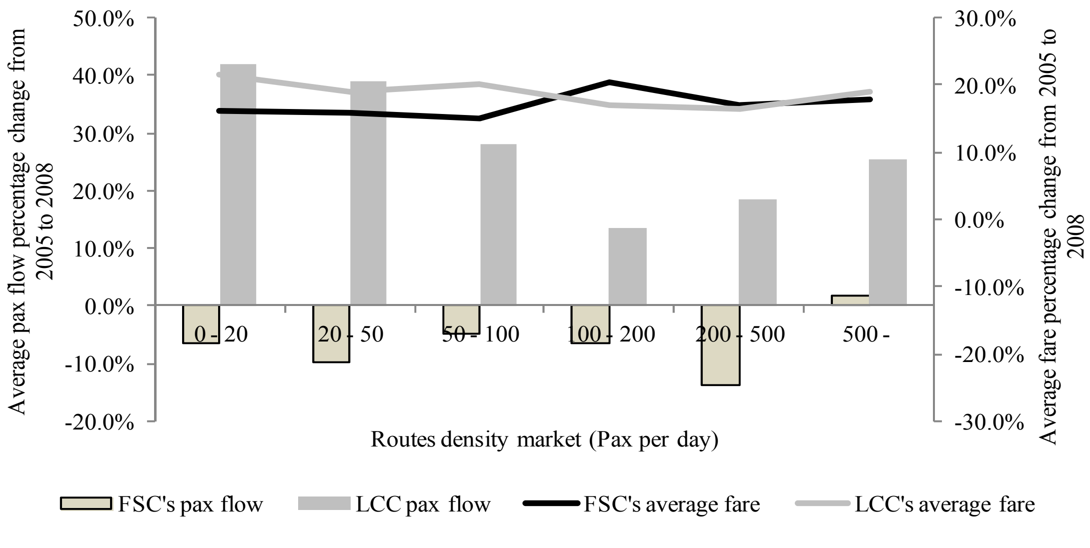


Figure 4.4 FSC's and LCC's pax flow and average fare at different route densities [DOT US Consumer Report, 2005-2008]

FSC's average fares increased on low density route markets and on high density route markets. LCC's pax flow increased less on routes between 100 and 500 pax per day than on the other density markets. These results suggest that all US carriers suffered the impact of the economic and fuel crisis during the years under study since FSC's and LCC's increased fares almost in the same percentage.

In high density, both business models increased average fares. However, LCC's average fares were cheaper than FSC's. LCC's and FSC's increased average fares by 37.4 in low density markets (< 100 pax per day). Although, the increase was higher for LCC's in percentage, LCC's average fares were cheaper than FSC's. In general, the increase of pax flow, from 2005 to 2008, has been caused by the increase of LCC's operations.

A useful point of reference for evaluating changes in the industry's pricing structures is the Standard Industry Fare Level (SIFL) [Peña, 1996]. The SIFL adjustment factor is updated periodically by The Department of Transportation. The SIFL can be used to estimate changes in carrier pricing. The ratio of the average fares to SIFL by mileage block or a distance range (Table 4.3) explains that any ratio above 1.0 is an indication that average fares are increasing above fare level. A ratio less than the SIFL indicates a general reduction on fare level. The bases of this analysis assure that any increase on the average fare/SIFL ratio reduces the consumer welfare and passenger traffic. Any reduction would enhance it. The SIFL adjustment factor can be found at the US Department of Transportation Office (DOT). Table 4.3 shows the values of the SIFL formulas from years 2005 to 2008.

Table 4.3 SIFL fare formulas [DOT SIFL levels, 2005-2008]

Release date	*Effective date*	*SIFL adjustment factor*		
		0-804.5km	*804.5-2,413.5km*	*>2,413.5km*
08/04/05	01/01/05	0.1197	0.0913	0.0878
08/23/06	01/01/06	0.1287	0.0981	0.0943
08/02/07	01/01/07	0.1289	0.0983	0.0945
08/04/08	01/01/08	0.1437	0.1096	0.1054

The SIFL factor ($F_{r,t}$) is calculated by Equation 4.2. As an example, in 2005, for a route with distance (D_r) 2,476km, the SIFL level using Equation 4.2 and Table 4.3 is equal 248.6 usd per pax. In 2006, 2007 and 2008, the same route SIFL levels were 267.4 usd per pax, 267.7 usd per pax and 298.5 usd per pax respectively.

$$F_{r,t} = D_{r1} \times SIFL_{0-805,t} + D_{r2} \times SIFL_{805-2414,t} + D_{r3} \times SIFL_{2414,t} \qquad (4.2)$$

Where:

$$D_{r1} = \begin{cases} D_r \text{ if } D_r \leq 805 \\ 805 \text{ if } D_r > 805 \end{cases} \qquad \text{[km]}$$

$$D_{r2} = \begin{cases} 0 \text{ if } D_r \leq 805 \\ D_r - 805 \text{ if } 805 < D_r \leq 2{,}414 \\ 2{,}414 \text{ if } D_r > 1{,}500 \end{cases} \qquad \text{[km]}$$

$$D_{r3} = \begin{cases} 0 \text{ if } D_r \leq 2{,}414 \\ D_r - 2{,}414 \text{ if } D_r > 2{,}414 \end{cases} \qquad \text{[km]}$$

SIFL = SIFL factor [usd/km/pax]

Figure 4.5 reveals an interesting difference between LCC's and FSC's pricing structure at different density markets. It suggests a high competition between airlines business models. As the number of pax flow increases on a route, the difference between FSC's and LCC's SIFL levels decrease. Apparently, LCC's fares were slightly cheaper at low density markets than at high density markets. This suggests that LCC's could be opening new services at low density markets where the possibility appears to exist. Apparently, LCC's are entering into low density routes be selling at lower prices, with the aim of attract passengers, since the FSC's fares are 43% more expensive than LCC's fares. It may suggest that LCC's are applying a "pricing war" strategy to get in low density markets.

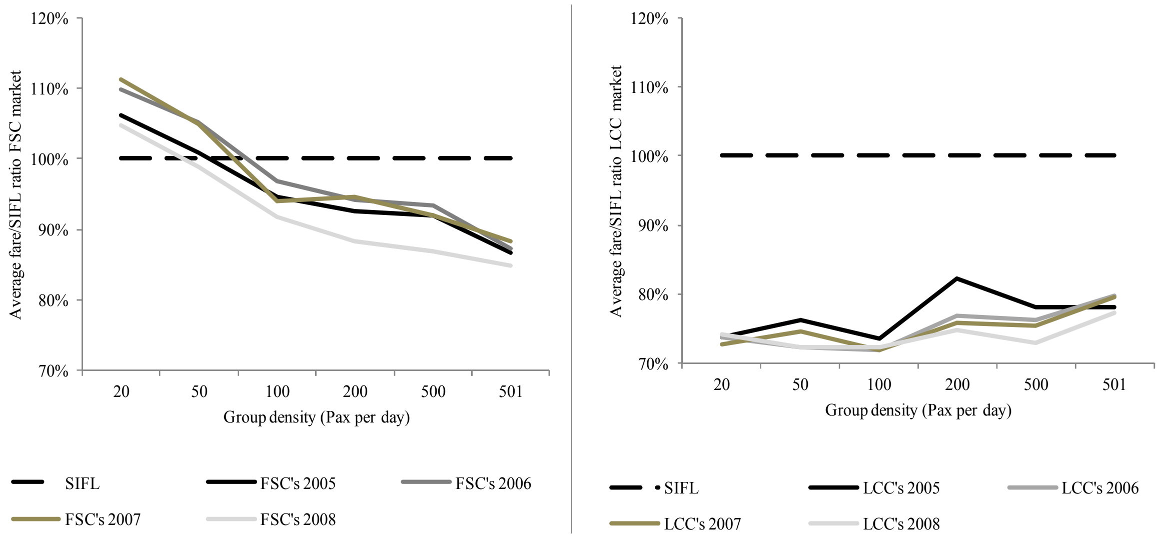


Figure 4.5 Airline business models fares in relation to costs of providing service at different pax density group routes

Figure 4.6 demonstrates that fares on short-haul routes are higher than SIFL fares. LCC's reach SIFL fares after 804.5km D_r, and FSC's after 1,206.8km D_r. Prices on short-haul routes decline significantly and at the shortest D_r (<402km) fares are extremely high for both business models but in particular for FSC's. At long-haul routes, fares are similar for both models. This is a reason why a long-haul low cost model is difficult to operate. Airlines change on fare levels is notorious at group density but not by range group from 2005 to 2008.

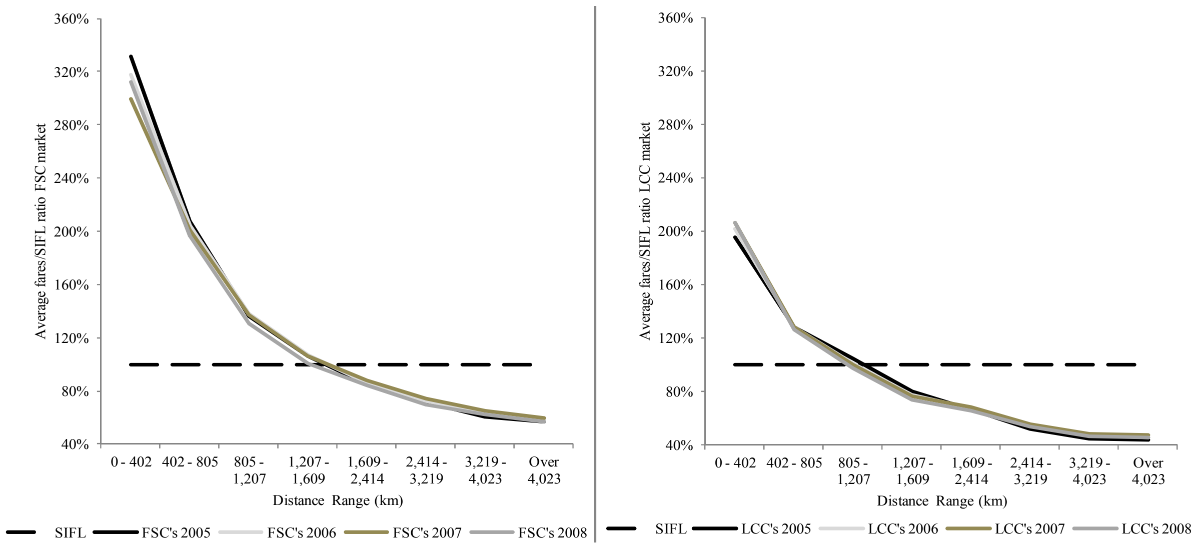


Figure 4.6 Airline business models fares in relation to costs of providing service at different distance group ranges

This subchapter focused on airlines fares because of the significant competitive pressure that LCC's are exerting on FSC's. It reports the rapid growth and competitive advantages of LCC's. It justifies the fact that low fares are the main reason allowing airlines to open new services on routes with and without competition. As a result, a mathematical model that calculates the average route fare and determines the most competitive fare according to market conditions is the first step to select routes that represent an opportunity to open services.

4.3 Fare estimation model

In this section, a mathematical fare estimation model to calculate airlines routes fares is developed. The model main parameters come from the airfare pricing models in literature review (Table 4.2). Different route classification parameters have been developed to be used in the model.

In Chapter 3, the airline and aircraft operation costs models have route length as one common variable. It is because airline and aircraft operating costs are highly correlated with the route length. Aircraft consume more jet fuel as route length increases. Since operating costs increases as route length increases, fares increases too. It is clear that the main factor affecting fares is the route length.

Chapter 3 also showed that airline operating costs are parameters that influence route fares. One reason is the level of competition between airlines. Competition makes airlines develop strategies that affect their operating costs. Airlines with lower operating cost can offer lower fares. The difference between airlines operating costs increase fare dispersion, which makes it more complicated to calculate route fares. Thus, the fare estimation model (FEM) needs to consider that airlines, flying similar D_r, have different operating costs.

The airlines route fares are not just affected by how airlines perform their operations and strategies. Cities airports also have an impact on airline route fares generating dispersion and making it difficult to estimate fares. Airport variables such as geographical location, tourism, population, passenger catchment area, accessibility and available capacity of the airports determine the advantages and disadvantages that airports have over each other and over airlines. These affect contractual conditions between an airport and an airline. In other words, some airports have the power of charging airlines and other need to finance routes. Airports finance routes to attract more passengers to increase revenues and minimize costs. By increasing the number of passengers using the airport facilities, airports decrease unit costs. When airports pay airlines for operating a route, airlines have the possibility to lower fares. Thus, the FEM model has to consider airport cost to estimate airlines route fares.

Air transportation fares are also affected by the origin and destination cities main source of economic growth. In Vowles [2000; 2006] model, a parameter that takes into account whether a city is a tourism city or not, depending on the main source of economic growth is used. Information about the main source of economic growth on each city it's not available. In Appendix F, the total number of low-cost passengers transported at each airport is compared with the tourism cities identified by Vowles [2000; 2006]. It has been found that the tourism cities in Vowles [2000; 2006] are the cities with more LCC pax flow. Thus, all cities need to be classified into four different groups: Tourism, Business, Normal and Remote (Table Appendix F. 9 to Table Appendix F. 11). The classification criteria's are:

1. Firstly, cities were classified by the total percentage of LCC pax flow per day. If the percentage of LCC pax is more than 70%, the city is classified into the low cost or tourism group. If the percentage of LCC pax is lower than 20%, the city is classified into the full service or business group.
2. Secondly, cities were classified into expensive, cheap, normal and remote groups. If the city average fare is over 25% the market average fare, the city is classified in the expensive or business group. If the city average fare is 25% below the market average fare, the city is classified into the cheap or tourism group. If the percentage of low-cost

passengers is in between 20% and 70%, the city is classified into the normal group. Finally, cities located in remote areas with little passenger flow are placed into the remote group. Table 4.4 shows examples of cities that belong to each economic group.

Table 4.4 Example of tourism, business, normal and remote cities

Group	*Cities*
Tourism	Orlando (MCO), Ft. Lauderdale (FLL), Honolulu (HNL), Las Vegas (LAS), San Juan (SJU)
Business	Atlanta (ATL), New York Newark (EWR), New York La Guardia (LGA), New York John F. Kennedy (JFK), Philadelphia (PHL), Dallas Ft. Word (DFW), Boston (BOS)
Normal	Los Angeles (LAX), San Jose/Palo Alto (SIT), Salt Lake City (SLC), Nashville (BNA), Tulsa (TUL)
Remote	Dutch Harbor Alaska (DUT), Guam Island (GUM), San Angelo Texas (SJT), Helena (HLN), Bar Harbor Maine (BHB)

In Appendix F, the analysis of the US domestic airlines fares consumer report database is presented to discover possible determinants of airfares. The analysis compares the average fare, average distance, total pax per day, average fare per distance, average pax per distance and number of routes between the FSC and the LCC markets. It also makes an analysis of the competition between airlines business models: Routes without LCC's operations (FSC-FSC), routes with FSC's and LCC's operations (FSC-LCC), and routes without FSC's operations (LCC-LCC). In Appendix F, each US airport is classified according to the number of passengers served by the airport per day: A, B, C, D and E (Table Appendix F. 3).

Each route can be classified in 15 different route types (AA, AB, AC, AD, AE, BB, BC, BD, BE, CC, CD, CE, DD, DE and EE) depending on the origin and destination airports type. This classification has been used to analyze airline fares between airport groups. It was found that airline fares are influenced by the airports sizes. The numbers of FSC's flying operations are higher than the number of LCC's flying operations for each of the 15 different route types (Table Appendix F. 7 and Table Appendix F. 8). It can be an indication about the possibility of increase low-cost services.

Another aspect is the impact of the length of a route on the parameters. Therefore, routes are classified as follows: very short-haul (D_r < 402km), short-haul (402km < $D_r \geq$ 804km), medium-haul (804km < $D_r \geq$ 1,930km) and long-haul (D_r > 1,930km).

Other parameters are the airlines market share (MS), low-cost airline market share (LCMS), and lowest fare airline market share (LOWMS).

Finally, different dummy parameters were developed to take into account the presence of LCC's, an airport hub (HUB), no competition with other airlines (ALONE) and competition (NOTALONE).

The mentioned parameters were developed based on literature (Table 4.2), the fare analysis (Section 4.2) and the US domestic airlines fares consumer report database (Appendix F).

Table 4.5 summarizes the variables that have been explained through this section and that form the multi-regression equation. This FEM equation is as follows:

$$F_{est\,r} = A_4\, D_r^{\alpha} f_a^{\beta_a} C_m^{\gamma_m} C_k^{\gamma_k} Route_b^{\varphi_1} Comp_y^{\varphi_2} Eco_e^{\varphi_3} Haul_q^{\varphi_4} WN^{\varphi_5} HUB^{\varphi_6} LOW^{\varphi_7} LOWMS^{\varphi_8} LCMS^{\varphi_9} Z^{\varphi_{10}} \quad (4.3)$$

Where:

F_{est} = average fare estimation or prediction [usd]

The FEM model parameters and their units are explained in Table 4.5

The fare estimation model is a union between the AOC model (Chapter 3) and airport fees, social, economic and competitive factors. This model considers airlines operating costs and other factors such as competition between airlines business models, route airport types, route airports relationship type and main source of cities economic growth.

Table 4.5 FEM model parameters

Type of parameter	*Name*	*Variable*	*Units*	*Type of parameter*	*Name*	*Variable*	*Units*
Route link distance	Distance	D = actual value	km	Airport fees factor	Origin (ORI)	M	usd / pax
Airline operating cost factor	f	a = airline	usd / km / pax		Destination (DES)	K	usd / pax
Haul classification	Very short	If q = 1	-	Cities main source of economic growth variables	T-T	If e = 1	-
	Short	If q = 2	-		T-B	If e = 3	-
	Medium	If q = 3	-		T-N	If e = 5	-
	Long	If q = 4	-		T-R	If e = 7	-
Airport/city relationship route classification	AA	If b = 1	-		B-B	If e = 9	-
	AB	If b = 3	-		B-N	If e = 15	-
	AC	If b = 5	-		B-R	If e = 21	-
	AD	If b = 7	-		N-N	If e = 25	-
	AE	If b = 11	-		N-R	If e = 35	-
	BB	If b = 9	-		R-R	If e = 49	-
	BC	If b = 15	-	Presence of Southwest Airlines (WN)	WN	WN = 1	-
	BD	If b = 21	-		NO WN	WN = 0	-
	BE	If b = 33	-	Either the airport origin or destination is a hub	HUB	HUB = 1	-
	CC	If b = 25	-		NO HUB	HUB = 0	-
	CD	If b = 35	-	Presence of other LCC different than WN	LCC	LCC = 1	-
	CE	If b = 55	-		MORE THAN 1	LCC = 0	-
	DD	If b = 49	-		NO LCC	LCC = 2	-
	DE	If b = 77	-	Airline market share	MS	Value	-
	EE	If b = 121	-		LOWCMS	Value	-
Comp	FSC-FSC	If y = 1	-		LCMS	Value	-
	LCC-LCC	If y = 2	-	Airlines operating alone	Alone	Z = 1	-
	FSC-LCC	If y = 3	-		Not Alone	Z = 0	-

The multi-regression (Equation 4.3) can be transformed to its linear form (Equation 4.4) to estimate its coefficient values by the OLS method.

$$\ln F_{est\,r} = \ln A_4 + \alpha \ln D_r + \beta_a \ln f_a + \gamma_m \ln C_m + \gamma_k \ln C_k + \varphi_1 \ln Route_b + \varphi_2 \ln Comp_b + \varphi_3 \ln Eco_e + \varphi_4 \ln Haul_q + \varphi_5 \ln WN + \varphi_6 \ln HUB + \varphi_7 \ln LOW + \varphi_8 \ln LOWMS + \varphi_9 \ln LCMS + \varphi_{10} \ln Z + \varepsilon_r \quad (4.4)$$

The parameters of Equation 4.4 have been determined by analyzing approximately 18,000 US domestic routes. However, some fares in this database might be outliers. An outlier is an observation that is numerically far from the rest of the data. It is data that are not indicative that it can happen again in future years [Balakrishnan and Childs, 2002]. They occur by chance in any database due to incidental errors, false or erroneous procedures. In a very large database, a small number of outliers can be expected and must be removed. For example, in the US domestic airlines fares consumer report database, two routes operated by Spirit Airlines (OO) had an average fare less than 1 usd. These routes were operated from Los Angeles Int. (LAX) to St. George Utah (SGU) and from San Francisco Int. (SFO) to Modesto City County (MDO). Comparing these fares with similar OO routes in the database and with the OO operating costs (AOC model), it is fair to assume that both these fares are errors in the database or the airline has lowered fares to attract more passengers. In any case, it is not realistic to expect that these fares will be that low again in subsequent years. Therefore, these fares were considered as outliers.

Chi and Koo [2009] used two methods to eliminate outliers. The first method removes the top and bottom 1% of airfare data. The second method removes airfares that are five times higher than the US SIFL levels [Borenstein, 2005]. Here, both methods are used to eliminate outliers on the DOT US Consumer Reports [2005-2008].

The coefficient values of Equation 4.4 are calculated by the OLS method by minimizing the sum of square percentage error ($SSE\% = \frac{F_{est_r} - F_{real_r}}{F_{real_r}}$) between real fares data points and the fares calculated by the FEM model. The model coefficient values are presented in Table Appendix G. 5, Table Appendix G. 6, Table Appendix G. 7, and Table Appendix G. 8.

The model can be validated by discussing three questions:

1. Is the FEM model a useful model?
2. Is there little variability or low fluctuation around the regression line of the FEM model?
3. In a linear regression model, it is assumed that the dependent variable (DV) is normally distributed [Lumley et al, 2002]. Does the model hold this assumption?

The analysis is comprised of all the significant parameters that form the average fare estimation model (FEM). Table 4.6 shows the correlation analysis between logarithm fares estimated by Equation 4.4 and the logarithm of the fares data points from years 2005 to 2008. In Appendix G, the analyses of variances (ANOVA test) are presented. The ANOVA tests analyse if all the multi-regression coefficient values could be zero, if all of them are zero, none of the IV's has a relationship with the DV. At least one of the coefficient values must not be zero (alternative hypothesis (H_a)) to reject the hypothesis null (H_0) (Equation 4.5).

F-test statistical test:

H_0: $\beta_a = \gamma_m = \gamma_k = \varphi_1 = \varphi_2 = \varphi_3 = \varphi_4 = \varphi_5 = \varphi_6 = \varphi_7 = \varphi_8 = \varphi_9 = \varphi_{10}$ (4.5a)

H_a: at least one coefficient must be different than zero (4.5b)

The F distribution test results (Table 4.6) show that the significant values (Sig. F test) for all the years are 0.000. The F test only tells if there is a relationship between the IV's and the DV. It does not really speak about what the relationships are between the IV's and DV. If a 5% level of significant is used, it can be assumed that at least one of the model coefficient values is not zero since the Sig. F test are smaller than 0.05. It rejects the hypothesis null (H_0).

It proves the IV's in Equation 4.4 do have an influence on logarithm of fares, proving Equation 4.4 is useful to calculate the logarithm of route fares.

Table 4.6 Logarithm FEM model analysis

	Average ln $F_{est\,r}$ (usd)	*R*	*Adj. R^2*	*S_{xy} ln $F_{est\,r}$ (usd)*	*F test*	*Sig. F test*	*CV_{reg} (%)*
2005	5.23	0.86	0.73	0.1417	130.87	0.000	2.7
2006	5.33	0.86	0.73	0.1478	135.93	0.000	2.8
2007	5.33	0.86	0.75	0.1509	147.12	0.000	2.8
2008	5.38	0.86	0.73	0.1530	140.35	0.000	2.8

The student's t statistic test (Equations 4.6) looks if each IV has a significant relationship with the DV. In other works, the t test explains whether a particular parameter contributes significantly to the regression model or not.

Student's t-test statistical test:

H_0: $\beta_a = 0\,;\ \gamma_m = 0\,;\gamma_k = 0\,;\ \varphi_1 = 0\,;\ldots;\varphi_{10} = 0$ (4.6a)

H_a: whether the parameter contributes significantly to the regression model or not (4.6b)

The student's t statistic test results are shown in Table Appendix G. 5, Table Appendix G. 6, Table Appendix G. 7, and Table Appendix G. 8. The model parameters t test p values indicate that most of the IV's are significant at 5% level. Few parameters have a greater p value than 5% suggesting that these variables are not significantly related to fares. The logarithmic multi-regression (Equation 4.4) looks at the convention that predicts better the DV (route fares). Despite having a weak relationship, all IV's help to increase the predicting power of the model. The FEM model predictions are better with the apparently none significant variables than without them because the correlation between the logarithm of real fares and Equation 4.4 calculations increases, and the dispersion of the errors are narrow. Since the intention of this model is to predict fares, rather than looking into the interpretation of the IV's impact on fares, the model as given in Equation 4.3 is used.

The variability of the model is discussed by the adjusted coefficient of determination and the standard error of the estimate calculated by SPSS software (Table 4.6). The closest the adjusted correlation (Adj. R^2, Table 4.6) is to 1, the less variability of fares. The FEM model adjusted correlation results are over 0.73 for all the years. Over 73% of the variability of the estimated fares is explained by the variability of the model IV's.

Equation 4.7 defines the coefficient of variation that evaluates the variability of the data set. Since the CV_{reg} is smaller (Table 4.6) than 10% a little variability on predicted fares by the FEM model exists. The FEM model prediction intervals are accurate because 10% variability between Equation 4.4 calculations and the logarithm of the fares data indicates small dispersion. This confirms that the model can be used for prediction purposes.

$$CV_{reg} = \frac{S_{xy}}{\text{Average}\ln(F_{est_r})} \tag{4.7}$$

In a linear regression model, it is assumed that the dependent variable (DV) is normally distributed [Lumley et al, 2002], and since the coefficient values of the IV's parameters have been estimated by OLS method, Equation 4.4 calculations need to fulfill the assumption of normally distributed. The central limit theorem partially explains the predominance of the normal probability distribution. The theorem states that the distributions of means will increasingly approximate a normal distribution as the size of data samples increases [Dekking, Kraaikamp, Lopuhaa, Meester, 2005]. The central limit theorem also explains that the average of a large number of independent random parameters is normally distributed around the mean. Thus, the central limit theorem guarantees that it will be normally distributed in a large sample sizes, and then the statistic t-test, F-test and the coefficient of variation are valid [Lumley et al, 2002]. The linear regression, Equation 4.4, coefficient values have been estimated by using 18,000 domestic routes. A data sample of 18,000 routes is high enough to hold the central limit theorem. At the same time, the central limit theorem also holds for the distribution of the residuals as normally distributed. Figure 4.7 shows the regression standard residuals histogram. It can be noticed that they are normally distributed.

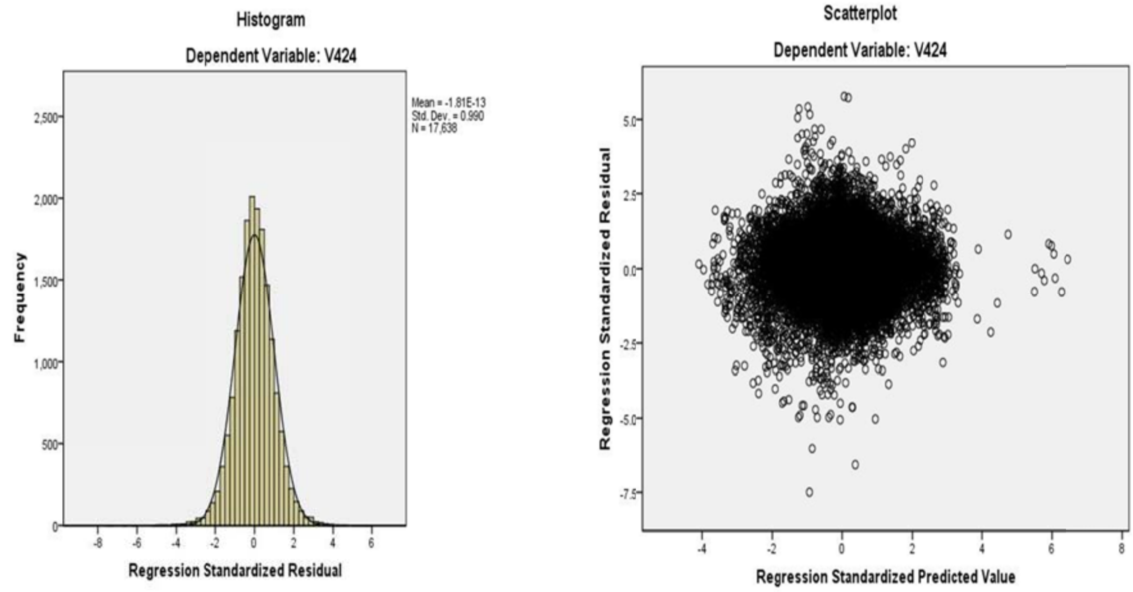


Figure 4.7 Regression standard residuals SPSS results, for year 2005

Table 4.7 shows the correlation results, the sum of square percentage errors (SSE%), the total number of routes and the routes inside ±10% and ±20% SSE%. The FEM model calculates fares within 20% with a correlation over 85% for the complete air transportation market from years 2005 to 2008 databases. The results confirm that the model reduce the dispersion since over 54% routes fares calculations are inside ±10% interval error and over 83% are inside ±20% interval error. The results confirm that the FEM models IV's (Table 4.5) are airfare pricing determinants. 85% from approximately 18,000 routes inside ±20% interval error confirm that the FEM model calculates airfares accurate enough.

Table 4.7 FEM model results

	Relation values between FEM model fares calculations and real fares route data points					*Models percentage of data interval errors*		
	R	*R^2*	*SSE%*	*Min SSE%*	*Max SSE%*	*Total routes*	*% Routes inside ±10%*	*% Routes inside ±20%*
2005	0.86	0.74	370.61	-0.56	1.89	17,639	58	87
2006	0.85	0.73	402.38	-0.61	1.24	17,584	55	85
2007	0.86	0.73	413.75	-0.63	1.45	17,502	54	84
2008	0.86	0.74	412.01	-0.59	1.55	17,162	55	83

Figure 4.8 shows the correlation between real fare data and the fares calculated using the FEM model, Equation 4.4, and the error distribution results for the years 2005, 2006, 2007 and 2008. As it can be noticed, 95% of the fares calculated by the model are inside the ±25% interval error, except for the case for the year 2007 where more fare dispersion is found. The model is equally accurate for expensive and cheap routes since the accumulative distribution is symmetric, except the case for the year 2007. During this year, the model is less accurate for cheap routes where the percentage error is negative. Figure 4.8 shows how accurate the model according with the SSE%. The FEM model calculated over 56% of the routes inside ±10% error, and over 78% of the routes inside are calculated inside ±15% error. It proves that even when some calculations still having an enormous difference with the real data, most of the calculations are accurate enough.

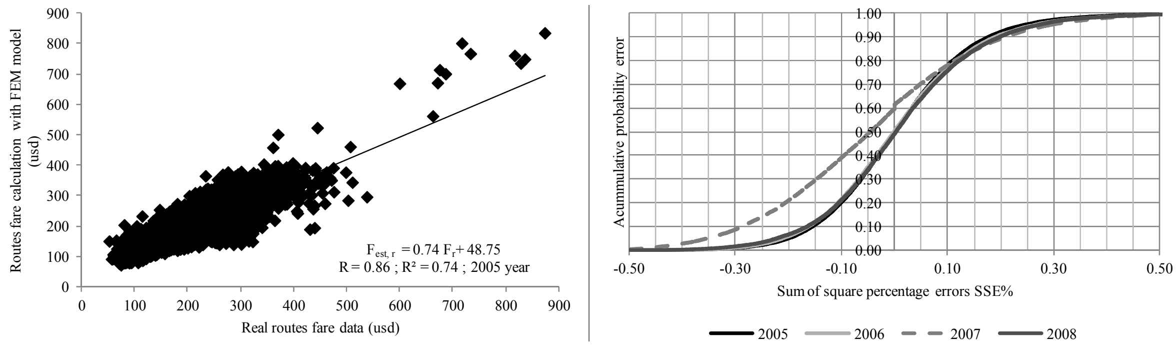


Figure 4.8 Correlation analyses fares calculated with the FEM model

Figure 4.9 shows how accurate the model is according with the number of routes. The FEM model calculated over 17,000 routes inside ±25% error. This results point out that the FEM model is a good model that calculates over 90% of route fares with accuracy of ±25% error.

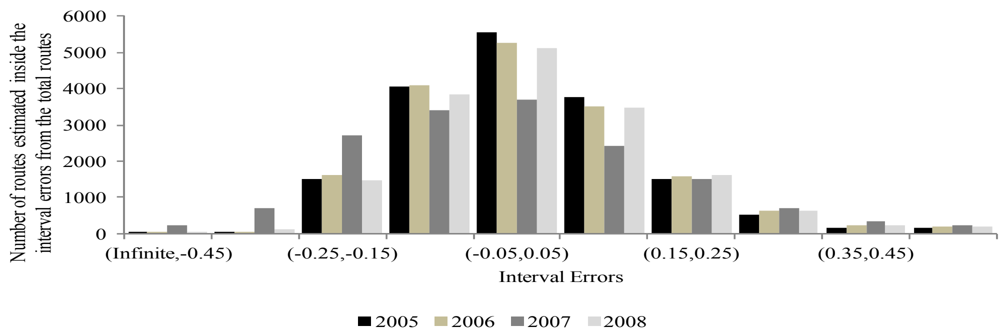


Figure 4.9 Total numbers of routes calculated inside different interval errors

Collinearity happens when a multi-regression model has symptoms of exact linear relationships within variables [Sundberg, 2002]. The problem is that, as the IV's become more correlated to each other, it becomes more and more complicated to determine which IV is actually producing what effect over the DV. However, the predictive power of a multi-regression equation can be more accurate using collinear IV's. Although multicollinearity can be a major problem in the interpretation of multi-regression coefficients, it is not really a mathematical statistical problem because it does not adversely affect the regression equation if the purpose is only to predict the DV's. For this reason, tests for collinearity determination between IV's have not been performed. This is supported by Grosche, Rothlaf and Heinzl [2007]. They state that multicollinearity is not important for forecasting if the model offers a good fit between real data and its calculations.

4.4 Competitive fare estimation model (CFEM)

The FEM model calculates airline routes fares sufficiently accurate. However, the objective is to calculate the most convenient fare to identify routes where an airline can open new services. The FEM model can calculate the airlines averages route fares at different markets. The FEM model cannot calculate the expected range between airlines route fares. This is important. Under competition airlines need to know how low the other airlines fares can be. Airlines can identify routes to open new service by knowing the other airlines possible minimal and maximum route fares.

In this section, a mathematical model to calculate airlines route fares range is proposed. A method to identify possible routes to open services is designed. This helps airline managers to determine what routes can be successfully operated by an airline based on the calculation of the most competitive low fare. The competitive fare estimation model (CFEM) uses route distance (D_r) as only parameter to calculate route fares:

$$F_{est_r} = m_j D_r + b_j \tag{4.8a}$$

Subject to:

$$m_j = \begin{cases} m_1 & \text{if} \quad D_r < D_1^* \\ m_j & \text{if} \quad D_r \geq D_{j-1}^* \end{cases} \tag{4.8b}$$

$$b_j = \begin{cases} b_1 & \text{if} \quad D_r < D_1^* \\ b_j & \text{if} \quad D_r \geq D_{j-1}^* \end{cases} \tag{4.8c}$$

$$b_{j-1} = b_j + D_{j-1}^* \left(m_j - m_{j-1}\right) \tag{4.8d}$$

$$j \geq 2 \tag{4.8e}$$

Where:

F_{est}	= Route fare estimation	[usd]
r	= route	[-]
D_r	= Route distance	[km]
m	= coefficients	[usd / km]
b	= coefficients	[usd]
D*	= Distance division segment point	[km]
j	= number of segments	[-]

The CFEM model ensures the continuity of the straight lines by recalculating the values of the parameters m_j and b_j at each distance division point D*.

The CFEM model is based on the generation of a linear equation that calculates airline fares using distance as the only parameter. The CFEM divides the database under study into different segments. The model finds the D*'s where the regression line has to change its slope (m) in order to minimize the difference between real fares and the CFEM fares calculation. The maximum number of segments j is equal to the total number of D*'s plus 1 (Figure 4.10).

Figure 4.10 shows an example of how the CFEM is set-up to find four distance points. In this case, if the database is divided in more than four segments the CFEM coefficient values are not going to change after D_4*. The reason is that the model coefficient values (m and b) for D_4* and D_5* are going to be the same. In Figure 4.10, the line changes its slope at four distance points (300km, 500km, 900km and 1,100km).

The CFEM finds the maximum number of D*'s by iteration. First, the model is set up for one D*. Then for two D*'s and so on, until the $m_{j-1} = m_j$ and $b_{j-1} = b_j$.

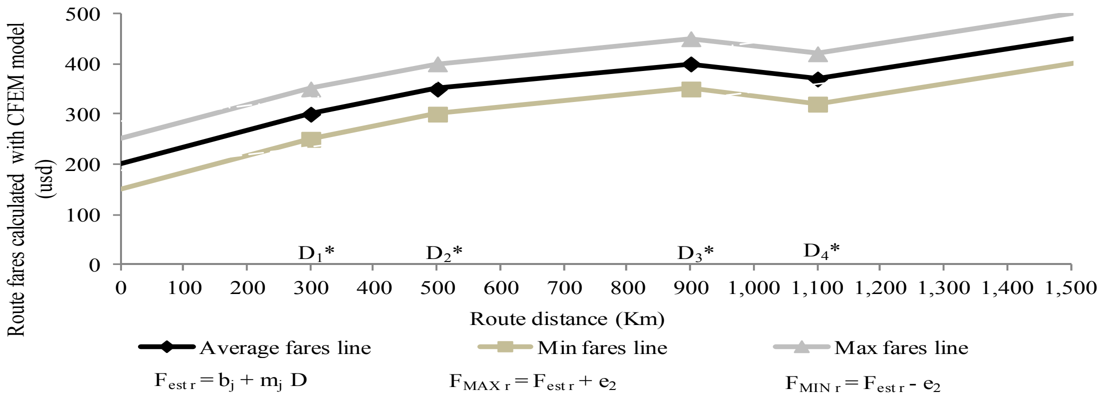


Figure 4.10 CFEM model theoretical example

The CFEM number of D*'s can be chosen by the user as long as it does not exceed the maximum number of possible segments. For example, it is possible to divide Figure 4.10 in three segments: short-haul, medium-haul and long-haul. The model will find the distance where D_1* and D_2* are.

The CFEM coefficient values and the distance division points segments (D*'s) are determined by the OLS method by minimizing the sum of square error (SSE) (Equation 4.9) constrained to ensure the continuity of the straight lines at D*'s (Equation 4.8b and Equation 4.8c).

$$S = \sum_{r=1}^{R} e_{1_i}^2 = \sum_{r=1}^{R}\left(b_j + m_j D_r - F_{real_r}\right)^2 \qquad (4.9)$$

Where:

$$e_{1_r} = F_{est_r} - F_{real_r} \qquad (4.10)$$

F_{real} = Real route fare database [usd]

R = Total number of routes in the market under study [-]

The CFEM model also calculates a minimum and maximum routes fares lines (Figure 4.10). These fare values are calculated to include a required percentage of routes between both lines. In this thesis, this percentage is the standard deviation, what means 68% from the total routes fares are inside the minimum and maximum lines. The standard deviation has been chosen because it is a measurement of variability. It shows how much dispersion exists in the data (Equations 4.11).

$$|e_{est}|_r = \Delta m_j D_r + \Delta b_j \qquad (4.11a)$$

Subject to:

$$\Delta m_j = \begin{cases} \Delta m_1 \text{ if } D_r < D_1^* \\ \Delta m_j \text{ if } D_r \geq D_{j-1}^* \end{cases} \qquad (4.11b)$$

$$\Delta b_j = \begin{cases} \Delta b_1 \text{ if } D_r < D_1^* \\ \Delta b_j \text{ if } D_r \geq D_{j-1}^* \end{cases} \qquad (4.11c)$$

$$\Delta b_{j-1} = \Delta b_j + D_{j-1}^* \left(\Delta m_j - \Delta m_{j-1}\right) \qquad (4.11d)$$

$$j \geq 2 \qquad (4.11e)$$

Where:

Δm = coefficients [usd / km]

Δb = coefficients [usd]

The CFEM model ensures the continuity of the straight lines by recalculating the values of the parameters Δm_j and Δb_j at each distance division segment point D*.

The CFEM minimum and maximum straight lines coefficient values are determined by the OLS method by minimizing the SSE (Equation 4.12) constrained to ensure the continuity of the straight lines at D*'s (Equation 4.11b and Equation 4.11c).

$$S = \sum_i e_{2_i}^2 = \sum_{r=1}^{R}\left(\Delta b_j + \Delta m_j D_r - F_{real_r}\right)^2 \tag{4.12}$$

$$e_2 = e_{est} - |e_1| \tag{4.13}$$

If low dispersion exists, data fares tend to be very close to the average fare line. If high dispersion exists, data fares tend to be far away from the average fare line. The CFEM considers fare dispersion by calculating fare values of those routes that are cheaper (Equation 4.14a) and more expensive (Equation 4.14b) than the market average fare.

$$F_{est\,r_{min}} = F_{est\,r} - e_2 \tag{4.14a}$$

$$F_{est\,r_{max}} = F_{est\,r} + e_2 \tag{4.14b}$$

The calculation of the minimum and maximum route fares is important. An airline intending to identify routes that represent a possibility to open new services needs to compare its fares with the cheapest possible fares that other airlines can charge. For example, on average LCC's fares are cheaper than FSC's, but FSC's show more fare dispersion (Chapter 3, AOC model analysis). This means FSC's minimum route average fare ($F_{min_{FSC}} = F_{est_{FSC}} - e_{2_{FSC}}$) might or might not be as cheap as the LCC's route average fare ($F_{est\,r_{LCC}} = F_{est_{LCC}}$).

Finally, by multiplying the absolute standard deviation $e_{est\,r}$ by all the numbers in the range U [-3, 3], all possible route fares at distance D_r are calculated (Equation 4.15). At ±1 standard deviation, 68% of the possible route fares are calculated [-1, 1]. At ±2 standard deviations, 95% of the possible route fares are calculated [-2, 2]. Thus, at ±3 standard deviations 99.7% route fares are calculated.

$$F_{est_{r_U}} = F_{est_r} + |e_{est}|_r = \left(D_r + b_j\right) + U\left(\Delta m_j D_r + \Delta b_j m_j\right) \tag{4.15}$$

Table 4.8 shows the CFEM model parameters calibrated for the US domestic market and the FSC and the LCC domestic markets separately. The CFEM model has divided the route lengths in two segments at the division distance point D*. With these coefficient values, routes fares dispersion at D_r can be observed, for these markets, by plotting fares versus the normal distribution function (Equation 4.16). Figure 4.11 shows the fares values calculated for these markets at 1,207km route length.

$$f\left(F_{est_{r_U}}\right) = \frac{1}{\sqrt{2\pi|e_{est}|_r^{\,2}}} \exp^{\left(-\frac{\left(F_{est_r}\right)^2}{2|e_{est}|_r^{\,2}}\right)} \tag{4.16}$$

Table 4.8 US CFEM model coefficient values

Market	D* (km)	m_1	b_1	m_2	b_2	Δm_1	Δb_1	Δm_2	Δb_2
US 2005	4,035	0.03	152.33	0.06	66.30	-0.0001	40.00	0.01	14.06
FSC	3,950	0.03	160.19	0.06	83.30	-0.0004	37.55	0.01	13.71
LCC	4,145	0.03	110.29	0.09	65.91	-0.0001	25.00	0.01	-1.65

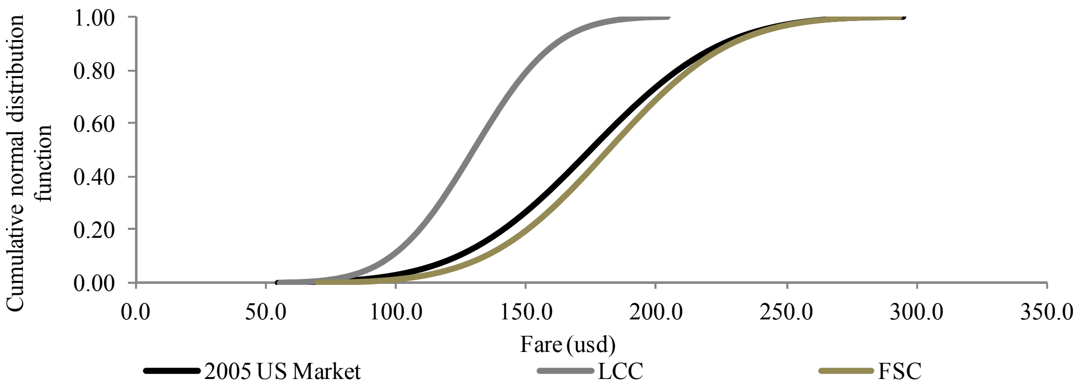


Figure 4.11 US Market fares cumulative normal distribution at 1,207km

As an example, assume that the CFEM model has been set up for three general segments: short-haul, medium-haul and long-haul:

$$F_{est_r} = m_j D_r + b_j \quad (4.17a)$$

Subject to:

$$m_j = \begin{cases} m_1 \text{ if } D_r < D_S^* & \text{"Short − haul"} \\ m_2 \text{ if } D_r \geq D_S^* & \text{"Medium − haul"} \\ m_3 \text{ if } D_r \geq D_L^* & \text{"Long − haul"} \end{cases} \quad (4.17b)$$

$$b_j = \begin{cases} b_1 \text{ if } D_r < D_S^* & \text{"Short − haul"} \\ b_2 \text{ if } D_r \geq D_S^* & \text{"Medium − haul"} \\ b_3 \text{ if } D_r \geq D_L^* & \text{"Long − haul"} \end{cases} \quad (4.17c)$$

$$b_2 = b_1 + D_S^* \, (m_1 - m_2) \quad (4.17d)$$

$$b_3 = b_2 + D_L^* \, (m_2 - m_3) \quad (4.17e)$$

$$D_L^* > D_r^* \geq D_S^* \quad (4.17f)$$

$$j \in \{1, 2, 3\} \quad (4.17g)$$

Where:

D_L* = Distance division segment point between long and medium-haul [km]

D_S* = Distance division segment point between medium and short-haul [km]

Calculation of the minimum and maximum straight lines:

$$|e_{est}|_r = \Delta m_j D_r + \Delta b_j \quad (4.18a)$$

Subject to:

$$\Delta m_j = \begin{cases} \Delta m_1 \text{ if } D_r < D_S^* & \text{"Short − haul"} \\ \Delta m_2 \text{ if } D_r \geq D_S^* & \text{"Medium − haul"} \\ \Delta m_3 \text{ if } D_r \geq D_L^* & \text{"Long − haul"} \end{cases} \quad (4.18b)$$

$$\Delta b_j = \begin{cases} \Delta b_1 \text{ if } D_r < D_S^* & \text{"Short − haul"} \\ \Delta b_2 \text{ if } D_r \geq D_S^* & \text{"Medium − haul"} \\ \Delta b_3 \text{ if } D_r \geq D_L^* & \text{"Long − haul"} \end{cases} \quad (4.18c)$$

$$b_2 = b_1 + D_S^* \, (m_1 - m_2) \quad (4.18d)$$

$$b_3 = b_2 + D_L^* \, (m_2 - m_3) \quad (4.18e)$$

$$D_L^* > D_r^* \geq D_S^* \quad (4.18f)$$

$$j \in \{1, 2, 3\} \quad (4.18g)$$

$$\Delta b_2 = \Delta b_1 + D_S^* \, (\Delta m_1 - \Delta m_2) \quad (4.18h)$$

$$\Delta b_3 = \Delta b_2 + D_L^* \, (\Delta m_2 - \Delta m_3) \quad (4.18i)$$

4.4.1 CFEM model routes selection method

The model can be used to study the fare competition between airlines business models (FSC-LCC, FSC-FSC and LCC-LCC), the behavior of fares at a different airport types (A, B, C, D and E) or to analyze fares at different airports relationship types (AA, AB, AC, AD, AE, ..., EE). The CFEM can study and compare specific airlines fares strategies such as American Airlines (AA), Southwest Airlines (WN), Continental (CO), Delta (DL), etc. First, all routes that belong to the market under study must be separated. Second, using these routes data points the CFEM model coefficient values must be calibrated by OLS method. In Appendix H, a study on the behavior of fares at different markets using the CFEM model is presented. In general, the CFEM model can study any specific market or any market division derived from Table 4.5.

To identify the possible routes that could be operated by a LCC with chances to be successful, the markets under study must be the FSC-FSC and the FSC-LCC. The FSC-FSC is left out of consideration because this market has the routes that are not operated by any LCC's. The FSC-LCC market describes the effects that LCC's cause when entering routes operated only by FSC's.

In this section, the CFEM method to identify possible new routes for airlines to operate is as follows:

1. The competitive fare is calculated by the CFEM model using the FSC-LCC market parameters values. Thus, the CFEM model needs to be calibrated to study the competition between LCC's and FSC's.
2. The routes that represent an opportunity to open new services are found by comparing the FSC-FSC routes with the routes fares calculated for the CFEM model using the model coefficient values of the FSC-LCC market.
3. If the route fare is more expensive than the CFEM FSC-LCC max route fare calculation plus five times the FSC-FSC market standard deviation or error (e_2) $F_r \geq F_{max_{FSC-LCC}} + 5\ e_{2_{FSC-FSC}}$, the route is chosen as candidate.
4. Now, the CFEM model is calibrated per airline operating each candidate route under FSC-LCC market conditions. It calculates all the airlines routes fares ranges in competition. Then, the airlines minimum route fare can be compared with the FSC-LCC max route fare $F_{max_{FSC-LCC}} \leq F_{min_a}$, the route is a possible candidate to open new services.
5. The airline entering a route needs to supply enough number of seats to avoid bad scenarios such as war prices. Enough demand must exist on the candidate routes. This demand is forecasted by the induced passenger forecasting model introduced in Chapter 5.
6. Finally, an optimization model that maximizes an airline net present value selects the airline network from the routes candidates. Here, additional factors are considered such as aircraft and airport characteristics (Chapter 6).

In the next paragraphs, an explanation of the CFEM methodology is presented. This example is based on Carmona Benitez and Lodewijks [2012]. The ten most expensive short-haul and long-haul routes in the US Domestic fare consumer report database are identified by using the CFEM model. The 5 standard deviations criteria (Point 3), to select routes candidate, are also explained.

4.4.2 Example

Figure 4.12 shows the results of analyses, using the CFEM model, of the US FSC-FSC, LCC-LCC and FSC-LCC competition markets for year 2005. In all these cases, the CFEM model found only one required division point D*. In all these markets, after D*, fares become more expensive faster as routes distances increase (Figure 4.12).

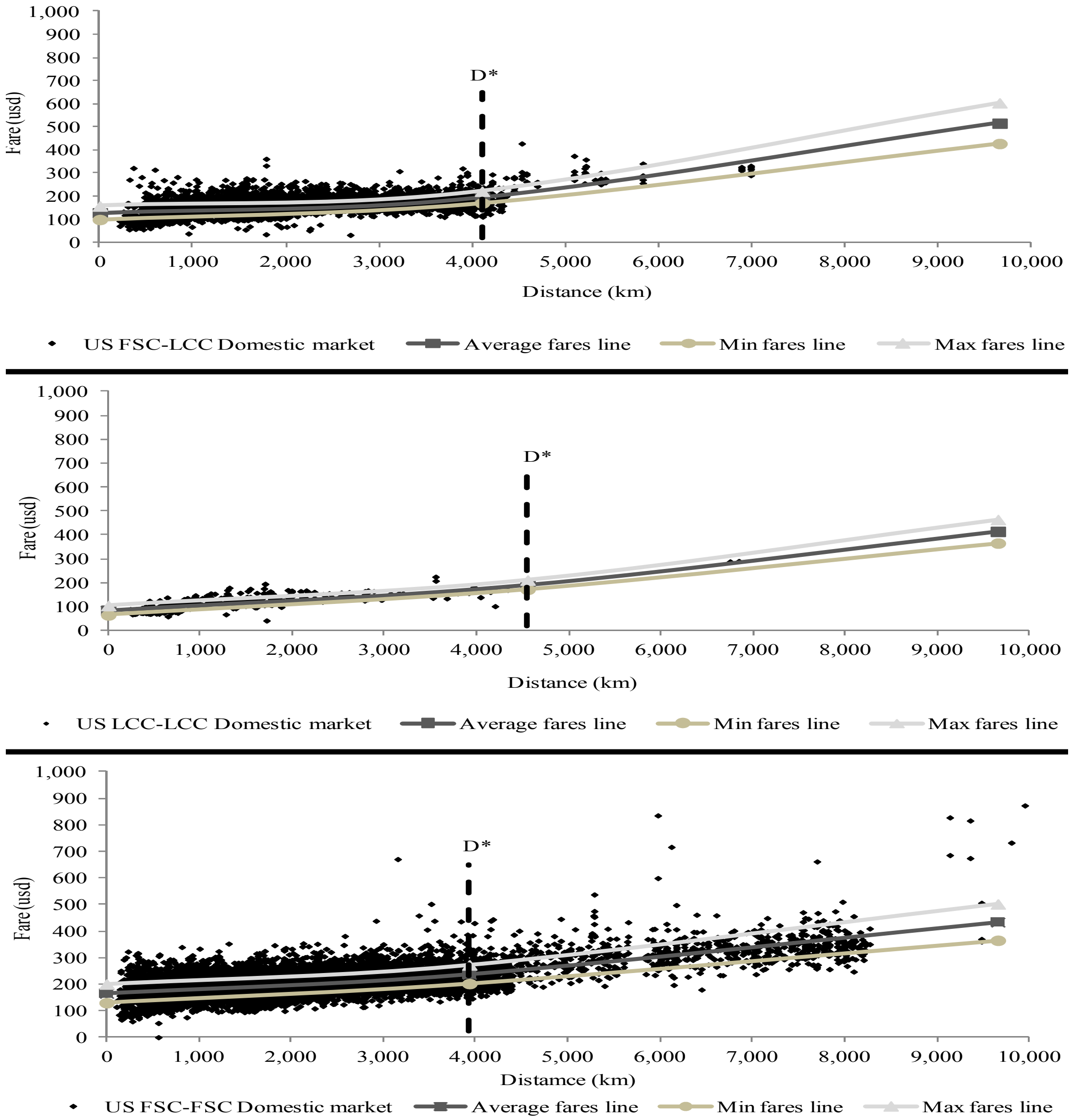


Figure 4.12 US 2005 business model airlines competition market

Table 4.9 shows the model coefficient values for each competition market. FCS-FSC routes are two times more expensive than LCC-LCC routes. Routes under competition (FSC-LCC) are half a time cheaper than FSC-FSC routes and half a time more expensive than LCC-LCC routes.

Table 4.9 US 2005 business model airlines competition market

Market	D* (km)	m_1	b_1	m_2	b_2	Δm_1	Δb_1	Δm_2	Δb_2
FSC-FSC	3,929	0.03	165.65	0.06	103.01	-0.0001	35.30	0.01	12.52
LCC-LCC	4,550	0.04	84.93	0.07	-7.38	-0.0001	19.65	0.01	-6.74
FSC-LCC	4,101	0.03	128.64	0.09	-40.14	-0.0020	29.25	0.02	-20.85

More dispersion is found for FSC-FSC routes in comparison with LCC-LCC and FSC-LCC markets. Thus, the difference between FSC-FSC routes maximum possible fare and the minimum possible fare is higher than FSC-LCC routes. The dispersion decreases after D*; fares are closer to the market average fares. LCC-LCC market had the lowest dispersion. FSC-LCC routes showed less dispersion than routes operated only by FSC's (FSC-FSC).

In Table 4.10, the number of routes that are more expensive than the FSC-LCC route maximum fare plus 1, 1.25, 1.5, 1.75, 2, 3, 4 and 5 times the FSC-FSC standard deviations ($e_{2_{FSC-FSC}}$) are counted. Airline managers can choose in which routes they want to open new services. They can select a number of standard deviations that they consider as criterion. In this thesis, as it has been mentioned, the selected criterion is five standard deviations. Therefore, 157 routes are considered from which 56 have a route length shorter than D* and 101 have a route length longer than D*.

Table 4.10 Number of FSC-FSC routes that represent an opportunity for a LCC to enter the market according with the FSC-LCC average fare at different standard deviations

Standard Deviation	*1*	*1.25*	*1.5*	*1.75*	*2*	*3*	*4*	*5*
Number of routes	7,374	6,498	5,594	4,717	3,921	1,495	476	157

In Figure 4.13, the cumulative normal distribution function is plotted to compare the FSC-FSC and FSC-LCC markets. It also shows the cumulative normal distribution function for routes fares that are, a certain number of standard deviations (stdv), more expensive than the FSC-LCC routes max fare. At three standard deviations, $F_r \geq F_{max_{FSC-LCC}} + 3\ e_{2_{FSC-FSC}}$, 50% of the data routes fares only operated by FSC's were as cheap as the FSC-LCC routes fares in the range U[0, 3]. At four standard deviations, $F_r \geq F_{max_{FSC-LCC}} + 4\ e_{2_{FSC-FSC}}$, 93% of the FSC-FSC routes fares were more expensive than the $F_{max_{FSC-LCC}}$. Finally, at five standard deviations, $F_r \geq F_{max_{FSC-LCC}} + 5\ e_{2_{FSC-FSC}}$, $F_{max_{FSC-LCC}}$ is cheaper than the $F_{r_{min}}$. This is the reason why 5 standard deviations is the criterion set to select route candidates. This criterion depends on the dispersion. Other databases might have higher or lower dispersions. Little dispersion increases the difference between $F_{r_{min}}$ and $F_{max_{FSC-LCC}}$.

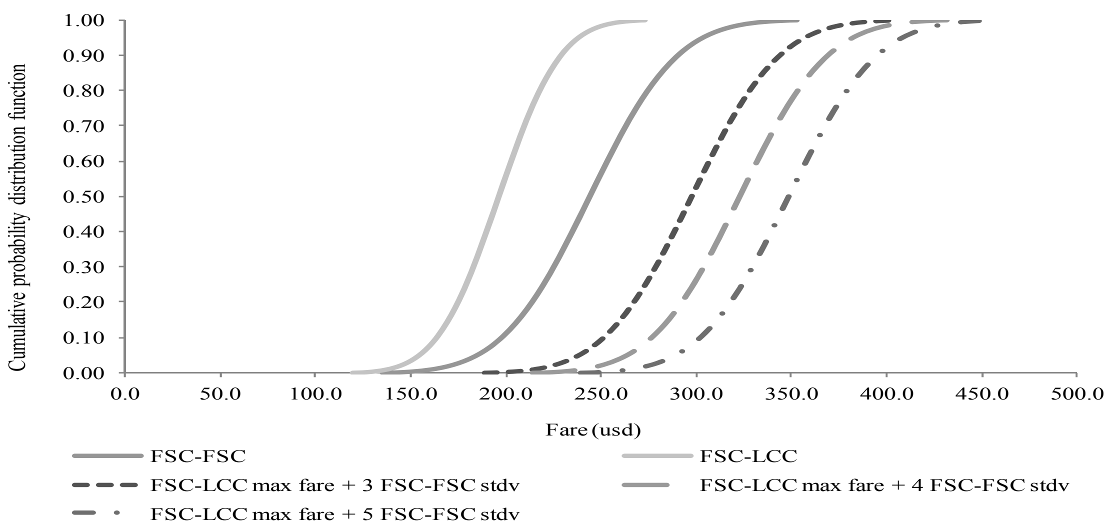


Figure 4.13 FSC-FSC and FSC-LCC fares cumulative normal distribution at 4,101km

Table 4.11 shows the most expensive short-haul routes from airport to airport. Eight of these routes represent an opportunity to open a new service. First, because they just have one airline providing service. Second, because they fulfilled the condition $F_{max_{FSC-LCC}} \leq F_{min_a}$.

Table 4.11 Ten most expensive short-haul routes

Airport 1	*Airport 2*	*Airline*	*Competitors*	*Distance (km)*	*Fare ($)*	*% MS*	*Fare – FSC-LCC 1 Stand. Dev. ($)*
ISP	PHL	US	-	209	301.15	91	140.01
CMH	PIT	US	-	232	323.10	97	161.61
HYA	LGA	US	-	317	309.45	97	146.64
BWI	PIT	US	-	338	316.38	95	153.24
CHO	PHL	US	-	338	317.52	95	154.39
ALB	PHL	US	-	341	303.04	94	139.85
DFW	LFT	CO	-	565	306.27	81	139.61
CRW	PHL	US	-	573	311.96	83	145.18
EWR	TOL	CO	AA, DL, NW	814	340.16	30	169.63
EWR	FWA	CO	AA, DL, NW	928	309.08	16	136.77

Two examples of short-haul routes with expensive fares are shown in Figure 4.14. Here, two different cases are presented. First, two routes from Charlottesville (CHO) to Philadelphia (PHL) and from Baltimore (BWI) to Pittsburgh (PIT) are found to be more expensive than two times the average FSC-LCC market fare. Second, from Newark (EWR) to Fort Wayne International Airport (FWA) Continental airlines (CO) average fare is more expensive than two times the average FSC-LCC market average fare. The other airlines operating this route are not. This also demonstrates how the CFEM model compares the pricing strategies for different airlines on the same route.

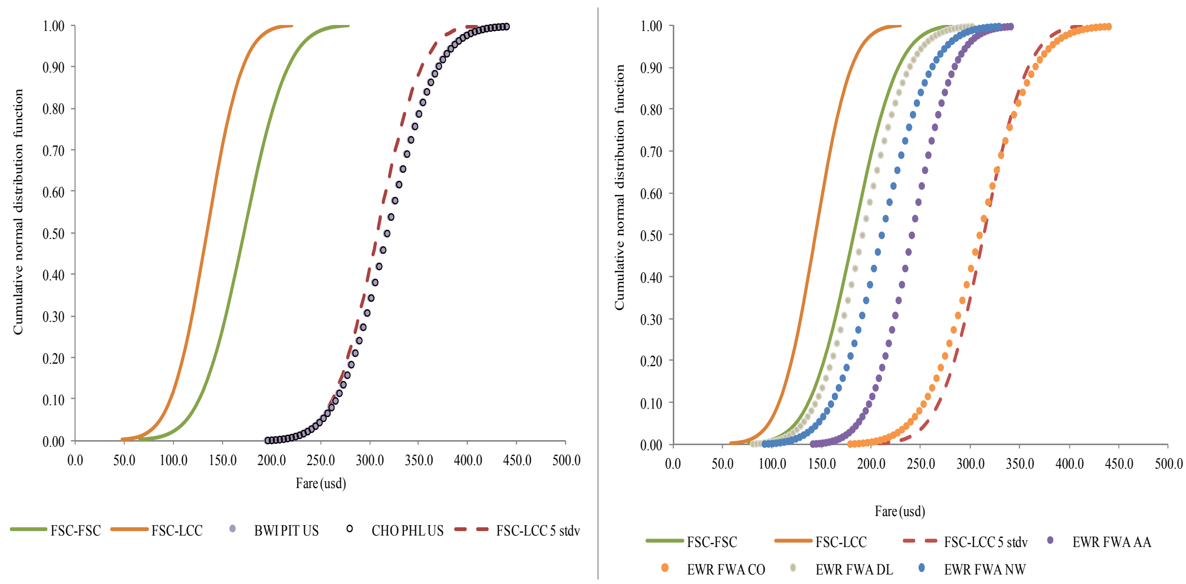


Figure 4.14 BWI PIT and CHO PHL routes (left) and EWR FWA route (right)

In the first case, these routes would represent an opportunity if the criterion is 5 standard deviations. However, if the criterion is 6 standard deviations, both routes do not represent an opportunity any more to open new services. Contrary, in the second case, although all airlines are more expensive than the FSC-FSC and FSC-LCC markets fares levels, all the airlines, except for CO, are cheaper than the selected criterion. This route is not an opportunity to open services given the applied criteria.

Table 4.12 shows the ten most expensive long-haul routes from airport to airport. Although, in these routes competition between FSC's does exist, in some of these routes, the lowest fare is more expensive than the FSC-LCC market average fares. In the US domestic passenger market, most of the most expensive routes have been found in long-haul markets. Thus, the possibility for low-cost operations in the long-haul routes exists but with a high risk. As the distance increases, the CFEM model fares calculations for the FSC-FSC and the FSC-LCC markets get closer (Figure Appendix H. 8). According to the criteria used 101 routes have a potential.

The most expensive route on the US long-haul market operated from Honolulu Int. (HNL) to Saipan Int. (SPN), and it was operated by CO and Northwest airlines (NW) (Figure 4.15). Figure 4.16 shows the most expensive routes founded by the proposed model. All these routes are five FSC-FSC standard deviations more expensive than the FSC-LCC average route fare. It is important to notice that some routes compete against other routes connecting airports nearby. For example, John F. Kennedy (JFK) is near La Guardia (LGA) and Newark (EWR), San Francisco Int. (SFO) is near San Jose/Palo Alto (SJC) and Oakland (OAK), and Los Angeles Int. (LAX) is near Glendale/Burbank (BUR), Long Beach (LGB) and Santa Monica (SMO). All routes between these airports compete between each other. Thus, when an airline operating a route connecting two airports have a high fare, another airline can be operating a similar route by connecting other airports in the cities. To solve this problem, the database has to be clustered by city pair. Then, the CFEM coefficients just need to be calibrated using the city pair database.

Table 4.12 Ten most expensive long-haul routes

Airport 1	*Airport 2*	*Airline*	*Others*	*Distance (km)*	*Fare ($)*	*% MS*	*Fare – FSC-LCC 1 Stand. Dev. ($)*
CSG	SEA	DL	-	3,550	438.84	98	225.85
DUT	SEA	AS	-	3,152	671.33	98	464.50
FAI	SLC	AS	DL	3,514	502.51	13	290.06
FAY	SEA	DL	US	3,836	436.53	37	219.09
HNL	PPG	HA	-	4,183	444.56	100	217.35
HNL	SPN	CO	NW	5,969	835.80	85	485.54
IAH	STX	AA	-	3,381	458.84	80	248.47
JFK	LAX	UA	AA, DL	3,982	430.53	15	210.82
JFK	SFO	UA	AA, DL	4,161	439.27	27	213.61
MSY	STX	AA	-	2,917	438.89	88	235.72

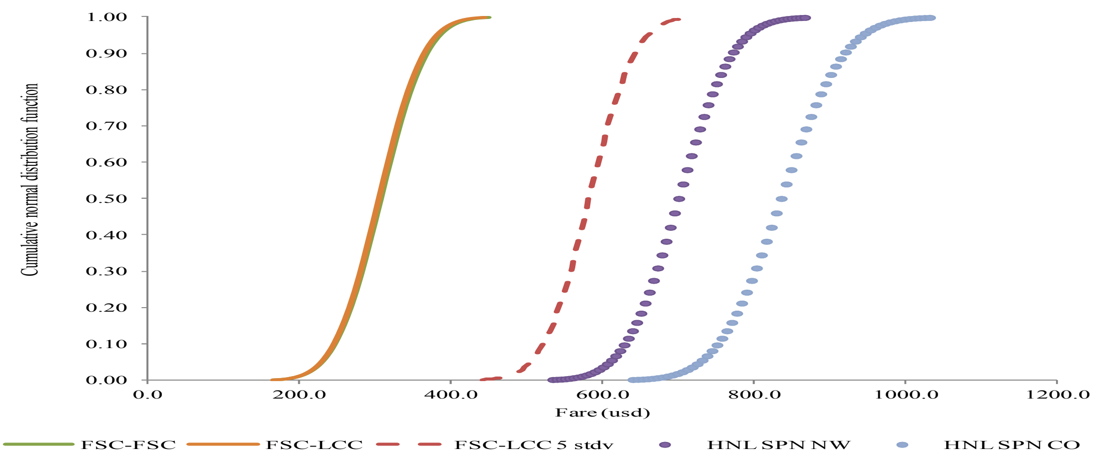


Figure 4.15 The most expensive long-haul route fare is operated by CO

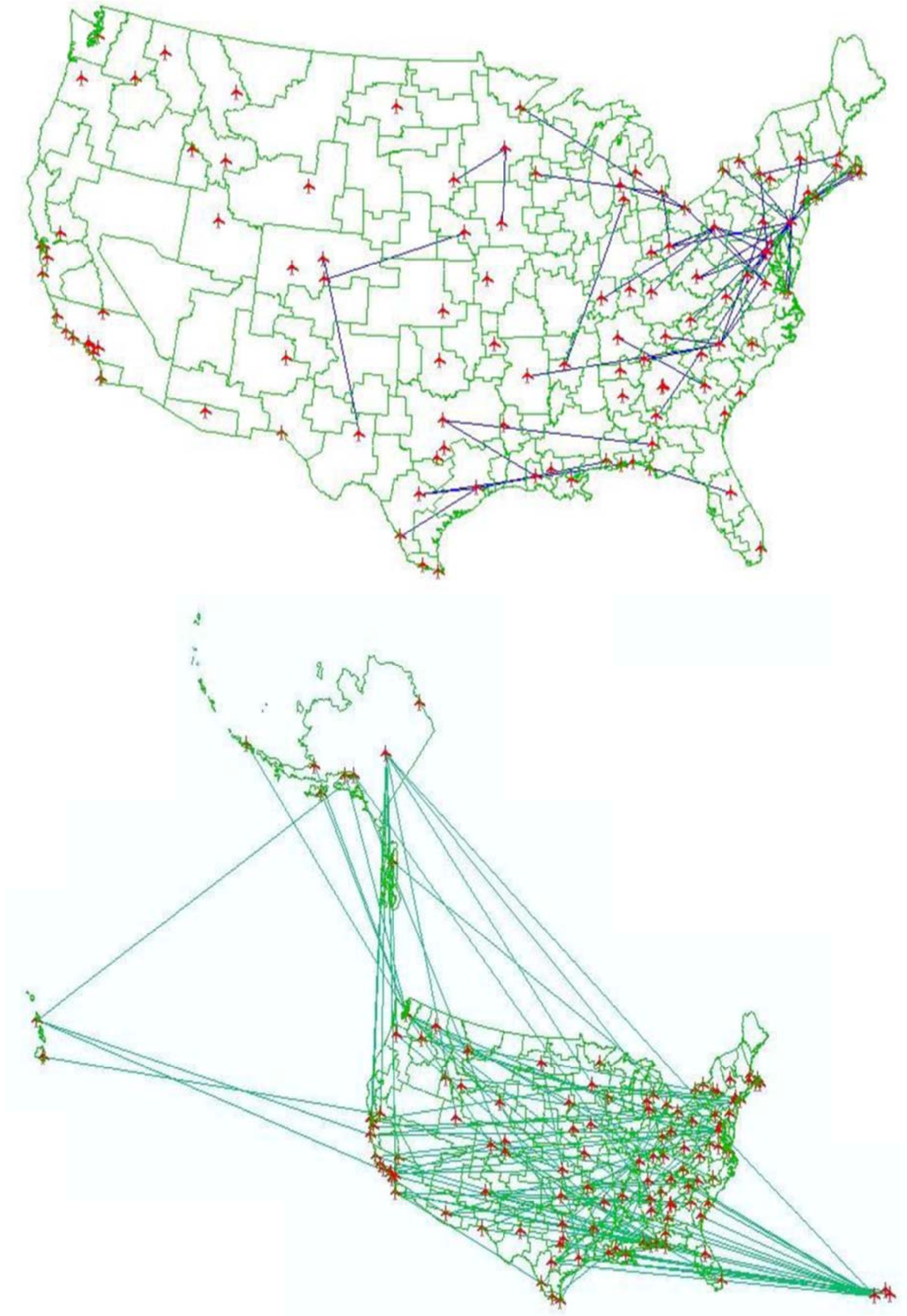


Figure 4.16 Most expensive short-haul routes (Dr < 1,126km) "up", and long medium-haul routes (Dr ≥ 1,126km) "down" selected by CFEM model methodology

4.5 Air fares forecasting method for long-term

The maximization of an airline network net present value (NPV) requires forecasting route fares values for future years. Economic agents are often used to estimate the future price of goods into the future. The consumer price index (CPI) quantifies changes in the price level of goods from one year to another year. The index is calculated by a combination of different items that form a market basket that represent the basic needs of a person in a country such as food, beverage, housing, transportation, medical care, etc. The CPI index expresses increases or decreases of goods and services prices. The CPI index represents the average amount spent by a household in a country for purpose of consumption.

The annual percentage change in a CPI between year t and t-1 calculates the inflation (INF). Inflation is a raise in the general level of prices of goods and services in an economy over a period of time, one year to another. The inflation rate can be used to calculate the value of money in a future year. This rate allows estimating the price of route fares in a future year (Equation 4.19). It is because the value of money increases or decreases as the inflation does. Then the prices of goods increase and decrease as inflation does.

$$F_{r,t} = F_{r,0}(1 + INF_t)^t \quad (4.19)$$

Where:

$F_{r,t}$	= Average price in year t	[usd]
$F_{r,0}$	= Average Fare present value	[usd]
INF	= inflation rate	[-]
t	= time in future (forecast number of year)	[-]

Figure 4.17 shows inflation rates and CPI's values from 1991 to 2010 [Inflationdata.com]. A Grey Model (GM) has been used to forecast the CPI values for future years. Appendix I explains in detail the Grey model (GM). This model has been used because its estimations are extremely accurate. The correlation between CPI's and CPI's estimates from 1991 to 2010 has a correlation of 98.45%.

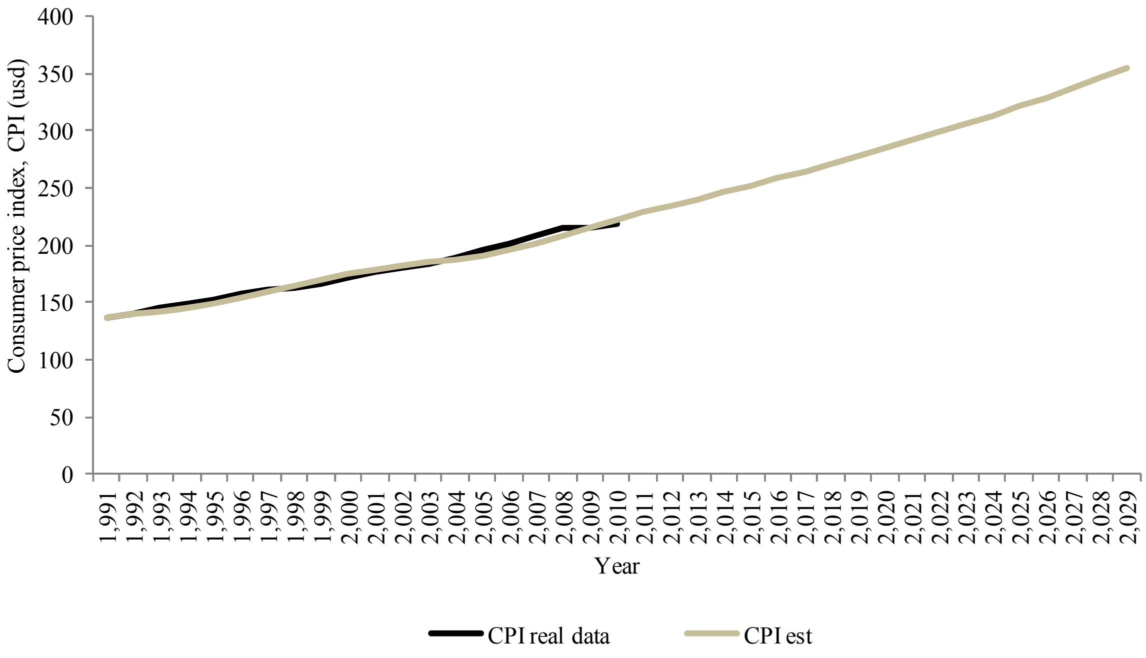


Figure 4.17 CPI values forecasted for future years using a GM model

4.6 Discussion

An airline thinking to open new services on a route needs to reduce its route fares on that route to enhance the flow of passengers coming from other airlines or from the induced demand or non served passengers. This indicates that fare is the variable that can be controlled to increase airline competitiveness, and low fares are the most important reason allowing airlines to open services on routes with and without competition. Then, for any airline is necessary to find and analyze the principal parameters determining routes fares to develop a mathematical model to identify how is possible to reduce fares in existing routes, what routes are attended with expensive fares and what new connections are potential new routes to extend its air passenger transport business.

In this chapter, two mathematical models, the fare estimation model (FEM) and the CFEM model, where developed to calculate airline fares, and to identify routes that represent an opportunity to open new airline services and invest. Both models were developed using real data. The FEM model has been found to be satisfactory accurate to calculate airline routes average fares, and the CFEM model calculates the most competitive fare. The CFEM model is the most suitable model for the purpose of this research because it is a method that determines the routes that represent an opportunity to open services by an airline based on the calculation of the most competitive fare.

The FEM model is a regression function that has been developed using the air passenger transportation industry determinants. Here, this equation has been confirmed to be an accurate mathematical function to calculate airlines average fares per route. The FEM is a union between the AOC model (Chapter 3) and airports fees, social, economic and competitive factors (Table 4.5). The model works well for the US Domestic market, but the numbers of variables make it difficult to know if the model is able to calculate airline route fares in other markets, as a general model. However, the analyses of the passenger transportation system and the literature review conclude these variables as airlines route fares determinants, and they are proved to be parameters that determine airline route fares according with the FEM model calculation results.

While discussing the results, it was evident that the FEM model can calculate airlines routes average fares at different markets, but it cannot determine the most convenient fare and identify routes where an airline can open new services. The FEM model cannot calculate the range between airlines routes fares, something very important considering the competition with other airlines. This is important to understand because under competition airlines need to know how low the other airlines fares can be. This information allows airlines to calculate route fares, identify routes and open new services.

The CFEM model calculates the most competitive fare and the expected range between airlines route fares by simulating the behaviour of the complete market, a business model market, or a specific airline market. For an airline using the CFEM model as a pricing method, this information is an advantage. Under competition, airlines need to know how low the other airlines fares can be. Airlines can identify routes to open new service by knowing the other airlines possible minimal and maximum route fares. Airlines can calculate the most convenient fare and compare with the other airlines operating the routes. The CFEM model allows an airline to decide whether or not to open a route based on fare competition.

In this chapter, the CFEM method has been applied on routes only operated by FSC's (FSC-FSC) market. FSC-FSC routes have been compared to FSC-LCC market behaviour. This is because these routes have high fares, and this market has higher average fare than the LCC-LCC or LCC-FSC markets. It does not mean that FSC-FSC routes are the only routes where airlines may find an opportunity to open services. However, in this market, the CFEM model finds more possibilities to open services. The CFEM model is made to analyze each route and calculates the airline fares ranges. Then, it compares the airlines market average, minimum and maximum fares, and advices decide whether or not to open services.

The main conclusion of this chapter is that the calculation of the competitive fare and the expected range between airlines route fares can be used to identify routes that give opportunities to open services. However, identifying routes based on the competitive fare is just a first approach to assist in the decisions to open new services. Other parameters are involved such as airline operating costs, passenger demand, aircraft and airport capacities and constraints. The CFEM methodology must be complemented by the aircraft operating cost model (POC) (Chapter 3), a passenger forecasting model (Chapter 5) and different airport and aircraft operating constraints that allow operating routes (Chapter 6). An optimization model that maximizes the net present value of a network identifies what final routes to operate (Chapter 6).

The application of a Grey model (GM) to forecast routes fares for the long-term has been found to be satisfactory accurate. The GM model was selected because it has the capacity to forecast data that have unknown parameters and it requires little data to approximate the behaviour of unknown systems.

5 Airlines passenger induced demand forecasting model

In the commercial aviation industry, air passenger (pax) demand plays an important role. The International Air Transport Association (IATA) has forecasted 3.3 billion air pax and 28 million tons of air cargo by 2014 [IATA, 2011a]. By 2050, the forecasting estimates 16 billion air pax and 400 million tons of cargo [IATA, 2011b].

Forecasting the air pax demand is important for economic decision making, research and development, production planning, airplane design [Carson, Cenesizoglu, Parker, 2011], network planning, network management, fleet assignment, man power planning [Shaw, 1979], aircraft routing, flight scheduling, revenue management, new routes and investments.

The main problem for an airline when opening a new route is forecasting the induced demand. An airline making the decision to enter a route needs to calculate the total number of people that are willing to fly between the route cities, especially if the route is already operated by other airlines. The new airline needs to estimate the total number of people that want to travel but did not because of high fares or lack of capacity supplied by the other airlines.

Within this research, it has not been possible to use forecasting tools such as passenger's invoices and data regarding information about passengers desires to travel from one airport/city to another. First, it is a highly costly method. Second, this research analyzed approximately 18,000 US domestic routes, what makes it complicated to use invoices or data questionnaires direct from passengers. Thus, a mathematical model to calculate the possible induced demand between airports/cities based on the passenger's distribution function is proposed.

The aim of this chapter is to develop a forecasting method that allows airlines to estimate the possible induced demand between airports/cities origin and airports/cities destination. In literature, several models have been developed to forecast air routes pax demand. In Section 5.1, a review on different air pax forecasting models is presented. In Section 5.2, a pax estimation model (PEM) is developed to calculate the possible induced demand per route. In Section 5.3, a Grey Model is adapted and used to perform long-term forecasting's for the civil aviation industry. Finally, a discussion on the forecasting models and the PEM method is presented in Section 5.4 as a conclusion to this chapter.

5.1 Forecasting methods applied to the airline industry

Demand is equal to the amount of product that clients are willing to buy over a certain period of time and at a certain price [Holloway, 2008]. In the case of the airline industry, it is the pax number of seats demanded between two different airports, cities, regions, and countries or even global. Airlines forecast routes pax demand to know the number of seats they need to supply in each route at time t. Based on the forecast, airlines make decisions to open new routes, increase/decrease route frequencies, and buy aircraft and equipment to handle the increase of pax flow per route [Grosche, Rothlauf, Heinzl, 2007].

Forecasting air passenger's demand can be done for short, medium or long-terms. A short-term forecast is normally made for operational planning. Medium and long-term forecasts are used to evaluate and assess major capital investments. When forecasting demand, there is not such a thing as the best forecasting method. Multiple forecasting methods are available and all are suitable for forecasting passenger demand for their respective purpose.

Forecasting methods can be divided into quantitative forecasting methods, based on the analyses of the attended demand in previous years (historical data), and qualitative forecasting methods based on the judgment of experts on the air transportation field. Quantitative forecasting methods are used when there is enough data available. Qualitative forecasting methods are used when no information is available. In that case, expertise or knowledge is required from airline experts (i.e. airlines chief executive officers).

The forecasting methods can also be divided into time series methods, causal or econometric methods and judgmental methods. Each method is suitable for different purposes. A number of studies documenting forecasting airlines pax flow can be found in the literature on air transport management and economics applying different forecasting methods.

Linear regression models to calculate airline passenger flow per route are very common. Many of them can be found in the literature. As an example, Rengaraju and Arasan [1992] developed a linear regression model to study forty routes between twenty cities in India. The model calculated air pax demand. They differentiate between three different classes of IV's. First, the demand variables are named supply variables: route distance, frequencies, and ticket fares. Later, they took fares out because it was too correlated with distance. Second, the demand variables consist of different OD socioeconomic factors: population, number of households, percentage of literates, percentage of migrants, percentage of employees, and percentage of university degrees. Third, the unclassified variables are: ratio between travelling by train and by airplane and the distance between small cities to big cities.

In Coldren et. al [2003], a logit model for aggregate air travel itinerary shares at major US airlines was developed. They did research on the considerations made by pax for flight choice. The study comprehended almost all the city pairs in the US. The US was divided into 5 regions: East, Central, Mountain, West and Alaska, and Hawaii, and then divided by 18 entities. The authors used five different groups of IV:

1. Level of service variables: non-stop flight, connecting without changing aircraft, connecting and changing aircraft, and flights with two connections.

2. Connection quality variables: second best itinerary connection, second best connection time, best connection time difference and distance ratio (distance divided by the shortest itinerary distance multiply by 100).
3. Carrier attributes variables: point of sale weighted city presence, fare ratio (carrier average fare divided by the overall average fare multiply by 100), DMV carrier representing more than 0.5% of the total itineraries in the entity and code share DMV.
4. Aircraft size and type variables: Regional jet DMV, propeller aircraft DMV, number of seats on the smallest airplane on the route, regional jet and propeller aircraft seats.
5. Time of the day variables: DMV for each hour of the day (05.00 – 22.00).

Their models clarify the relative importance of different services variables on pax choice. The parameters used by their models are consistent for all the 18 regional entities. The validation results suggest the logit based model as a good method to forecast routes pax demand.

In Shen [2004], the aim was to study pax flow for intercity airlines between twenty five cities in the US. His gravity model is based on the spatial interaction or flow between OD, nodal attraction between OD, impedance measure as a function of distance, cost or time, and a constant of proportionality. Their simplification of the gravity method demonstrates that even when the OD matrix is not complete; the model can estimate the number of pax per route.

Grosche, Rothlauf and Heinzl [2007] developed two gravity models for calculating airline pax volumes between routes for a given time interval. In the first model, they excluded routes situated in multi-airport cities. The reason, these cities minimize the effects of competing destinations. The second model is an extension of the first model by including multi-airport cities and additional variables that describe the effects of the competing airports. Both models used geo economic variables as inputs such as population, catchment area, buying power index, GDP, distance, average travel time, number of competing airports nearby, and number of competing airports weighted by distance.

Srinidhi [2007] combined the Gravity model with micro economic theory. This model assumes that the travel demand depends on ticket fares and the income of the people. Srinidhi [2007] established different assumptions for the DV (route pax flow). First, it aggregates both ORI and DES traffic flow. Second, no distinction between business and non business passengers was made. Third, no difference between cities with more than one airport is made, just city to city traffic is considered. The final model is a combination between variables from the gravity model (population and distance) and variables from the micro economic theory (income and fare). Other variables considered are whether an airport is a major airline hub or not. In this research, no results were published.

Janic [2007] introduced the so-called demand function as a method to calculate the number of passenger's demanding transportation services in a route. The so-called demand function is a regression model based on route length (D_r), ticket price (F_r), GDP, population (POP), and a variable that express the supply such as the number of seats (NS_r) or frequency ($freq_r$). These are the main parameters, but the so-called demand function can use additional parameters (Table 5.1) to calculate airlines routes passenger Q_r more accurate.

Hwang and Shiao [2011] developed an econometric model. The objective was to analyze air cargo flows in thirty six international routes for the Taiwan Int. Airport. The dependent variable (DV) is the total cargo volume between airports. The independent variables (IV) are year, GDP per capita, population, distance, and frequency. They included three dummy variables (DMV). The first states if the airport connection is Hong Kong or Macau. The second points out when an open skies agreement between countries exist. The third indicates if the other airport is located in a country with colonial links. They concluded that the parameters used by the model are determinants for international cargo flows from and to Taiwan.

In Hsu and Wen [2000; 2002], a model to generate pax flow data, from origin ORI and destination DES (OD pair), was developed based on a Grey model GM (N, M) theory. In this model, N's are the socio econometric variables such as income per capita and gross domestic product (GDP) per capita. M's are the total flight frequencies per OD pair. The objective of their study was to design airline networks by determining the route frequency. In Hsu and Wen [2003], the same model was used to calculate Chinese passenger volume from 1990-2007. The purpose was to use the results of their calculations as input to design airline networks.

Wei and Jinfu [2009] developed a passenger traffic forecast based on the GM theory and the Markov chain. Their purpose was to study passenger transport capacity and strategies. They compare the Grey-Markov model with the GM. They found that using the Grey-Markov model, the pax demand can be forecasted better than using the GM.

Profillidis [2000] developed a model mixing fuzzy logic models with econometric theory. The objective was to forecast the annual number of international pax of Rhodes airport. He developed three different models. First, a linear equation was used to forecast the future demand from 3 to 10 years. The parameter that determines the passenger demand was the money exchange rate (Greek currency vs. the currencies of the passenger's origin countries). Second, an econometric model was developed using the money exchange rate. The econometric model was converted into a fuzzy linear regression. A DMV was included to take into account the Persian Gulf War in 1991. After comparing different models results, he concluded that the human behavior will never be fully predicted.

Grubb and Mason [2001] use and modify the Holt-Winters model to forecast long-term air pax flow traffic in the United Kingdom (UK). The modification consists in adjusting the long-term forecasts to return the average trend estimated over some period in the past. Their purpose was to forecast pax flow for planning air transport infrastructure such as a building or expanding airports. They used transport movements (ATM's) variables for planning the runaway capacity and required airspace. They used pax flow variables for planning airport terminal capacities. They evaluated the model performance by sensibility analysis. They used different values for the model coefficients and they compared the results. They concluded that the standard Holt-Winters model does not perform as good as the ARIMA model.

In Samagio and Wolters [2010], a comparison between different non-causal models is presented. Their objective was to find the most reliable long-term forecast for estimating passenger's volume from 2008 to 2010 at Lisbon airport.

Firstly, they used a Holt-Winters model due to the trend and seasonal characteristics of their data series. Secondly, they compared the Holt-Winters model with an ARIMA model. They found that the accuracy of the estimated forecasted data was very high. The ARIMA model showed problems with the accuracy of their model for a long-term forecast. It calculated larger values comparing with the Gardner and McKenzie [1989] model. Thirdly, a SARIMA model was introduced. The forecast produced by the SARIMA model appeared to be acceptable for short-terms time series. However, for medium-term forecast the predicted values started to assume larger number of pax flow. Finally, using the model proposed by Gardner and McKenzie [1989], the most reliable results for the long-haul terms were calculated. This model is based on exponential smoothing model. It was designed to damp unpredictable trends.

It can be concluded that all mentioned models seem to be accurate for the short-term. However, when forecasting pax flow through the future, the models calculate too large numbers. As in Gardner and McKenzie [1989], the Holt-Winters model seems to be reliable in the short-term but not in the long-term. The ARIMA and SARIMA models also showed the same problem.

A neural model was built by Alekseev and Seixas [2002]. The objective was to calculate Brazilian pax per km transport demand (PKTD). This model was designed to evaluate the national institute for aviation's (IAC) forecasting model. The IAC is a linear forecasting model based on GDP, average fare per km and a DMV representing the decrease of pax in 1992. Their model included additional variables that could not be used in the IAC model. These variables are: income from tickets, total number of pax transported, total number of landings and total number of city connections.

Two different neural networks were built. One used DMV's and the other did not use DMV's. The models result in five input neurons, three hidden neurons and one output neuron (5-3-1) and (6-3-1). Before implementing the models, two approaches were implemented for training the neural networks. The first approach divided the data sample into two sets, training, validation and testing sample. The second approach divided the data sample sets, training and testing sample. The training samples were used to adjust the weights of the neurons by back propagation method; the validation sample was used to determine when to stop training, and the testing sample to evaluate the performance of the models. In comparison with the IAC model, their models perform very well. They did not find difference in performance between both models using DMV's and not using them. However, the results of the neural network using DMV's were not published.

Finally, different distributions can be used to forecast airlines pax demand. The distribution of demand is determined by the statistics such as the mean and standard deviation Swan [2002].

Beckmann and Bobkoski [1958] found that pax flow had a tendency to approximate to the Poisson shape. They fitted the Poisson distribution to the histograms of the observed pax flow data. On the other hand, the pax reservation data showed more dispersion. They forecasted this dispersion by fitting a gamma shape to the observed reservation data. They concluded that setting the optimal price needs consideration of the demand distribution for its effects on revenues.

Zeni [2001] examines the problems of forecasting airlines pax demand for an airline revenue management system. The passenger demand was generated using three distributions: Normal, Gamma and Weibull. They estimated the parameters of each distribution using censored data.

Swan [2002] studied revenue management and scheduling flight aircraft. They needed to calculate the expected demand to estimate the total number of seats needed per scheduled flight. They explained that pax demand normally assumes either the Normal or the Gamma distribution. Their results found that demand does not behave as a single uniform distribution.

They mixed the Gamma and the Normal distributions. Although, the Normal distribution is dominant, they found a group of routes data that behave as a Gamma distribution.

Table 5.1 summarizes the air pax forecast demand models and their forecasting methods found in literature.

Table 5.1 Summary of literature review of the pax demand forecasting methods

Source	*Forecasting method*	*Parameters*
Sammagio and Walters [2010]	Holt-Winters, Arima, Sarima and Exponential Smoothing	Time, trend and seasonality
Gardener and McKenzie [1985; 1989]	Exponential Smoothing	Time, trend and seasonality
Grubb and Mason [2001]	Holt-Winters	Time, trend and seasonality, ATM and Pax
Hsu and Wen [2000]	Grey model	Income and GDP and per capita, and freq
Wei and Jinfu [2009]	Mix grey model with Markov chain	-
Grosche, Rothlauf and Heinzl [2007]	Gravity model	Multi-airport cities, GDP, Distance, Flying time, Population, Catchment area, Buying power index, and number of airports nearby
Shen [2004]	Gravity model	Spatial interaction or flow between ORI and DES, nodal attraction between ORI and DES, impedance measure as a function of distance, cost or time, and constant of proportionality
Hwang and Shiao [2011]	Gravity model	Total volume of cargo, time, GDP per capita, Population, Distance, Frequency, Tourism, Colonial links and open skies agreements.
Srinidhi [2007]	Mix gravity model and economic theory	Ticket fares, Income, Population, Distance, and major airline hub.
Rengaraju and Arason [1992], Janic [2007]	Linear regression	Route distance, Ticket fares, Frequency, Population, GDP, Number of households, % of literates, % of migrants, % of employees, % of university degrees, Ratio between flying time and train time, and small-large cities distances.
Coldren et. al [2003]	Logit model	Non-stop flight, connection without changing airplane, connection changing airplane, two connections, best flight itinerary, Second best itinerary connection, Second best connection time difference, dist. ratio, fare ratio, code share, carrier with more than 0.5% of the itineraries, Regional jet, propeller aircraft, number of seats on the smallest airplane on the route, regional jet and propeller aircraft seats, and DMV per day.
Profillidis [2000]	Mix fuzzy logic with econometric theory.	Money exchange rate between countries OD and Persian Gulf War
Alekseev and Seixas [2002]	Neural network	PKTD, GDP, Ticket fare per km, Decrease number of pax per route, Income, Number of pax connections, Number of landings
Beckmann and Bobkoski [1958], Swan [2002] and Zeni [2001]	Distribution function	Poisson, normal and gamma distributions respectively

5.2 Induced demand forecasting model

To achieve success airlines have to developed accurate forecasting models to predict possible increase/decrease on their routes pax demand (Q_r). Based on the forecast, airline can decide between opening or not opening new routes and increase or decrease frequencies on routes already operated by the airline [Grosche, Rothlauf, Heinzl, 2007].

The objective of this section is to develop a passenger estimation model (PEM) that calculates the induced Q_r or none served Q_r. In the air passenger transport system, the Q_r is the quantity of seats that passengers are willing and able to buy at a certain ticket price (F_r) during a particular period of time. It means that more passengers may be willing and able to buy at lower prices than the actual route average F_r. In this thesis, the induced demand refers to the total number of passengers that are not transported. In other words, the total route market size is the sum of met, or passenger transported, and induced, or passengers not transported.

Three forecasting models have been used, and two have been developed, to calculate the passenger Q_r demand between two cities/airports. First, the so-called demand function is tested. Second, a multi-regression model is developed to eliminate the supply variable needed in the demand function. Third, the Q_r is generated by fitting a log-normal distribution.

In this section, the so-called demand function (Equation 5.1) has been used to calculate airlines Q_r including an extra parameter. As it was mentioned in Chapter 5.1, Janic [2007] introduced this function as a method to calculate the passenger demand in a route. The airline average number of seats (S) has been incorporated to the Demand function because airlines offer different number of seats per flight.

$$Q_r = A_5\, D_r^{\delta_5}\, F_r^{\alpha_5} GDP_r^{\omega_5} POP_r^{\rho_5} NS_r^{\theta_5} (S)^{\pi_{5a}} \tag{5.1}$$

Where:

A_5	= Constant value	[pax/km/usd^2]
D	= Distance	[km]
GDP	= Gross Domestic product	[usd]
POP	= Population	[pax]
NS_r	= total number of seats supply on route r	[pax]
S	= number of seats (Table Appendix C. 1)	[pax]
a	= Airline	[-]
$\alpha_5, \delta_5, \omega_5, \rho_5, \theta_5, \pi_a$	= constant exponent values	[-]

In Chapter 1, it was shown that a high correlation existed between demand of air travel and the national GDP (Figure 1.1). In this thesis, the GDP route parameter (GDP_r) is calculated as follow:

$$GDP_r = GDP_{ORI} GDP_{DES} \tag{5.2a}$$

Where:

$$GDP_{ORI} = \left(\frac{PAX_{ORI}}{PAX_{STATE_{ORI}}}\right) GDP_{STATE_{DES}} \tag{5.2b}$$

$$GDP_{DES} = \left(\frac{PAX_{DES}}{PAX_{STATE_{DES}}}\right) GDP_{STATE_{DES}} \tag{5.2c}$$

PAX	= Total number of passenger flying to or from airport/city ORI or DES	[pax]
PAX_{state}	= Total number of passenger flying to or from state ORI or DES	[pax]
GDP_{state}	= Total Gross Domestic Product (GDP) generated by the state[14]	[usd]

The number of people living near the airport origin (POP_{ORI}) and near the airport destination (POP_{DES}) increases the attraction between cities. The highest the population is, the highest the Q_r can be expected. In this thesis, the POP route parameter (POP_r) is calculated as follow:

[14] The US Census Bureau GDP and POP data per state [US Census Bureau, 2005-2008]

$$\mathrm{POP_r = POP_{ORI}POP_{DES}} \quad (5.3a)$$

Where:

$$\mathrm{POP_{ORI}} = \left(\frac{\mathrm{PAX_{ORI}}}{\mathrm{PAX_{STATE_{ORI}}}}\right)\mathrm{POP_{STATE_{ORI}}} \quad (5.3b)$$

$$\mathrm{POP_{DES}} = \left(\frac{\mathrm{PAX_{DES}}}{\mathrm{PAX_{STATE_{DES}}}}\right)\mathrm{POP_{STATE_{DES}}} \quad (5.3c)$$

POP_{state} = total number of person living on the state [person or pax]

The route ticket average fare (F_r) and the total number of seats (NS_r) supplied on the route will be, soon or later, in equilibrium taking the load factor (LF_r) into account. This is supported by the economic law of supply and demand. This law confirms that the price for a particular good will change until the consumers demand will be equal to the producers supply. In other words, the F_r will be located where the Q_r demand and the NS_r supply per route are in economic equilibrium. Thus, F_r and NS_r are possible candidates to be Q_r demand determinant.

In Chapter 2, it was explained that each airline uses different strategies. One of their strategies concerns the optimum number of seats (S) and the aircraft type. Airlines decide their aircraft number of S configuration to provide different quality services. Thus, the S per flight is different per airline. A number of aircraft seats parameter (S_r) must be considered. The airlines S constant exponent value (π_a) is to consider airlines routes LF_r.

Finally, in Chapter 4, the CFEM model calculated F_r by using D_r as the only parameter. This is because D_r and F_r are highly correlated. Since, air F_r is highly correlated to Q_r demand; it is highly probable that D_r is an air Q_r demand determinant. In Rengaraju and Arasan [1992], F_r was eliminated because it was highly correlated with D_r.

In the so-called demand function, the parameters that are airline dependent are F_r, NS_r and S_r. Airlines are able to increase or decrease these parameters according with their strategies. GDP and POP are parameters that depend on cities economic conditions and population grow.

Equation 5.1 can be transformed into a multi-regression (Equation 5.4) to estimate its coefficient values (Table 5.2) using SPSS software, but they can be estimated by the OLS method as well. This can be done by minimizing the sum of square percentage error ($\mathrm{SSE\%} = \frac{Q_r - Q_{real,r}}{Q_{real,r}}$). Similar to the FEM model, the top and bottom 1% of the routes with the highest and smallest errors ($\mathrm{SSE} = Q_r - Q_{real,r}$) were removed after the first estimation to eliminate outliers.

$$\ln Q_r = \ln A_5 + \alpha_5 \ln D_r + \delta_5 \ln F_r + \omega_5 \ln GDP_r + \rho_5 \ln POP_r + \theta_5 \ln\left(NS_{a_r}\right) + \pi_{5_a} \ln(S) + \varepsilon_r \quad (5.4)$$

In Chapter 4, it has been discussed that a linear regression model can be validated by analyzing the variability of the model calculations around the regression line and the assumptions of normally distributed. Similar to the FEM model the demand function can be validated by discussing three questions:

1. Is the demand function a useful model to calculate route pax flow?
2. Is there little variability or low fluctuation around the regression line of the demand function?
3. Does the demand function hold the assumption of normal distribution?

Table 5.2 Demand function coefficient values for year 2005 to 2008, Equation 5.4[15]

Coef.	*2005*	*2006*	*2007*	*2008*	*Coef.*	*2005*	*2006*	*2007*	*2008*
$\ln A_5$	0.1726	0.1695	0.2391	0.2320	π_{U5}	0.0116	-0.0124	-0.0110	-0.0107
α_5	-0.0309	-0.0267	-0.0210	-0.0216	π_{UA}	-0.0010	0.0001	0.0011	0.0028
δ_5	-0.0083	-0.0137	-0.0334	-0.0314	π_{US}	-0.0041	-0.0012	-0.0037	-0.0053
ω_5	-0.0052	-0.0057	-0.0045	-0.0049	π_{WN}	-0.0125	0.0086	0.0100	0.0094
ρ_5	0.0070	0.0084	0.0073	0.0077	π_{YV}	NA	NA	0.0051	-0.0039
θ_5	0.9996	0.9985	0.9978	0.9979	π_{YX}	0.0023	-0.0033	-0.0046	-0.0011
π_{AA}	-0.0014	0.0010	0.0014	0.0030	π_{CX}	NA	NA	NA	NA
π_{AQ}	-0.0068	-0.0030	-0.0061	-0.0065	π_{DH}	0.0062	NA	NA	NA
π_{B6}	-0.0053	0.0047	0.0073	0.0108	π_{E9}	NA	-0.0083	NA	NA
π_{CO}	0.0124	-0.0103	-0.0084	-0.0067	π_{HP}	0.0130	-0.0116	-0.0090	NA
π_{DL}	0.0060	-0.0061	-0.0047	-0.0040	π_{OO}	-0.1397	0.1335	0.1526	0.1598
π_{AS}	0.0000	0.0007	0.0028	0.0002	π_{PN}	NA	NA	NA	NA
π_{F9}	0.0102	-0.0083	-0.0074	-0.0067	π_{QX}	0.0070	NA	NA	-0.0060
π_{FL}	0.0089	-0.0052	-0.0039	-0.0076	π_{TZ}	0.0117	-0.0137	-0.0151	-0.0130
π_{G4}	0.0132	-0.0135	-0.0095	-0.0093	π_{XP}	0.0121	NA	NA	NA
π_{NK}	0.0112	-0.0101	-0.0039	0.0084	π_{HA}	0.0034	NA	-0.0003	0.0001
π_{NW}	0.0015	-0.0014	-0.0020	-0.0021	π_{NA}	0.0199	NA	NA	NA
π_{SY}	0.0128	-0.0130	-0.0116	-0.0129	π_{7H}	NA	NA	NA	NA

The analysis is comprised of all the significant parameters that form the so-called demand function. Table 5.3 shows the correlation analysis between the logarithms Q_r calculated by Equation 5.4 and the logarithms $Q_{real,r}$ data points [DOT US Consumer Report, 2005-2008] from years 2005 to 2008. The analyses of variances (ANOVA test) are presented for the years 2005 to 2008 in Table Appendix J. 1, Table Appendix J. 2, Table Appendix J. 3, and Table Appendix J. 4 respectively.

Table 5.3 Logarithm demand function model analysis

Year	*Average ln $Pax_{est\ r}$*	*R*	*Adj. R^2*	*S_{yx} ln $Pax_{est\ r}$*	*F test*	*Sig. F test*	*CV_{reg} (%)*
2005	8.5885	1.00	1.00	0.046407	557,522	.000	0.54%
2006	8.5893	1.00	1.00	0.045442	660,815	.000	0.53%
2007	8.6051	1.00	1.00	0.045982	622,058	.000	0.53%
2008	8.6160	1.00	1.00	0.047048	575,796	.000	0.55%

The F distribution test results (Table 5.3) show the significant values for all the years. If a 5% level of significant is used, it can be assumed that at least one of the model coefficient values is not zero since the significant F test values are smaller than 0.05. It rejects the F distribution test hypothesis null (H_0) (Equation 4.5). It proves the model is useful to calculate routes ln Q_r because at least one of the parameters has a relationship with DV.

The t test statistic tests whether or not each parameter is significantly related to the DV. The student's t statistic test (Equation 4.6) results are shown in Table Appendix J. 5 to Table

[15] The coefficient parameter is equal "NA", when airlines did not report to the DOT US Consumer Report database.

Appendix J. 8 from year 2005 to year 2008. The demand function parameters t test p values indicate that all IV's are significant at 5% level. The CV_{reg}'s are smaller than 1%. This confirms very little variability on the demand function calculations. The demand function is a useful model to estimate ln Q_r. The logarithmic multi-regression (Equation 5.4) looks at the convention that predicts accurate the DV in this case ln Q_r. The aim of each IV is to increase the power of the model. The demand function variables are ln Q_r determinants and, therefore, Q_r determinants.

In the case of the demand function, collinearity does not exist. The model can be used to calculate the increase or decrease of Q_r if one of the demand function parameters increases or decreases, especially if routes fares decrease under current fares.

The demand function adjusted coefficient of determination (Adj. R^2) is equal to 1 (Table 5.3). This means, 100% of the variability between the logarithms of the Q_{real} data points and the demand function calculations, logarithms of the Q_r, is explained by the variability of the demand function IV's. The exponential function (exp^x) converts the logarithms of the Q_r into Q_r values. This result is shown by Figure 5.1. The demand function is a model that calculates airlines Q_r very accurate because most of the calculations are between ±20% SSE% (Figure 5.1). This is mainly caused by the high relation between ($NS_{r,a}$) and ($Q_{r,a}$) and supported by the economic law of supply and demand.

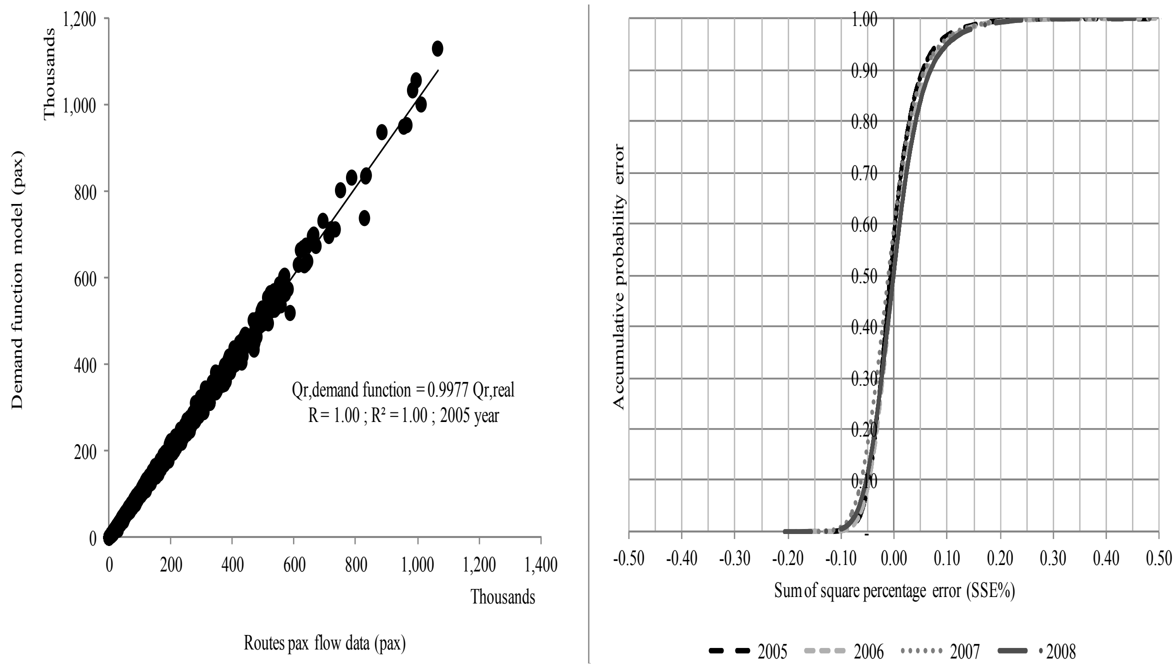


Figure 5.1 Q_r correlation analyses calculated with the demand function for year 2005

Similar to the FEM model, the demand function coefficient values have been estimated by the OLS method. Then, the Q_r demand function needs to fulfill the assumption of normally distributed function. The average of a large number of independent random parameters is normally distributed around the mean according with the central limit theorem. Thus, the central limit theorem guarantees that large samples size data are normally distributed [Lumley et al, 2002]. The linear regression, Equation 5.4, coefficient values have been estimated by using 18,000 domestic routes. A data sample of 18,000 routes is high enough to hold the central limit theorem. Then, the distributions of the residuals are normally distributed.

Table 5.4 shows the correlation results, the sum of square percentage errors (SSE%), the total number of routes and the routes inside ±10% and ±20% SSE% (Figure 5.1). The demand function model calculates Q_r with a correlation over 99% for the US domestic air transportation market from years 2005 to 2008 databases. The results confirm over 90% routes Q_r calculations inside ±10% interval error and over 99% inside ±20% interval error. The demand function model calculations show more positive variability (SSE%) than negative. It means, the demand function model calculates slightly high Q_r per route. It could be attributed to routes LF_r.

Table 5.4 Demand function model results

	Relation values between the demand function model pax flow calculations and real routes pax flow data points					*Models percentage of data interval errors*		
	R	*R^2*	*SSE%*	*Min SSE%*	*Max SSE%*	*Total routes*	*Routes inside ±10%*	*Routes inside ±20%*
2005	1.00	1.00	40.37	-0.16	0.68	17,334	96	100
2006	1.00	1.00	44.41	-0.17	0.93	17,229	92	99
2007	1.00	1.00	46.84	-0.18	0.45	17,161	91	99
2008	1.00	1.00	49.36	-0.17	0.54	16,587	93	99

In the right side of Figure 5.1, the demand function model Q_r calculations SSE% errors are shown for the years 2005, 2006, 2007 and 2008. More than 12,000 routes are calculated inside ±5% SSE%, however, not the case for years 2006 and 2007. In those years, more than 11,000 routes are calculated inside ±5% SSE%. Since, all routes Q_r calculations are inside ±20% SSE%, it can be concluded that the demand function is sufficiently accurate to calculate airlines routes passenger Q_r.

The demand function model is a sufficiently accurate model to calculate routes pax flow (Q_r) when airlines total number of seats supplied per route (NS_r) is known. This is the main problem and the main disadvantage of this model. It always calculates a higher number of passengers as the parameter that represents the supply of air services (NS_r) increases. The demand function requires the total number of NS_r to supply per route. The question then is: how many NS_r satisfy the demand?

The question forces to find those parameters that calculate the demand without using NS_r or $freq_{a,r}$ as a parameter. The NS_r parameter was, therefore, removed to avoid this question. Then, different multi-regression models were developed, during this research, to calculate routes Q_r without using NS_r as a parameter. The parameters used in the models were based on the pax forecasting models found in literature (Table 5.1), and the fare estimation models parameters found in literature (Table 4.2). The FEM model parameters were considered as possible Q_r demand determinants because of the economic law of supply and demand. This law indicates that F_r must be located where the supply (NS_r) and the demand (Q_r) are in equilibrium. This suggested that all air fare pricing determinants might be Q_r determinants.

Equation 5.5 is the regression model that better calculates Q_r, without using NS_r as parameter, from all the models made by the combination of parameters using variables in Table 5.1 and Table 4.2. It is the model that less dispersion between $Q_{real,r}$ and Q_r values showed from all. Equation 5.5 uses parameters from Table 4.5 to calculate Q_r. Analyzing the results of Equation 5.5 (Figure 5.2), its calculations are not accurate enough because 40% of the calculations are inside ±20% SSE% and 73% are inside ±40% SSE% (Figure 5.2). It is difficult to assume that the parameters of Equation 5.5 are simulating the behaviour of the US domestic market because it is not an accurate model[16]. For this reason, this model cannot be used to calculate Q_r; therefore, it cannot be used to estimate the induced demand. It is clear that a parameter to represent the supply of air services (NS_r or $freq_r$) is needed.

$$\ln Q_r = \ln A_6 + \delta_6 \ln F_r + \alpha_6 \ln D_r + \beta_{6_a} \ln f_a + \gamma_{6_m} \ln C_m + \gamma_{6_k} \ln C_k + \varphi_{11} Route_b + \varphi_{12} Comp_b + \varphi_{13} Eco_e + \varphi_{14} Haul_q + \varphi_{15} WN + \varphi_{16} HUB + \varphi_{17} LOW + \varphi_{18} LOWMS + \varphi_{19} LCMS + \varphi_{20} Z + \varepsilon_r \quad (5.5)$$

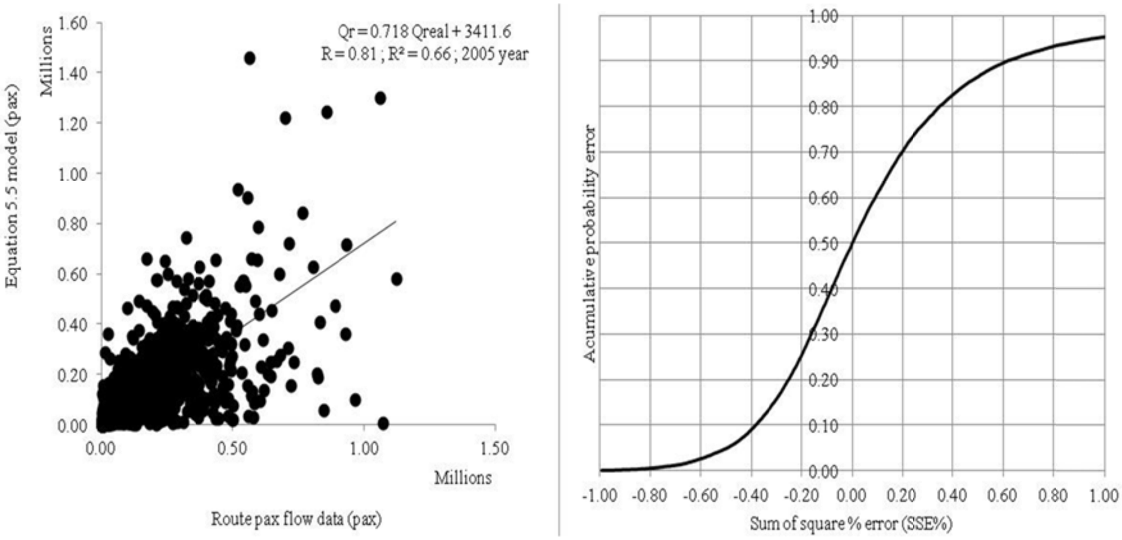


Figure 5.2 Q_r correlation analyses calculated with Equation 5.5 for year 2005

5.2.1 Pax induced demand estimation model (PEM)

The main problem to develop the PEM model is that, if real airline Q_r data is used, it is not possible to know what the real induced Q_r is [Zeni, 2001]. In reality, the real induced Q_r cannot be known, but the possible induced Q_r can be calculated by measuring the total market size of a route by simulating the passenger Q_r data behaviour. This can be done by describing the distribution of the Q_r behaviour. A distribution function gives the possibility to calculate the demand without knowing the parameters that have an influence on it.

To find the distribution that simulates the US domestic Q_r behaviour, the route distance (D_r) domain has been divided into interval classes (IC) of 80.54km (50mi). Every 80.54km, along the distance domain, has at least one route pax flow data point. Then, the average Q_r per IC is calculated. After fitting different distribution shapes, the log-normal distribution is the function that describes the US Domestic Q_r behaviour best. The log-normal distribution (Equation 5.6) showed the max correlation between the average Q_r per IC data points and the estimates. The log-normal coefficient values are K = 124,598, μ = 2.74 and σ = 0.63 (Figure 5.3). These values are calculated by minimizing the SSE%.

$$Q_r = \frac{K}{\sigma\sqrt{2\pi}} \exp^{\left(\frac{-(\log(D_r)-\mu)^2}{2\sigma^2}\right)} \quad (5.6)$$

Where:

μ	= Log-normal distribution average	[-]
σ	= Standard deviation	[-]
K	= Constant value	[pax]

[16] The parameters were estimated by using SPSS and their coefficient values are not presented in this thesis because the model is not a useful method to calculate airline pax flow demand.

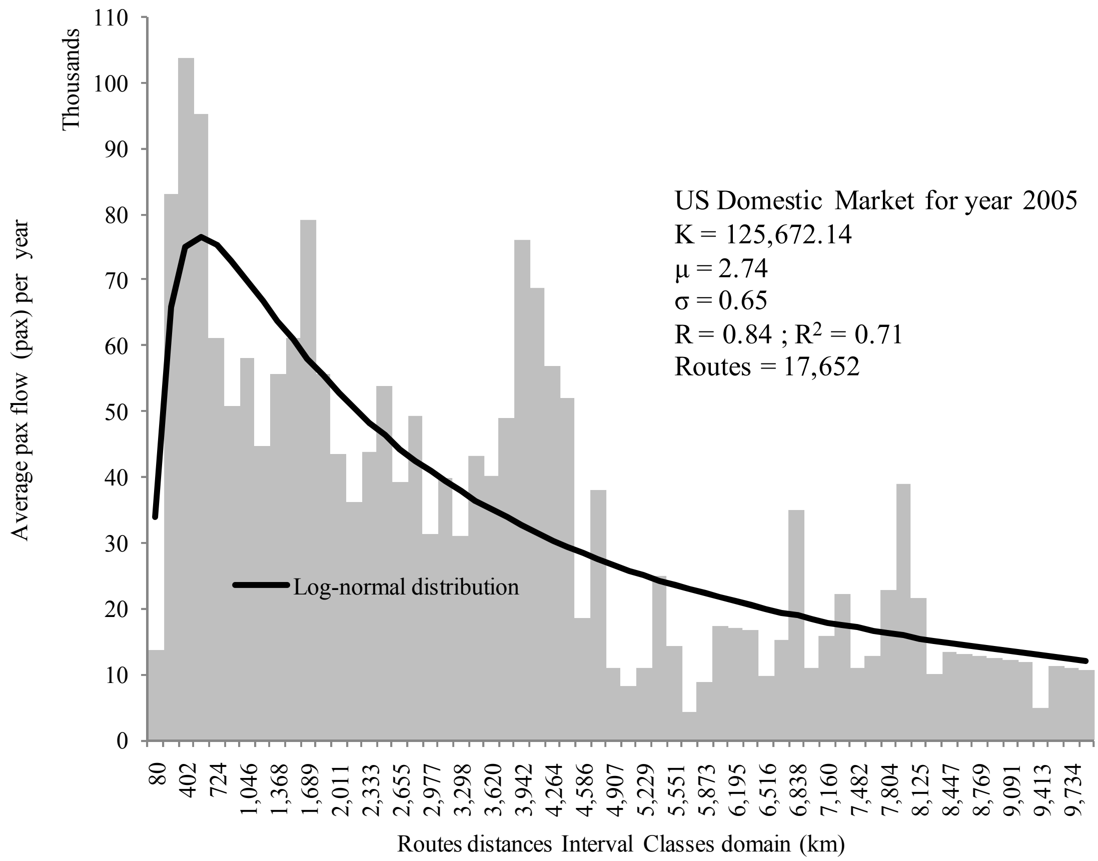


Figure 5.3 US domestic market average Q_r log-normal distribution fit for year 2005

Equation 5.6 has to be calibrated for different airport classes. The reason is that one route connecting two hub airports and another route connecting two small airports at same IC distance cannot have similar Q_r. This shows the necessity to verify if the log-normal distribution can simulate the Q_r behaviour for different airport and airport relationship types.

Similar to the FEM model (Chapter 4) and Equation 5.5, airports are classified into five different types depending on the total Q_r transported through the airport per day (Table 5.5). The route airport $TYPE_r$ is calculated as follows:

$$\mathrm{TYPE_r} = \min(\mathrm{TYPE_{ORI}}, \mathrm{TYPE_{DES}}) \quad (5.7)$$

Since there are no flights between airports type E, information to simulate routes type E do not exist.

Table 5.5 Airport type classification characteristics

Airport type	*Pax per day (1000)*	*Airports*	*TYPE*
A	≥ 65	5	1
B	50 – 65	23	2
C	20 – 50	33	3
D	10 – 20	117	4
E	0 – 10	139	5

The analyses of the airport route types have revealed that the log-normal distribution (Equation 5.6) showed a clear relationship between the average Q_r per IC data points and the estimates. Figure 5.4 shows the log-normal coefficient values and the correlation results per route airport type. These values are calculated by minimizing the SSE%.

In Figure 5.4, major dispersion exists on routes connecting to the biggest airports, A and B. The dispersion increases as the total Q_r transport through the airport increases. This is because the averages Q_r per IC data points for routes connecting two big airports and routes connecting one big airport with a small airport are very different. The dispersion can be reduced by dividing the database into 14 airports routes relationship: AA, AB, AC, AD, AE, BB, BC, BD, BE, CC, CD, CE, DD and DE. Table Appendix F. 6 shows the number of routes and the characteristics for each of the airports routes relationships.

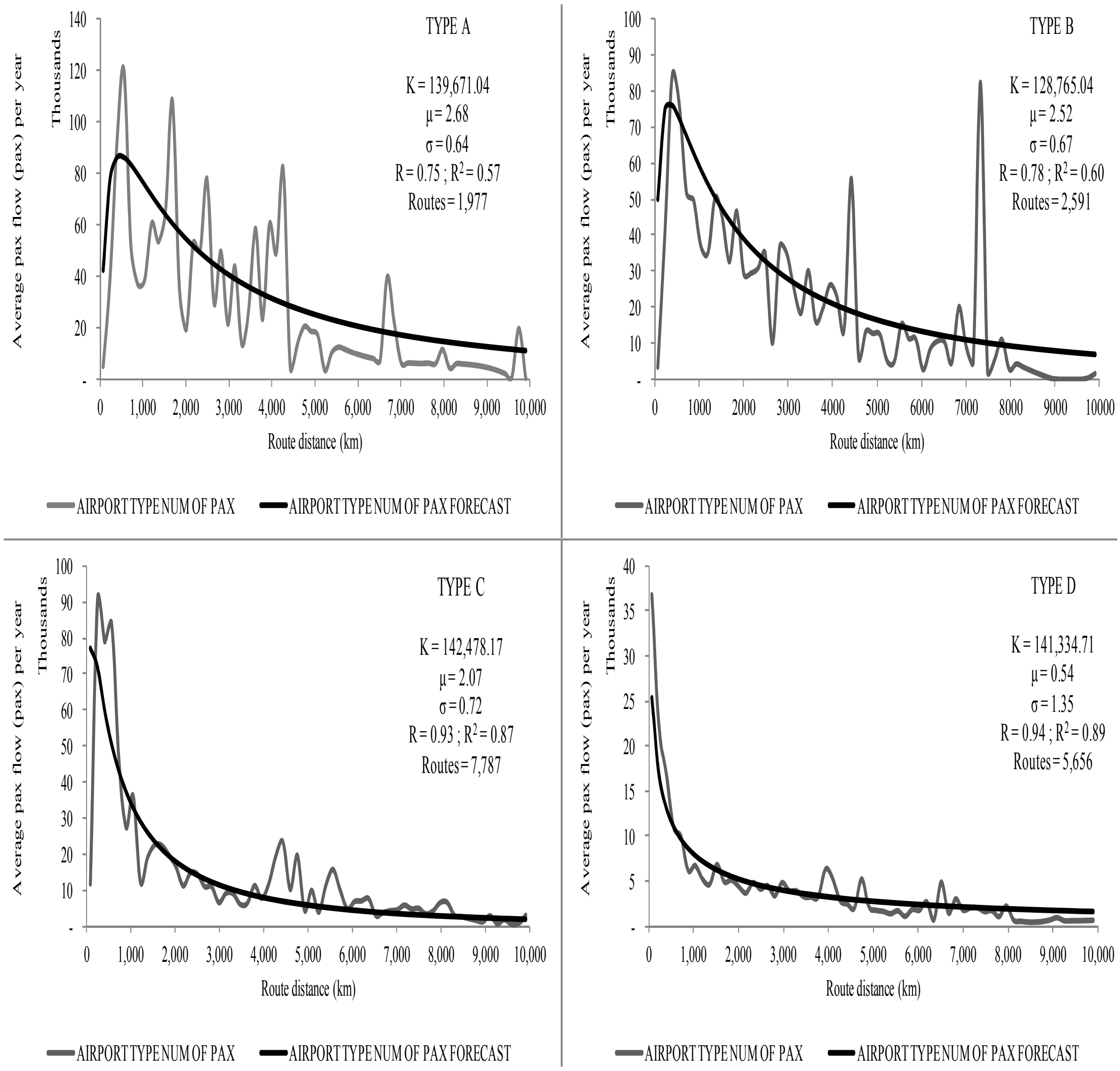


Figure 5.4 Airports routes types' average Q_r log-normal distribution fit for year 2005

Now Equation 5.6 has to be calibrated for the 14 different airports relationships to verify if the log-normal distribution simulates the Q_r behaviour for the different airports relationships.

Figure 5.5 shows that the DD airport route relationship average Q_r per IC behaves similar to a log-normal distribution (Equation 5.6). The log-normal coefficient values and the correlation results are calculated by the OLS method.

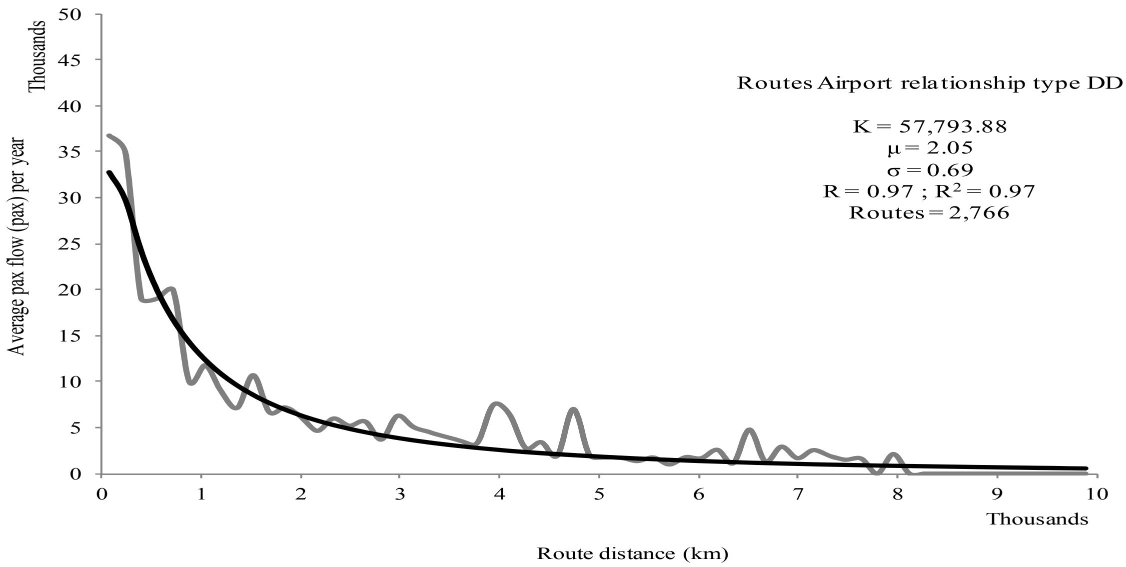


Figure 5.5 DD airport classification average Q_r log-normal distribution fit for year 2005

Only the DD airport route relationship can verify if the log-normal distribution can simulate the Q_r behaviour for the airports routes relationships. The reason is that all the others airports routes relationships do not have Q_r data points every 80.54km. For example, 5 airports are A type (Table 5.5). The AA airport route relationship has 25 routes. Their routes distances are at 1,207km, 2,816km, and a 3,942km. Then, the average Q_r cannot be calculated for all IC accurate.

On the basis of the calibration result for the DD routes, it is further assumed that the log-normal distribution simulates the Q_r behaviour for the other different airports routes relationships.

The PEM model is a method that has been developed to calculate the possible total market size, in number of passengers, and then the possible induced demand for each route in the database. To do so, Equation 5.6 has to be calibrated for each airport route relationship. Then, the missing data for each airport route relationship needs to be artificially generated.

The general market probabilities of the log-normal distribution (Table 5.6) are used to calculate the average Q_r per IC for each airport relationship because these probability numbers describe the percentage of average Q_r expected for each IC for the US domestic market log-normal distribution (Figure 5.4).

The airports relationships non-existing data (IC averages Q_r) are calculated assuming that the averages passenger Q_r's are distributed in the same proportion as the general market for each IC (Table 5.6).

Equation 5.8 expresses the average number of Q_r per airport route relation.

$$Q_{r,IC} = \frac{Q_H \times \%IC}{\%IC_H} \qquad (5.8)$$

Where:

$Q_{r,IC}$	= Airport route relationship average Q_r at IC (interval class data calculation)	[pax]
Q_H	= Airport route relationship highest average Q_r at IC_H (existing data)	[pax]
$\%IC_H$	= log-normal distribution percentage at IC_H (Table 5.6)	[-]
$\%IC$	= IC log-normal distribution percentage at IC (Table 5.6)	[-]

Table 5.6 US domestic market IC_r probability percentages average Q_r log-normal distribution fit for year 2005

IC (km)	*Average Q_r (pax)*	*%IC*	*IC (km)*	*Average Q_r (pax)*	*%IC*	*IC (km)*	*Average Q_r (pax)*	*%IC*
80	33951	1.66%	3,459	36,384	1.78%	6,838	18,914	0.93%
241	65981	3.23%	3,620	35,053	1.72%	6,999	18,430	0.90%
402	74982	3.68%	3,781	33,796	1.66%	7,160	17,965	0.88%
563	76608	3.75%	3,942	32,609	1.60%	7,321	17,517	0.86%
724	75353	3.69%	4,103	31,485	1.54%	7,482	17,086	0.84%
885	72895	3.57%	4,264	30,422	1.49%	7,643	16,672	0.82%
1046	69957	3.43%	4,425	29,413	1.44%	7,804	16,272	0.80%
1207	66878	3.28%	4,586	28,456	1.39%	7,965	15,888	0.78%
1368	63822	3.13%	4,747	27,546	1.35%	8,125	15,516	0.76%
1529	60871	2.98%	4,907	26,682	1.31%	8,286	15,158	0.74%
1689	58061	2.85%	5,068	25,859	1.27%	8,447	14,813	0.73%
1850	55407	2.72%	5,229	25,075	1.23%	8,608	14,479	0.71%
2011	52911	2.59%	5,390	24,327	1.19%	8,769	14,157	0.69%
2172	50570	2.48%	5,551	23,614	1.16%	8,930	13,846	0.68%
2333	48376	2.37%	5,712	22,933	1.12%	9,091	13,544	0.66%
2494	46320	2.27%	5,873	22,282	1.09%	9,252	13,253	0.65%
2655	44393	2.18%	6,034	21,659	1.06%	9,413	12,971	0.64%
2816	42586	2.09%	6,195	21,063	1.03%	9,574	12,698	0.62%
2977	40890	2.00%	6,356	20,491	1.00%	9,734	12,434	0.61%
3138	39296	1.93%	6,516	19,944	0.98%	9,895	12,178	0.60%
3298	37796	1.85%	6,677	19,418	0.95%	**Sum of Average Q_r**	**2,040,208**	**100%**

In the US domestic market, for example, the maximum average pax flow was 519,275 pax per month between airports AA at 2,815km IC, in year 2005. There is no route connecting to airports type A at IC 402km (Table 5.7). Equation 5.8 express that the average Q_r is 914,295 pax per month between airports type A at 402km IC. In a similar way, Equation 5.8 has been used to calculate all the missing data (average Q_r) for each IC for each airport route relationship in the US domestic market (Figure 5.6).

$$Qr_{AA(402.25)} = \frac{Q_{AA,H(2815.75km)}\,\%IC_{(402.25km)}}{\%IC_{H(2815.75km)}} = \frac{519{,}275 \times 0.0368}{0.0209} = 914{,}321$$

Table 5.7 Example of US domestic market IC_r probability percentages for route relationship AA for year 2005 calculation

IC (km)	*Average Q_r (pax)*	*%IC*	*IC (km)*	*Average Q_r (pax)*	*%IC*	*IC (km)*	*Average Q_r (pax)*	*%IC*
1,207	258,527	3.28%	2,816	519,275	2.09%	3,942	273,388	1.60%

In the US network, there are no two airports category A closer than 1,207km. This example has been used to demonstrate how the PEM model calculates the average Q_r for each IC for each airport route demand. This calculation is the same for all the route airport type. Figure

5.6 shows the behaviour of the US market for all the route airport relationships at all distances. In reality, routes connections between big airports do not exist after approximately 4,400km. The longest route distance between big airports is New York - Los Angeles, approximately 3,946km. The model estimates the market size after 4,400km. Nevertheless, it cannot be proved because there are no data available, since big airports are not located at longer distances than 4,400km. However, it is logical that the model calculations indicate less air pax transportation demand as distance increases between cities/airports.

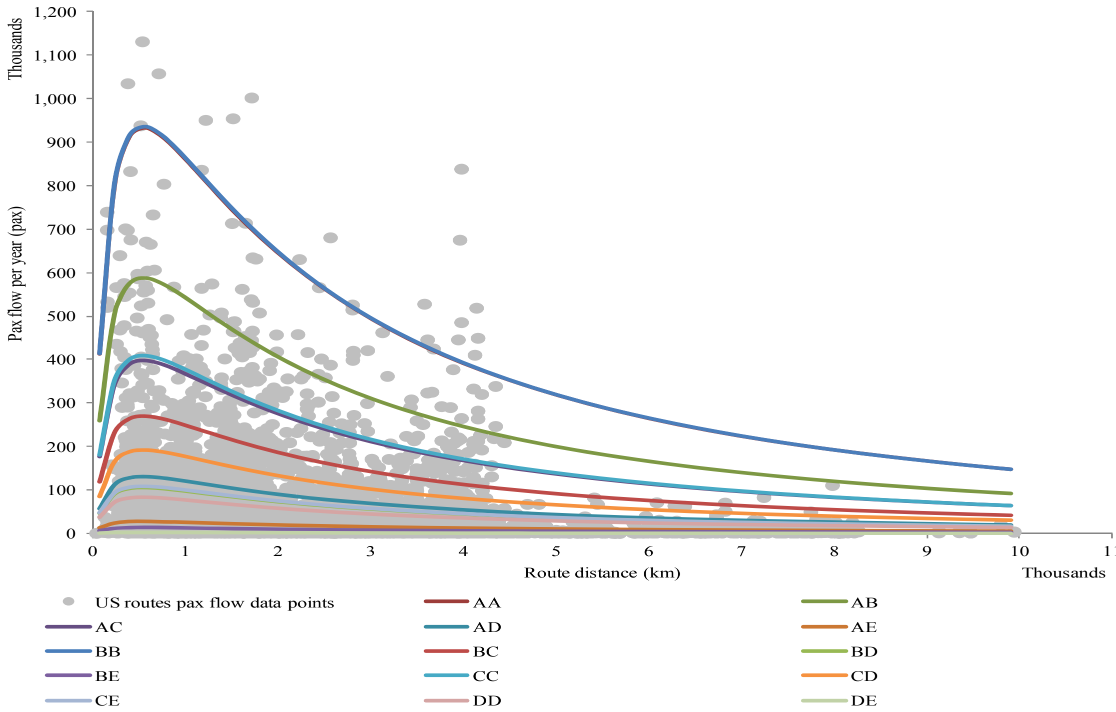


Figure 5.6 IC's average Q_r for each airport route relationship, US domestic market

Table 5.8 shows the log-normal distribution coefficient values for the routes airports relationships, for the US domestic market for the year 2005. The average Q_r per route can be calculated using Equation 5.6 and the coefficient values from Table 5.8. This is the average Q_r based on an analysis of the behaviour of the complete market for a route with distance D_r. Figure 5.6 colour lines show the pax flow market size for all routes distances up to 10,000km.

Table 5.8 Log-normal distribution coefficient values for the US domestic market routes airports relationships for year 2005

Routes airports relationships	*K*	*μ*	*σ*	*Routes airports relationships*	*K*	*μ*	*σ*
AA	1,526,659.55	2.74	0.65	BD	161,986.18	2.74	0.65
AB	925,518.92	2.74	0.65	BE	22,250.83	2.74	0.65
AC	606,440.42	2.74	0.65	CC	626,441.51	2.74	0.65
AD	198,916.99	2.74	0.65	CD	292,465.90	2.74	0.65
AE	41,495.24	2.74	0.65	CE	189,910.29	2.74	0.65
BB	1,514,812.86	2.74	0.65	DD	132,002.09	2.74	0.65
BC	411,578.01	2.74	0.65	DE	4,468.15	2.74	0.65

The PEM model can calculate the route market size and the route induced demand under competition between airlines and airports connecting the same cities as follows:

1) First, the average Q_r between all airports inside both cities must be estimated using Equation 5.6. The coefficient values depend on the route airport relationship type (Table 5.8).

2) Second, the total demand (Q_r) or total market size between two cities is equal to the sum of the average Q_r calculated between their airports (Equation 5.9).

$$TQ_r = \sum_{r=1}^{r} Q_r \quad (5.9)$$

Where:

TQr = Total pax demand between airports connecting two cities [pax]

3) Third, the actual $Q_{real,r}$ between two cities is equal to the sum of the airlines actual $Q_{real,r}$ connecting airports between both cities (Equation 5.10).

$$TQ_{real,r} = \sum_{r=1}^{r} Q_{real,r} \quad (5.10)$$

Where:

Qreal,r = Actual pax flow between airports in the cities [pax]

TQreal,r = Actual pax flow between two cities [pax]

4) Fourth, the possible induced demand ($TQ_{U,r}$) is the difference between the possible market size Q_r (TQ_r) and actual pax flow ($TQ_{real,r}$) transported by all airlines connecting both cities.

$$TQ_{U,r} = TQ_r - TQ_{real,r} \quad (5.11)$$

Where:

$TQ_{U,r}$ = Possible induced demand or possible market size [pax]

5) Fifth, now that the market size has been estimated, and the NS_r per route has as a maximum limit $TQ_{U,r}$, the demand function model (Equation 5.1) can be used to estimate the total Q_r that is willing to buy at a certain ticket price such as fares calculated by the CFEM model (Chapter 4).

The routes that represent an opportunity to open new services are selected using the next criteria. Routes that have a higher $TQ_{real,r}$ than TQ_r do not represent an opportunity to open services. In these routes, it is believed that most of the demand is already being attended. On the other hand, routes that have a smaller $TQ_{real,r}$ than TQ_r represent an opportunity to open services (Equation 5.12). In these routes, it is believed that a part of the demand has not been attended.

$$TQ_{U,r} \geq \Delta TQ \times TQ_{real,r} \quad (5.12)$$

Where:

ΔTQ = Number of times than $TQ_{U,r}$ must be higher than $TQ_{real,r}$ to represent an opportunity to open new services [-]

Finally, in Chapter 4, the CFEM model found the US domestic routes that represent an opportunity to open new services. The CFEM model asses the ticket fares competition between airlines. In this chapter, the PEM model has found the routes with the highest possible induced demand of those routes previously selected by the CFEM model method.

Table 5.9 shows ten routes that represent a possibility to open new services. In these routes, the average $F_{real,r}$ is almost twice as expensive as the average CFEM ticket fare calculation ($F_{est,r}$) for all routes. The total number of pax flow transported ($TQ_{real,r}$) by the airline operating these routes are at least ten times ($\Delta TQ = 10$) smaller than the PEM model induced TQ_r calculation. These are ten examples of expensive routes with a considerable amount of induced pax flow.

Figure 5.7 shows 81 routes where the PEM model calculate $TQ_{U,r}$ is at least 3 times ($\Delta TQ = 3$) higher than $TQ_{real,r}$. These routes were previously selected by the CFEM model (see Figure 4.16) because they showed to be at least 5 standard deviations more expensive than the route average fare value.

Table 5.9 Ten routes that represent a possibility to open new services

CITY 1	*CITY 2*	*Freal,r*	*Fest,r*	*TQreal,r*	*TQr*	*Airlines*
Columbus GA	Seattle	439	187	4,040	48,930	DL
Panama City	San Diego	350	178	4,060	57,731	DL
Columbus	Pittsburgh	323	132	3,700	65,604	US
Brownsville	Detroit	301	165	5,270	71,149	CO
Dayton	Pittsburgh	283	134	3,370	75,388	US
Aspen	Miami	316	176	7,400	91,707	UA
Dallas	Dothan	295	147	4,330	101,385	DL
Charlottesville	Philadelphia	318	134	6,810	106,499	US
Dallas	Lafayette	306	138	5,830	109,935	CO
Islip Long Island	Philadelphia	301	132	3,710	325,188	US

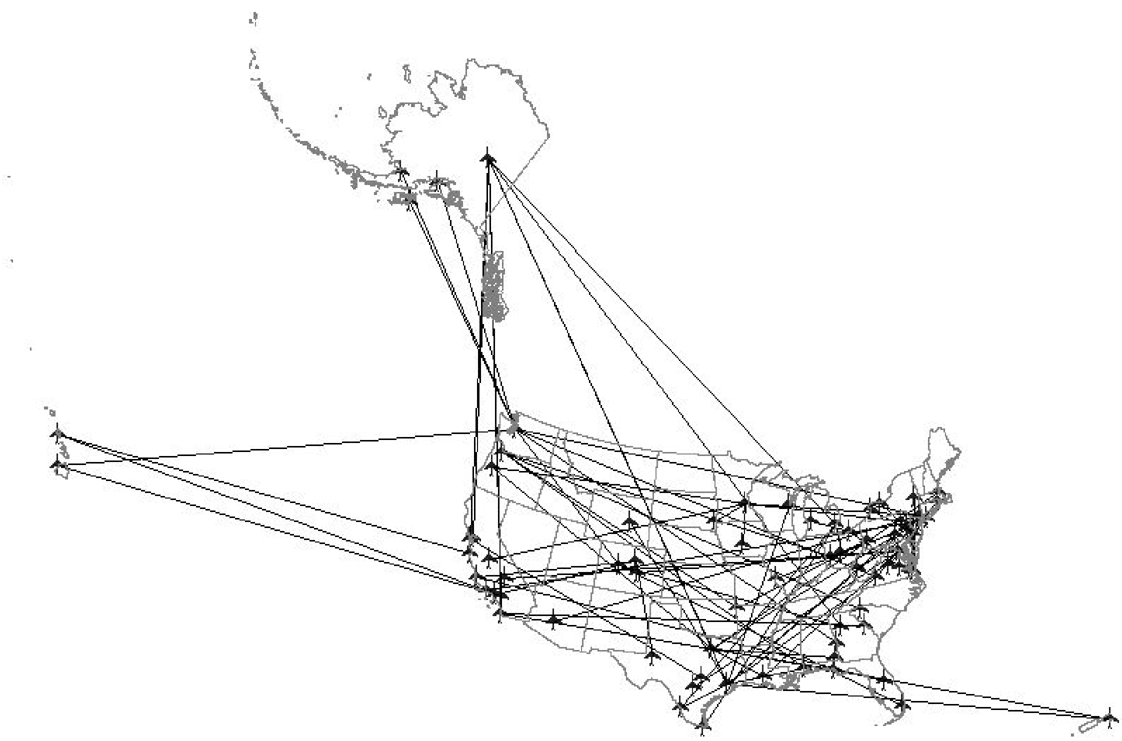


Figure 5.7 Most expensive routes with the highest induced pax flow selected by the CFEM model route selection methodology and PEM model

5.3 Air passenger forecasting method for long-term

The maximization of an airline network net present value (NPV) requires forecasting the pax demand for future years. The NPV optimization model is presented in Chapter 6. From literature review, it can be concluded that there is no best forecasting method. Multiple methods exist and all are suitable for forecasting the air pax demand in future years.

From literature review, the Grey model (GM) appears to be the most recommended for this project data. The first reason is that the GM model has the capacity to forecast data that have unknown parameters. The second reason is that the GM model requires few data to approximate the behaviour of unknown systems. This is a big advantage because there are many circumstances in which the data is not enough to perform a good forecast. The third reason is that the GM model has been used by other researches, such as Hsu and Wen [2000; 2002; 2003], to design airline networks.

In this thesis, the Grey model is based on Kayakan, Ulutas and Kaynak [2010] GM (1, 1) model algorithm (Appendix I), but it has been modified and applied to the civil aviation industry. After using Kayakan, Ulutas and Kaynak [2010] model, the calculations were found to increase/decrease to fast. Then, their model forecast high values or negative values if the tendency goes down (Figure 5.8). This values are completely unreliable because they are simply too high or negative. Negative values are not possible since the demand is always positve or equal zero.

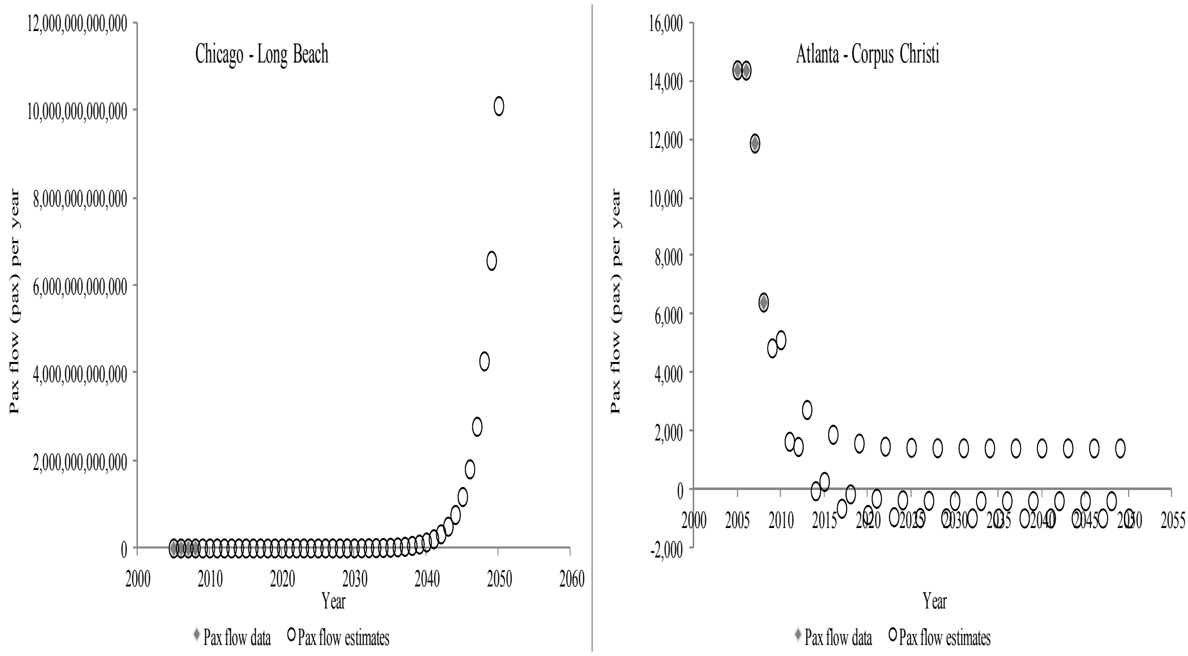


Figure 5.8 Air routes passenger forecasting with a GM model

In this thesis, Kayakan, Ulutas and Kaynak [2010] model has been modified to forecast more reliable values. A parameter that smoothes their model calculations has been added. This parameter is based on the assumption that routes pax flows get more stable as their demands increase. This means pax flow should grow in a slower rate than the rate assumed by the traditional GM prediction algorithm (Appendix I). Thus, in the first year's routes pax flows are expected to increase faster than at the end of the forecasting year.

The GM model adapted and used to perform a long-term forecast, for the civil aviation industry, is as follows:

Consider a time series data $Q_r^{(0)}$ that denotes the number of passengers on an airline route.

$$Q_r^{(0)} = \left(Q_r^{(0)}(1), Q_r^{(0)}(2), \cdots, Q_r^{(0)}(n)\right), \quad n \geq 4 \tag{5.13a}$$

Where:

n = sample size of the data, minimum four [-]

$Q_r^{(0)}$ is a non-negative sequence. Then applying the Accumulative Generator Operator (AGO) the following sequence $Q_r^{(1)}$ is obtained. The sequence $Q_r^{(1)}$ is monotonically increasing.

$$Q_r^{(1)} = \left(Q_r^{(1)}(1), Q_r^{(1)}(2), \cdots, Q_r^{(1)}(n)\right), \quad n \geq 4 \tag{5.13b}$$

Where:

$$Q_r^{(1)}(k) = \sum_{i=1}^{k} Q_r^{(0)}(i), \quad k = 1, 2, 3 \ldots n \tag{5.13c}$$

The generated mean sequence $X_r^{(1)}$ of $Q_r^{(1)}$ is defined as:

$$X_r^{(1)} = \left(X_r^{(1)}(1), X_r^{(1)}(2), \cdots, X_r^{(1)}(n)\right), \quad n \geq 4 \tag{5.13d}$$

Where:

$X_r^{(1)}$ = is the mean value of the next data [pax]

$$X_r^{(1)}(k) = 0.5\, Q_r^{(1)}(k) + 0.5\, Q_r^{(1)}(k-1), \quad k = 2, 3 \ldots n \tag{5.13e}$$

According with Kayakan, Ulutas and Kaynak [2010], the solution by least square method (OLS) of the grey differential equation of GM (1, 1) require calculating the coefficients a, b. $[a, b]^T$ is a sequence of variables where a solve the b estimation problem and can be found as follows:

$$[a, b]^T = (B^T B)^{-1} B^T Q^T \tag{5.13f}$$

Where:

$$Q^T = \left[Q_r^{(0)}(2) \;\; Q_r^{(0)}(3) \;\; \cdots \;\; Q_r^{(0)}(n)\right]^T \tag{5.13g}$$

$$B^T = \begin{bmatrix} -X_r^{(0)}(2) & -X_r^{(0)}(3) & \cdots & -X_r^{(0)}(n) \\ 1 & 1 & \cdots & 1 \end{bmatrix}^T \tag{5.13h}$$

The solution of $Q_{r,\,est}^{(1)}(t)$ at time k:

$$Q_{r_{est}}^{(1)}(k+1) = \left[Q_r^{(0)}(1) - \frac{b}{a}\right] e^{-ak} + \frac{b}{a}, \quad k = 2, 3 \ldots K \tag{5.13i}$$

Where:

$$Q_{r_{est}}^{(1)}(1) = Q_r^{(0)}(1) \tag{5.13j}$$

K = The year until the forecast wants to be performed [-]

est = estimation [-]

The GM model forecast high $Q_{r,\,est}$ (t) values for the long-term. For this reason, a smooth parameter was introduced to the GM model to forecast more reliable routes $Q_{r,\,est}$ (t). The smooth parameter intends to minimize the exponential increase of the GM model calculations, because as time increases the GM model calculations increase exponential. Then, the smooth parameter reduces the GM model calculations as distance increases. The $Q_{r,\,est}$ (t) estimation at time k is equal to:

$$Q^{(0)}_{r_{est}}(k) = \left(Q^{(1)}_{r_{est}}(k) - Q^{(1)}_{r_{est}}(k-1)\right)\frac{1}{e^{(\varsigma(k-n-1))}}, \quad k = n+1, n+2, \ldots, K \qquad (5.13k)$$

Where:

ς = Smooth parameter [-]

The smooth parameter works under the assumption that any route pax flow will not grow more than a maximum possible increment. In this thesis, the maximum possible grow is determined by the International Air Transport Association (IATA) forecast, from 2006 to 2050.

In 2006, 760 million passengers traveled around the world [IATA, 2007]. As it has been mentioned in the introduction of this chapter, IATA has forecasted 3.3 billion air pax by 2014 [IATA, 2011a] and 16 billion air pax by 2050 [IATA, 2011b]. Then, the maximum possible increment from 2006 to 2050 is expected to be 21.05 times. This allows forecasting the pax flow from 2009 to 2050 by using the Grey model at the last time k, in this case 2050.

The smooth parameter is calculated as follows:

$$\varsigma = \frac{1}{K-n}\ln\left(\frac{\left(Q^{(1)}_{r_{est}}(K) - Q^{(1)}_{r_{est}}(K-1)\right)}{\left(Q^{(1)}_{r_{est}}(2) - Q^{(1)}_{r_{est}}(1)\right)}\right) \qquad (5.13l)$$

Equation 5.13m is the constraint that allows calculating the smooth parameter with Equation 5.13l:

$$Q^{(0)}_{r_{est}}(K) = \Delta Q_r \times Q^{(0)}_{r_{est}}(2) \qquad (5.13m)$$

Where:

ΔQ_r = The expected growth from $Q_2^{(0)}$ to $Q_k^{(0)}$. IATA expected growth, 21.05

K = It is the number of forecasting years, i.e. from 2005 to 2050, K = 45

In order to improve the accuracy of the model predictions, an error modification of the GM based on the Fourier series is explicated. This method is also described by Kayakan, Ulutas and Kaynak [2010] and corrected or slightly modified as follows:

Considering equation 5.13j and the predicted values given by the GM (1, 1) model the error sequence of $Q_r^{(0)}$ can be determined as:

$$\epsilon^{(0)}_r = \left(\epsilon^{(0)}_r(2), \epsilon^{(0)}_r(3), \cdots, \epsilon^{(0)}_r(n)\right) \qquad (5.13n)$$

Where:

$$\epsilon^{(0)}_r(k) = Q^{(0)}_r(k) - Q^{(0)}_{r_{est}}(k), \quad k = 2, 3 \ldots n \qquad (5.13o)$$

Now, expressing the residual error in equation 5.13o as Fourier series:

$$Error_t = \epsilon^{(0)}_{r_{est}}(k) \cong 0.5\, a_0 + \sum_{i=1}^{z}\left[a_i \cos\left(\frac{2\pi i}{T}k\right) + b_i \sin\left(\frac{2\pi i}{T}k\right)\right], \quad k = 2, 3 \ldots n \qquad (5.13p)$$

Where:

$$T = n - 1 \qquad (5.13q)$$

$$z = \left(\frac{n-1}{2}\right) - 1 \qquad (5.13r)$$

Rewriting equation 5.13p as follows:

$$\epsilon^{(0)}_{r_{est}} \cong PC \qquad (5.13s)$$

Where:

$$P = \begin{bmatrix} 0.5\cos\left(2\frac{2\pi}{T}\right) & \sin\left(2\frac{2\pi}{T}\right) & \cos\left(2\frac{2\pi 2}{T}\right) & \sin\left(2\frac{2\pi 2}{T}\right) & \cdots & \cos\left(2\frac{2\pi z}{T}\right) & \sin\left(2\frac{2\pi z}{T}\right) \\ 0.5\cos\left(3\frac{2\pi}{T}\right) & \sin\left(3\frac{2\pi}{T}\right) & \cos\left(3\frac{2\pi 2}{T}\right) & \sin\left(3\frac{2\pi 2}{T}\right) & \cdots & \cos\left(3\frac{2\pi z}{T}\right) & \sin\left(3\frac{2\pi z}{T}\right) \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ 0.5\cos\left(n\frac{2\pi}{T}\right) & \sin\left(n\frac{2\pi}{T}\right) & \cos\left(n\frac{2\pi 2}{T}\right) & \sin\left(n\frac{2\pi 2}{T}\right) & \cdots & \cos\left(n\frac{2\pi z}{T}\right) & \sin\left(n\frac{2\pi z}{T}\right) \end{bmatrix} \qquad (5.13t)$$

$$C = [a_0 a_1 b_1 a_2 b_2 \cdots a_z b_z]^T \qquad (5.13u)$$

$$C \cong (P^T P)^{-1} P^T \epsilon^{(0)}_r \qquad (5.13v)$$

Finally, the Fourier series correction can be solved as follows:

$$Q^{(0)}_{r_{pf}}(k) = Q^{(0)}_{r_{est}}(k) - \epsilon^{(0)}_{r_{est}}(k), \qquad k = 2, 3 \ldots n \qquad (5.13w)$$

The final pax flow estimated $Q_{r,\,est}$ (t) at time k is equal to:

$$Q_r(t) = Q^{(0)}_{r_{est}}(k) \qquad (5.13x)$$

Figure 5.9 illustrates the pax flow forecasting values by using the GM without the ς parameter (left side) and with the ς parameter (right side). The GM forecasts without the ς parameter are extremely high or low. It suggests untrustworthy routes Q_r calculations for long-term forecasts. The GM model with the ς parameter modification calculates more reasonable airlines routes Q_r. In Figure 5.9, the Q_r and the route that connects Long Beach with Chicago is shown. In this route, the pax flow increase too much from year 2006 to year 2007, Figure 5.9 left size. The model memorizes this increase to forecast future pax flow. This is the reason why the model forecast high values without using the ς parameter.

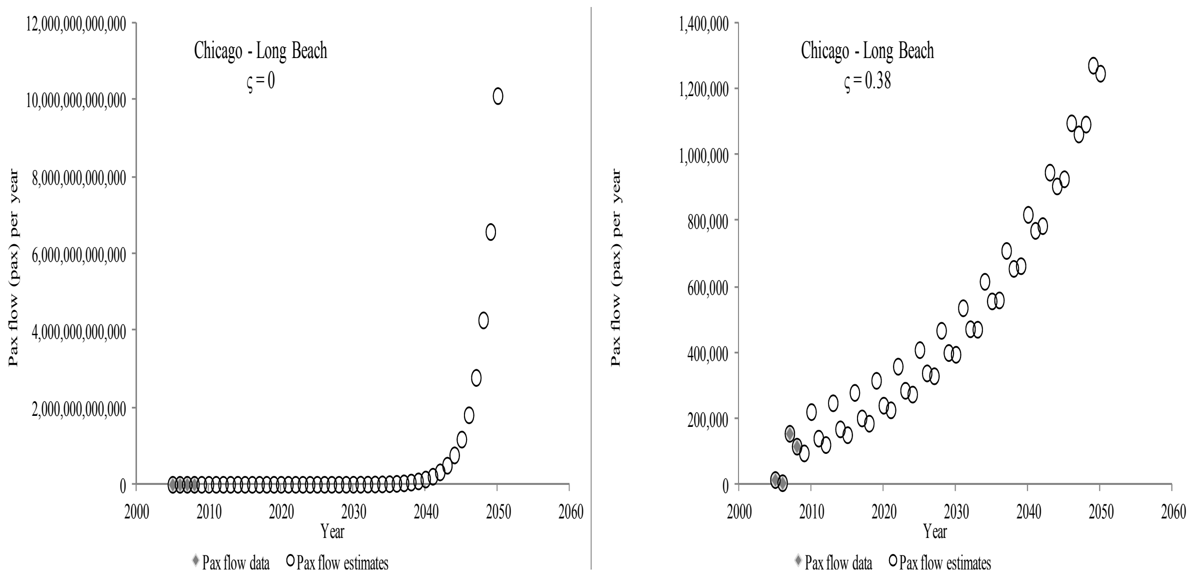
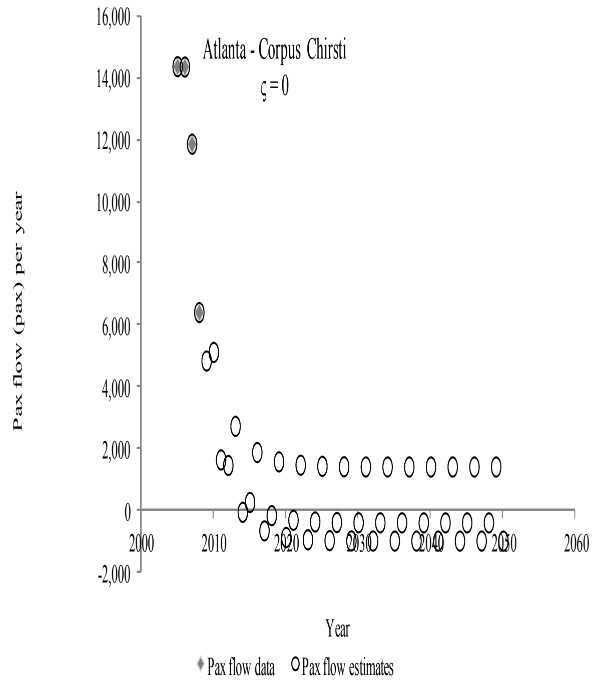


Figure 5.9 Grey model forecast without (left side) and with (right side) the ς parameter for the Long Beach – Chicago route from the year 2009 to the year 2050

Figure 5.10 shows the case of a route in which the GM model calculates negative values. In this case, the Q_r and the route that connects Atlanta with Corpus Christi. In this route, the pax flow decrease too much from year 2006 to year 2008. The model memorizes this decrease to forecast future passenger flow. This is the reason why the GM model without the ς parameter modification forecast negative values. On the right side, Figure 5.10 confirms that the GM model with the ς parameter modification forecast more realistic values. Although, the pax flow growths in future years, during the first years the pax forecasting decrease, and after some years it starts increasing.



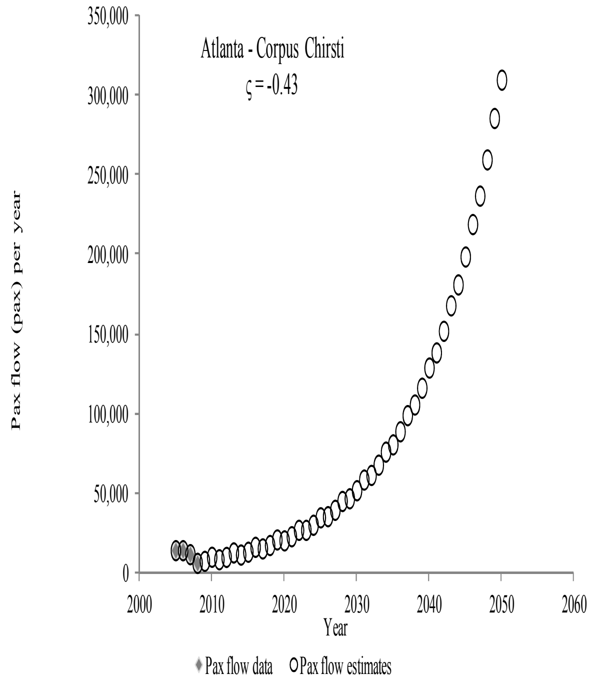


Figure 5.10 Grey model forecast without (left side) and with (right side) the ς parameter for the Atlanta-Corpus Christi route from the year 2009 to the year 2050

5.4 Discussion

The forecast of the air pax demand is important for economic decisions of network planning, fleet assignment, new routes and investment. For example, airlines use their pax forecast estimations to design its network and decide which routes to operate.

In this thesis, the so-called demand function has been tested. The demand function is a multi-regression model that calculates airlines routes pax flow very accurate. The model uses GDP, population, route ticket average fare, route distance, airline number of seats supplied, and airlines average aircraft number of seats. According to the results, these variables appear to be the determinants of air passenger transportation services. The influence of the supply parameter NS_r on Q_r does not allow the POP and GDP parameters to have a serious impact on Q_r. It means that changes in GDP and POP values do not have a high impact on Q_r. However, the statistics analyses suggest that all the demand function parameters determine the demands for air passenger transportation services.

The demand function model is a very accurate model to calculate routes pax flow. The problem with this model is that the parameter that represents the supply (NS) in relation with the demand (Q) needs to be known. The demand function analysis indicates that airlines can offer many seats because it grows their demand. This is not realistic since the passenger market size or induced demand is finite. The demand of air passenger transportation services can increase or decrease when the demand function parameters change, but the size of the market must have a limit. Even if the ticket price is zero, the passenger market size is limited by the number of people living in the airports catchment area. Thus, the demand function cannot be used to forecast the demand of air pax services unless routes passenger market size is known. It will limit the demand function model to a maximum limit of NS to supply.

Equation 5.5 is a multi-regression model that was developed using variables from literature review. The purpose was to eliminate the supply parameter needed in the demand function. However, Equation 5.5 calculations are not accurate enough what makes it difficult to assume that the parameters of Equation 5.5 are simulating the behaviour of the US air passenger demand. During this research, it was understood that a parameter that represents the economic relationship between cities could substitute the NS parameter. This parameter could be the total amount of GDP or percentage of GDP generated in a city as a product of the economic relations with the other city and vice versa. Unfortunately, a parameter that delivers information about the economic relations between cities is not available at least for the case of the United States of America. Based on this, the only parameter known to represent the relation between two airports/cities is the total number of seats (NS) or frequency. Then, it appears that a parameter that represents the supply is needed. However, the PEM model overcomes this problem by simulating the behaviour of the market, under certain assumptions.

The PEM model simulates the air passenger transportation demand using a log-normal distribution. The log-normal distribution considers the behaviour of the complete system. This allow to assume that the average Q_r for different airport relation types can be calculated with a general equation, without needing a parameter that is strongly related with Q_r. It is an easy model to use because it does not have parameters, and it is a model that does not change its estimations when one or more parameters change. At the same time, it is a model that has an indirect relation with economic parameters such as GDP and POP because the demand of air passenger transportation services is related to the airports sizes, and the airports relationships are determined by the airports sizes connecting the route. In the introduction of this chapter and in Chapter 1, it was further explained the existing relation between cities GDP and the demand of air passenger transport services. Finally, the model also considers airports catchment area, since the size of the airport is related to the total number of passengers that use the airport during a period of time. This number considers all airport customers, it means passenger connecting at airports, and not just the population of the cities where the routes airports are located.

The PEM model assumes that the passenger demand between airports behaves according to a log-normal distribution. The results make sense because the demand is low in very short-hauls where competition with other transports systems decreases the demand for air passenger transportation services. For the US air passenger transport system, the demand increases as distance increase until 563km distance. After crossing this distance demand begins to decline, reason why long-haul routes have low air passenger demand.

The PEM calculates the induced demand and selects routes that represent an opportunity to open new services using a simple and logic criteria. The induced demand is the difference between the PEM calculation and the total number of passengers already transport by other airlines. Routes where the difference is negative do not represent an opportunity to open services. In these routes, it is believed that most of the demand is already being attended. On the other hand, routes where the difference is positive may represent an opportunity to open services. In these routes, it is believed that part of the demand has not been attended. This difference expresses the number of non served passengers, and it is the maximum limit of passengers that an airline could attend on a route connecting two airports.

The market size is estimated by the PEM model. Then, the NS_r per route has as a maximum limit, and the demand function model could be used to estimate the total Q_r that is willing to buy at a certain ticket price such as fares calculated by the CFEM model (Chapter 4).

The PEM model is an option to calculate routes pax flow as a first step, it could save airlines a lot of money because it can find routes that represent an opportunity before paying for marketing studies for all routes. After the PEM model has identified those routes that have a high number of induced demand, airlines or governments should do invoices to regarded information about the desire of passengers for travelling from one airport/city to another in the selected routes.

Finally, in this thesis, it has been proposed a modification to the GM model to estimate more realistic results for long-term forecasts when the historic data is few, 4 measures in the case of this study. The proposed model routes pax flows forecasts are more reasonable than using the GM prediction algorithm. However, it is important to understand that the GM model could calculate good results when a major number of measures are used because the GM model will have more historical data to memorize the behavior of the air passenger demand. For databases with a good amount of historic data, it may be possible that the GM model without smooth parameter estimates logic values. In that case, the GM model with and without smooth parameter need to be compared.

6 Optimization model for airlines routes selection and large scale network design

The selection of an airline network is an important strategy activity that airlines plan between five to two years prior to take off [Niehaus, Ruehle and Knigge, 2009]. Airlines have to make sure that the set of routes forming their networks represent a business. Airlines have to evaluate the profitability of their networks before making the decision of extending or changing their routes and their networks. An airline needs to invest a significant amount of money before opening a new route. For this reason, airlines have to make sure that the expected profits, after a certain number of years, will exceed the investment required to operate the new routes in the network.

This chapter presents an optimization model that integrates aircraft performances and airports capacities. The model's main purposes are to select routes that form part of an airline network and assigning the aircraft type that returns the profitability of an investment.

A value-based design model is necessary to evaluate the long-term financial feasibility of an airline network and the optimum aircraft type to operate the routes. The net present value (NPV) is a very well known method to analyze the profitability of an investment project. This method compares the value of the money today to the value of the money after a certain number of years. The project is considered a business opportunity when the required investment is expected to be paid off by the total profits generated after a certain number of years.

The aim of this chapter is to develop an optimization model for route selection. This is a multi-criteria model that maximizes the NPV of an airline network by aircraft type assignment under competition. In Section 6.1, a review on optimization models for airline network design is presented. The optimization model concepts and parameters are explained in Section 6.2. In Section 6.3, the route generation algorithm to determine aircraft flying paths is developed. In Section 6.4, the summary of the optimization model is given considering airline competition. In Section 6.5, an equation to determine the number of employees that will be generated as a direct result of opening new services is calculated. Finally, a discussion on the optimization model is presented in Section 6.6 as a conclusion to this chapter.

6.1 Profit optimization models applied to the airline industry

Different financial methods, such as NPV, internal rate of return (IRR), a return on investment (ROI), have been used as objectives for designing aircraft [Peoples and Willcox, 2006], or for designing conceptual launch vehicles or spacecraft [Lee and Olds, 1997].

Network management optimization is mainly based on the maximization of the network profits and fleet assignment. This means the maximization of revenues and minimization of airline operating costs, and assigning the optimum aircraft to operate each route of an airline network. Although, this approach guarantees the maximization of an airline network profits, it does not guarantee the profitability of an airline network over investment.

A large number of profit, revenue maximization, and operating costs minimization studies applied to the airline industry exist. In this section, only four studies on airline network design and fleet assignment are presented as examples. These studies have been selected because they are similar to problem studied in this thesis. Although, they are similar, the main difference is their objective functions and time interval. In this thesis, the objective function is the maximization of the NPV to select routes that are part of an airline network to find the most profitable network. In the papers presented in this section, the objective function is the maximization of the network profits. Their aim was to assign each aircraft on their fleet to fly different links on their network. They solved the optimization by determining the number of frequencies per route link ($freq_r$) per aircraft on their fleet.

In the first study, Hsu and Wen [2002] developed a reliability method for airline network design. They created models for calculating the optimum flight frequency on individual routes by studying normal and unusual monthly passenger (pax) flow fluctuations. Their objective function was to minimize the total airline operating cost and the total passenger cost. They applied the model to a real case, China Airlines (CAL), with the objective to design and evaluate the CAL international network. They studied a network formed by ten cities in eight countries and twenty five aircraft (13 Boeing 747-400s and 12 Airbus 300s). Their main conclusion is that their model allows the evaluation of the performance of an airline network and measures the consequences of pax fluctuations on an airline network.

In an airline route optimization model, one of the most important factors to determine are the routes links $freq_r$ [Hsu and Wen, 2003]. The number of $freq_r$ directly affects the cost and quality of airline pax flight services, pax flow demand and total revenues (REV_r) per route. Profit maximization models are normally used to estimate the optimum number of $freq_r$ per route link on airlines networks. These flight frequency optimization models are normally based on a single airline network, and they are based on the assumption that pax flow demand is an exogenous and inelastic parameter [Hsu and Wen, 2003].

In the second study, Hsu and Wen [2003] developed a model that calculates the flight frequencies on an airline network with demand and supply interactions between pax flow demand and $freq_r$. They developed a pax airlines flight choice model and a model to calculate the airline routes $freq_r$. Their objective function is to maximize the network profit ($PROFIT_{NTW}$) subject to direct and indirect operation costs. The $freq_r$ parameter is used to maximize the objective function. They applied the model to a real case, CAL. They studied a network formed by ten cities in eight countries and fourteen aircraft. This paper demonstrates the interaction between supply and demand, and explains why this relation should be considered to assign route frequencies.

In the third study, Lohatepanont and Barnhart [2004] explained that the determination of airline routes frequencies is important in order to understand the air travel demand, supply and demand supply interaction. They focused on the schedule design and fleet assignment. The fleet assignment determines what aircraft type is the optimum to fly each route to maximize network revenues (REV_{NTW}) and minimize network operating cost (AOC_{NTW}). Their objective function was to maximize $PROFIT_{NTW}$. The case of study was base on a major US airline.

In the fourth study, Teodorvic and Drcmar-Nozic [1989] developed a multi-criteria model to determine airlines route links frequencies. Their model has three objective functions: maximization of airline profits, maximization of airlines route links pax flow (Q_r) and minimization of airlines pax schedule delay (Sd). Although, in this thesis the maximization of routes profits is changed to the maximization of routes NPV's, the minimization of the schedule delay is not taken into account by the optimization model for airlines routes selection and airlines network design, because scheduling comes after designing the network.

In this thesis, the optimization model differs from the models used in these studies. These studies do not consider aircraft performances and airport capacities as constraints. The study's design networks for existing airlines rather than for a new airline or for airlines thinking to invest an increase their networks. They do not consider airports available capacities, aircraft performance characteristics, or airport-aircraft characteristics as constraints. The first three studies focus on the optimization of an available airline fleet on the routes where these airlines provide services.

Finally, Janic [2000] makes a deep analysis of how the air transportation system can be modelled and analyzed. It is an extensive study on airline profit maximization, airline costs minimization and how to model airport airside, terminal and landside infrastructure capacities. His studies are highly relevant to the development of the optimization model for airlines route selection and airline network design. His findings are discussed through the chapter sections.

6.2 Optimization model concepts and parameters

6.2.1 Airline link, aircraft route/sub-network and network definitions

The optimization model development starts with the definition of the airline network concept. An airline network (NTW_a) is the complete set of routes that an airline (a) operates. From Chapter 2 to Chapter 5, the term "route" was defined as a flight from an origin (ORI) airport to a destination (DES) airport. In this chapter, a flight from an airport ORI to an airport DES is called a "link" and its abbreviation reminds as r. The vector L(r) = [ORI(r), DES(r)] determines what airport is connected by a link. In this chapter, the term "aircraft route" is considered as a set of links that are connected forming a sub-network in an airline NTW_a. The airline route term abbreviation is now $J_{j,a}$. The concepts of link, route and airline network are shown in Figure 6.1.

6.2.2 Optimization model main concepts

It is clear that airline aircraft operating costs, link fares, pax flow demand and link frequencies are the most important parameters for a model that maximize the NPV_a of an airline NTW_a from the optimization models in the literature review and also from the earlier chapters (Chapter 3, Chapter 4 and Chapter 5).

In this thesis, different models have been developed to calculate aircraft operating costs (AOC_r), average fares (F_r) and the induced pax flow demand (Q_r) for links. In Chapter 3.2.2, the aircraft operating cost model (POC) (Equation 3.11) calculates AOC_r based on aircraft jet fuel consumption. The model depends on link distance and current jet fuel price (JFP). Since the fuel consumption parameter represents most of the aircraft flying cost, it is a useful parameter to calculate AOC_r. Thus, the AGE model (Equation 3.10) and the JFP are multiplied. Then, the result of this multiplication divided by the jet fuel cost percentage (%JFC) calculates the AOC_r. Secondly, similar to the POC model, the competitive fare estimation model (CFEM) (Chapter 4.4) uses link distance (D_r) as only parameter to calculate airlines links fares range and average fares (F_r) under competition between airlines operating the same link. Finally, the induced pax estimation model (PEM) (Chapter 5.2.1) is a method that allows airlines to calculate their links possible Q_r. This model assumes that the passenger market distribution through the route distance domain behaves as a log-normal distribution. The POC, the CFEM and the PEM models are used to generate airlines data, study aircraft performance and market behaviours, and to select route links that represent an opportunity to open new services according with the behaviour of the market.

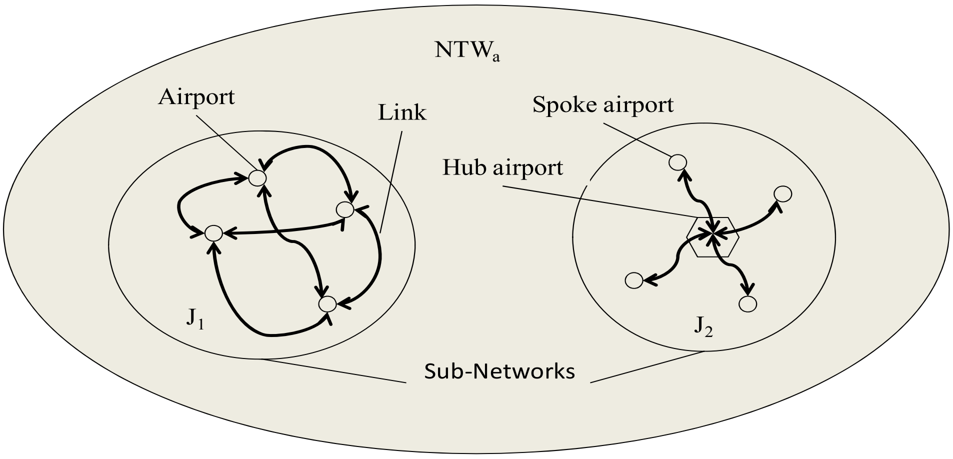


Figure 6.1 Airline NTWa with point-to-point (J_1) and hub-and-spoke (J_2) sub-networks

Link frequency ($freq_r$)

A link frequency, or in other words the number of flights between two cities or between two airports, is the most important variable in the optimization model. As was explained in Chapter 5, the pax flow demand and freq are highly correlated. However, a route link number of flights or $freq_r$ depends on many factors. These factors are Q_r to be served, time interval during which passengers expressed a desire to travel (Tp), pax perception of travelling in cost unit (Γ), airline aircraft operation cost per link (AOC_r), value that determine the pax schedule delay (Sd) in relation to the average headway (ξ). Aircraft number of seats (S_x), aircraft load factors (LF) and cargo (Cargo) are important because both variables are included in AOC_r.

It is important to define $freq_r$ as a function of the Q_r (Equation 6.1). The number of $freq_r$ that satisfy the demand on a route link in a given period of time (T) is constrained by the characteristics of the demand to be attended by the airline [Janic, 2000]. In general and assuming a monopolistic or niche market scenario, the $freq_r$ is calculated as follows:

$$freq_{x,L(r),t} = freq_{x,ORI(r),DES(r),t} = \frac{Q_{L(r),t}}{LF_{x,L(r),t}\, S_x} = \frac{Q_{ORI(r),DES(r),t}}{LF_{x,ORI(r),DES(r),t}\, S_x} \quad (6.1)$$

Where:

x	= aircraft type {Airbus; Boeing; Embraer; etc.}	[-]
t	= period of time, t = 1, ..., T	[-]
L	= [ORI(r), DES(r)] = link vector, it determines the link airport ORI and airport DES	[-]

According with Janic [2000], the airlines already operating a route always respond to the new airline entering the route by increasing the number of seats (NS_r). This agrees with the airfare pricing behaviour study in Chapter 4.1. The $freq_r$ can also be used as an airline competitive tool [Morrison and Winston, 1986] [Janic, 2000]. For this reason, Janic [2000] determined an equation to study airline competition based on airlines market share using $freq_r$ as main parameter.

Janic [2000] defined a model to determine the frequency that minimizes the total link cost taking into account passenger cost perception while waiting for takeoff, the passenger cost perception flying time, and airline operation costs. This method is called the cost minimization criterion. His model includes the perception of travelling time in cost unit on the ground, and pax time on-board. In this thesis, the cost minimization criterion equation has been slightly modified. It has been assumed that pax perception includes both ground and flying time together and not separately (Equation 6.2).

$$\mathrm{Cost}_{x,L(r),t} = Q_{L(r),t}\left\{\left[\frac{Tp_{L(r),t}}{\xi_{L(r),t}\, freq_{x,L(r),t}} + \frac{Dr_{L(r)}}{V_{x,C}} + WTD_{DES(r),t}\right]\Gamma_{L(r),t} + a_0\right\} + AOC_{x,L(r),t}\, freq_{x,L(r),t} \quad (6.2)$$

Where:

Cost	= total link cost in time t for aircraft type x	[usd]
Γ	= pax perception of travelling in cost unit	[usd/hrs/pax]
a_0	= airline fixed cost per pax	[usd/pax]
D_r	= route distance	[km]
V_C	= average cruise speed according with the aircraft type x manual	[km/hr]
Tp	= time interval during which passengers expressed a desire to travel	[hrs]
WTD	= average flying and waiting time at an airport destination DES	[hrs]
ξ	= value that determine the pax schedule delay to the average headway	[-]

The value that determines the pax schedule delay to the average headway in Swam [1979] is 4 (ξ = 4) or ¼ of the time interval during which passengers expressed a desire to travel (Tp). Teodorovic and Krcmar-Nozic [1989] developed a model to determine flight frequencies on an airline network under competitive conditions. They used the same value (ξ = 4) to develop a multi-criteria model to determine route links frequencies on an airline network under competition conditions. In that paper, Teodorovic and Krcmar-Nozic [1989] explain the process that calculates the schedule delay. Contrary, Janic [2000] determined this value as ½ (ξ = 2) of the average headway.

In this thesis, the ξ value is chosen equal to 4 because this number is validated in Teodorovic and Krcmar-Nozic [1989]. The value is also 4 for similar studies made by Swan [1979]. However, the value may be different per route link case. Pax schedule delay per pax data needs to be gathered. The probability function that describes the difference in time between pax demanding air flights on a route link and the next available flight can be derivate from the gathered data.

The minimum total cost function can be calculated by equalizing the cost function derivate to zero:

$$\frac{\partial C_{x,L(r),t}(T)}{\partial freq_{x,L(r),t}(T)} = -\left[\frac{Q_{L(r),t} Tp_{L(r),t}\, \Gamma_{L(r),t}}{\xi_{L(r),t}\, freq_{x,L(r),t}^{2}}\right] + AOC_{x,L(r),t} = 0 \quad (6.3)$$

The minimum total cost function is greater than zero, it is always positive:

$$\frac{\partial^2 C_{x,L(r),t}(T)}{\partial^2 freq_{x,L(r),t}(T)} = \left[\frac{2\, Q_{L(r),t}\, Tp_{L(r),t} \Gamma_{L(r),t}}{\xi_{L(r),t}\, freq_{x,L(r),t}^{3}}\right] > 0 \quad (6.4)$$

The flight frequency that minimizes a route link cost for an aircraft type x ($freq_r^*$) can be calculated, with Equation 6.3 [Janic, 2000]:

$$freq_{x,L(r),t}{}^* = \left[\frac{Q_{L(r),t}\, Tp_{L(r),t}\, \Gamma_{L(r),t}}{\xi_{L(r),t}\, AOC_{x,L(r),t}}\right]^{\frac{1}{2}} \tag{6.5}$$

The constant value of Γ is determined by using historical data. In the case of the United States (US), this data can be extracted from the US Domestic fares consumer report database [DOT US Consumer Report, 2005-2008]. The $freq_r$ data [RITA, 2005-2008] can be extracted from the Bureau of Transport Statistics per route link. The $freq_r$ data are average constant values of Γ according to the airlines already operating a route link. However, different values of Γ can be found by studying different scenarios through a sensibility analysis.

The optimum number of pax (Q_r^*) demanding air transport services can be computed from Equation 6.5, if the optimization model uses $freq_r$ as a parameter to optimize the NPV of an airline NTW_a.

$$Q_{x,L(r),t}{}^* = \frac{freq_{x,L(r),t}{}^{*2}\, \xi_{L(r),t}\, AOC_{x,L(r),t}}{Tp_{L(r),t}\, \Gamma_{L(r),t}} \tag{6.6}$$

Load factor per link (LF_r)

The second model variable is the load factor. An average aircraft load factor (LF) on a route is a measure of aircraft occupancy. It is calculated as the ratio between the total number of pax transported on a flight and the total number of seats available in the aircraft (S_x):

$$LF_{x,L(r),t} = \frac{Q_{L(r),t}}{freq_{x,L(r),t}\, S_x} \tag{6.7}$$

An airline aircraft needs to keep its load factor at least at the point where it achieves non-negative profits [Janic, 2000]. This means, besides the maximum seat capacity, they also have a minimum required LF. The revenues (REV_r) have to be at least equal to AOC_r. Thus, the optimization model can be constrained to assure profits per link (Equation 6.8). However, this constraint is not compulsory since a route link with negative profits can lead to high sub-network profits.

$$freq_{x,L(r),t}\, AOC_{x,L(r),t}\, y_{x,L(r),t} \leq \left(F_{L(r),t} Q_{L(r),t}\right) \tag{6.8}$$

Where:

y = decision variable {0, 1} [-]

Nowadays, the average LF is around 80% [Peeters, Middel and Hoolhorst, 2005]. The tendency over the last years is upwards. In industry, the breakeven LF varies for different aircraft types. For example, for big aircraft such as the B747-800 and the A380, the LF can be almost 70% [Arnold, 2009]. From Equation 6.7 and Equation 6.8, the breakeven LF providing non-negative profits can be determined as follow [Janic, 2000]:

$$LF_{x,L(r),t} \geq \frac{AOC_{x,L(r),t}}{F_{x,L(r),t} S_x} \tag{6.9a}$$

Subject to:

$$0 \leq LF_{x,L(r),t} \leq 1 \tag{6.9b}$$

Five scenarios can be distinguished to explain the load factor of a route link using Equation 6.8 (Table 6.1).

Finally, it is possible to determine the load factor ($LF_{x,L(r),t}$*) that minimizes the total route cost from Equation 6.5 and Equation 6.7:

$$LF_{x,L(r),t}^{*} = \left(\xi_{L(r),t} \frac{Q_{L(r),t}\, AOC_{x,L(r),t}}{(S_x)^2\, Tp_{L(r),t}\, \Gamma_{L(r),t}}\right)^{\frac{1}{2}} \quad (6.10)$$

Table 6.1 Load factor link main scenarios

IF	*Scenario per route*
$1 \leq \frac{AOC_{x,L(r),t}}{F_{L(r),t}\, S_x}$	The airline is losing money on the link. It can be acceptable when all the links in the route or sub-network achieve better profits than not providing service on the link.
$AOC_{x,L(r),t} = F_{L(r),t}\, S_x$	The airline needs to full fill all the seats per flight; otherwise the airline will lose money on the link. It can be acceptable when all the links in the route or sub-network achieve better profits than not providing service on the link.
$LF_{x,L(r),t} \geq \frac{AOC_{x,L(r),t}}{F_{L(r),t}\, S_x}$	Breakeven point
$LF_{x,L(r),t} \geq \frac{AOC_{x,L(r),t}}{F_{L(r),t} S_x}$ and $LF_{x,L(r),t} = 1$	Maximum profit
$0 \leq LF_{x,L(r),t} \leq 1$	The load factor cannot be smaller than zero for all the scenarios.

Aircraft optimal number of seats (S_x)

The optimal number of seats in an aircraft x is explained by the aircraft unit operating cost ($AOCu_r$) (Equation 6.11). It is calculated as the aircraft operation cost divided by the total number of seats in the aircraft (S_x).

$$AOCu_{x,L(r),t} = \frac{AOC_{x,L(r),t}}{S_x} \quad (6.11)$$

For a given aircraft type x, the higher is the S_x the lower is the $AOCu_r$. Thus, it is always the max number of possible seats giving a constant $AOCu_{x,L(r),t}$. The max number of seats in an aircraft type x is subjected to the quality of service that an airline wants to provide to its passengers. The optimum number of seats depends on aircraft cargo and jet fuel volume. The sum of these weights determine aircraft flying range, what has a direct relation to the number of links that can be operated by an aircraft. Finally, it also depends on the value of the constant Γ because it determines the optimum number of $freq_r$ and LF_r.

In the civil aviation industry, four travel classes can be distinguish: first class, business class, premium class and economy class [Jenkinson and Marchman, 2003]. An aircraft seat configuration depends on the size of the aircraft and the airline company. However, the aircraft can be configured in a single class for a max capacity, which is mostly the case for low cost carriers (LCC's), or in a mixed class configuration, which is normally the case of full service carriers (FSC's). Differences in D_r, usually explained as short-haul, long-haul or intercontinental flights determine aircraft seating's capacities. The quality of service can be reduced in short-hauls but probably less possible than in long-hauls.

Figure 6.2 shows the maximum number of seats for different aircraft types according with aircraft manuals [Boeing, Airbus, and Embraer]. Appendix K shows aircraft seat capacities.

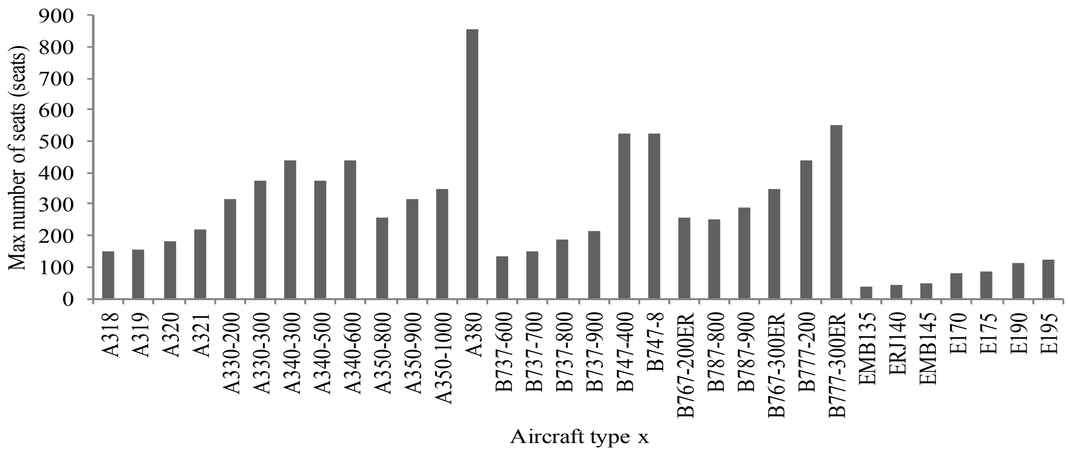


Figure 6.2 Aircraft max number of seats [Airbus, Boeing and Embraer manuals]

6.2.3 Business financial evaluation methods

The two most used methods for evaluating an investment are the NPV and the IRR. The weight average cost of capital (WACC) is normally used as a discount rate. It calculates the proportion of debt and equity that is used to finance a project. It is known as cost of invested capital or overall cost of capital [Shannon and Grabowski, 2008].

The WACC is calculated as the average between the costs of the firm assets. It combines all firms cost to determine the firm cost of capital or opportunity cost [Shannon and Grabowski, 2008]. The assets are financed either by debt, the amount of money borrowed by the company, or by equity (stocks). A firm's WACC allows share holders to see how much interest the firm pays for each dollar they invest [Shannon and Grabowski, 2008]. In other words, it captures the risk of investing in a firm. It allows the firm to invest in the project that returns more money at the less risk. An airline company WACC, cost of equity, cost of debt, firm's equity, firm's debt, percentage of financing equity and debt are published at Wiki Wealth Collaborative Research [Wikiwealth.com]. For example, Southwest Airlines (WN) WACC is equal to 7% and Delta Airlines (DL) WACC is also equal 7%.

In the case of evaluation of an airline network (NTW), a positive NPV indicates that the aircraft type x operating the routes in the network is an attractive business to invest. A negative NPV indicates the network operated by an aircraft type x will not return the investment. The NPV of an airline network using an aircraft x type in a period of time T is calculated as follows:

$$NPV_{NTW\,x} = \sum_{j=1}^{J} \sum_{t=0}^{T} \left(\frac{\left[\sum_{r=1}^{R}\left(F_{L(r),t,j}\, Q_{x,L(r),t,j}{}^{*} - AOC_{x,L(r),t,j}\, Freq_{x,L(r),t,j}\right)\right] - \left[Price_{x,t}\left(NAIR_{x,t,j} - ENAIR_{x,t,j}\right)\right]}{(1+WACC_t)^t} \right) \quad (6.12a)$$

Where:

J	= total airline sub-networks j or airline route j	[-]
j	= 1, ..., J (counter, number of routes)	[-]
T	= total period of time	[-]
t	= 1, ..., T (counter, number of years)	[-]
R	= total links per airline route j	[-]
r	= 1, ..., J (counter, number of links)	[-]
WACC	= Weight average cost of capital for airline a	[-]
Price	= aircraft type price in time t	[usd]
NAIR	= total number of aircraft required to operate NTW in time t	[-]
ENAIR	= total number of aircraft in the airline fleet in time t	[-]
F_r	= average fare per link	[usd]

On the other hand, a $PROFIT_{NTW}$ is calculated as:

$$PROFIT_{x,NTW} = \sum_{j=1}^{J}\sum_{t=0}^{T}\sum_{r=1}^{R}\left(F_{L(r),t,j}\, Q_{x,L(r),t,j}{}^{*} - AOC_{x,L(r),t,j}\, Freq_{x,L(r),t,j}\right) \qquad (6.12b)$$

The Internal Rate of Return (IRR) is one of the most widely used methods for project investment analysis. The IRR is the discount rate that equalizes the NPV of a project investment opportunity with zero for a series of future cash flows. The IRR express the annual rate of return that a company can expect if it invests in a project [Gitman, 2002]. It calculates the break-even rate of return. It is the rate at which the total cash outflows are equal to the total cash inflows. The IRR method can be used to select those projects whose IRR exceeds the cost of capital (Equation 6.13).

$$\sum_{t=1}^{T}\left(\frac{\sum_{r=1}^{R}(Profit_{x,L(r),t,j}) - \left(Price_{x,t}(NAIR_{x,t,j} - ENAIR_{x,t,j})\right)}{(1+IRR_{t,j})^{t}}\right) = 0 \qquad (6.13)$$

Where:
IRR = Route j internal Rate of return [-]

An investment parameter that can compare the efficiencies of different investments is the return on investment (ROI) (Equation 6.14).

$$ROI_{x,t,j} = \frac{\left(\sum_{t=0}^{T}\frac{\sum_{r=1}^{R}(Profit_{x,L(r),t,j}) - \left(Price_{x,t}\left(NAIR_{x,t,j} - ENAIR_{x,t,j}\right)\right)}{(1+WACC)^{t}}\right) + \frac{VA_{x,T,j}}{(1+WACC)^{T}}}{\sum_{t=0}^{T}\frac{\left(Price_{x,t}\left(NAIR_{x,t,j} - ENAIR_{x,t,j}\right)\right)}{(1+WACC)^{t}}} \qquad (6.14)$$

Where:
VA = Total value of assets [usd]

The ROI represents the benefits that the investment generates to a company divided by the cost of making such investment. It is a helpful method of comparing and evaluating projects and companies, in terms of how efficient each project is when it is compared with others [Downes and Goodman, 1998]. The ROI is not a constraint and it is not part of the optimization model. The importance of calculating the ROI is analyzing the efficiency between aircraft after optimization.

6.2.4 Optimization model main constraints

Routes revenues are equal to the sum of their links revenues:

$$REV_{x,t,j} = \sum_{r=1}^{R}\left[\left(F_{L(r),t}\, Q_{x,L(r),t}{}^{*}\right) y_{x,L(r),t}\right] \qquad (6.15)$$

Routes total costs are equal the sum of their links costs:

$$CT_{x,t,j} = \sum_{r=1}^{R}\left[\left(AOC_{x,L(r),t} freq_{x,L(r),t}\right) y_{x,L(r),t}\right] \qquad (6.16)$$

Routes or sub-networks revenues must be higher than their total cost:

$$\sum_{r=1}^{R}\left(F_{L(r),t} Q_{x,L(r),t}{}^{*}\right) = \sum_{r=1}^{R}\left(F_{L(r),t}\left(\frac{(freq_{x,L(r),t})^{2}\, \xi_{L(r),t}\, AOC_{x,L(r),t}}{Tp_{L(r),t}\, \Gamma_{L(r),t}}\right)\right) \geq \left[\sum_{r=1}^{R}\left(AOC_{x,L(r),t} freq_{x,L(r),t}\right)\right] y_{1_{x,t,j}} \qquad (6.17)$$

Where:
y_1 = decision variable {0, 1} [-]

The optimum number of seats to offer per route must be higher or at least equal to the optimum number of passengers travelling each route:

$$S_x \sum_{r=1}^{R}\left(freq_{x,L(r),t}\, y_{x,L(r),t}\right) \geq \sum_{r=1}^{R}\left(\frac{\left(freq_{x,L(r),t}\right)^2 \xi_{L(r),t}\ AOC_{x,L(r),t}}{Tp_{L(r),t}\, \Gamma_{L(r),t}}\right) \quad (6.18)$$

Equation 6.19 calculates the optimum number of flights per route (FREQ). It is equal to the sum of the optimum number of frequencies per route link.

$$FREQ_{x,t,j} = \sum_{r=1}^{R}\left(freq_{x,L(r),t}\, y_{x,L(r),t}\right) \quad (6.19)$$

A link total number of pax to be attended must be less or equal than its forecast Q_r (Equation 5.6). A route forecasted Q_r is calculated by using the PEM model per link per year.

$$Q_{x,L(r),t}{}^{*} = \frac{\left(freq_{x,L(r),t}\right)^2 \xi_{L(r),t}\ AOC_{x,L(r),t}}{Tp_{L(r),t}\, \Gamma_{L(r),t}} \leq Q_{L(r),t} \quad (6.20)$$

The total number of pax to be attended per route must not exceed the sum of links forecast demand per route per year (Equation 6.21).

$$\sum_{r=1}^{R}\left(Q_{x,L(r),t}{}^{*}\right) = \sum_{r=1}^{R}\left(\frac{\left(freq_{x,L(r),t}\right)^2 \xi_{L(r),t}\ AOC_{x,L(r),t}}{Tp_{L(r),t}\, \Gamma_{L(r),t}}\right) \leq \sum_{r=1}^{R}\left(Q_{L(r),t}\right) \quad (6.21)$$

Equation 6.22 constraints the total number of passengers to attend in each sub-network during T years so that it does not exceed the total demand forecasted for the future.

$$\sum_{t=1}^{T}\left[\sum_{r=1}^{R}\left(Q_{x,L(r),t}{}^{*}\right)\right] = \sum_{t=1}^{T}\left[\sum_{r=1}^{R}\left(\frac{\left(freq_{x,L(r),t}\right)^2 \xi_{L(r),t}\ AOC_{x,L(r),t}}{Tp_{L(r),t}\, \Gamma_{L(r),t}}\right)\right] \leq \sum_{t=1}^{T}\sum_{r=1}^{R}\left(Q_{L(r),t}\right) \quad (6.22)$$

Equation 6.23 constrains the total number of passengers to attend so that it does not exceed the total forecasted demand in the complete network for all the years.

$$\sum_{j=1}^{J}\sum_{t=1}^{T}\left[\sum_{r=1}^{R}\left(Q_{x,L(r),t,j}{}^{*}\right)\right] = \sum_{j=1}^{J}\sum_{t=1}^{T}\left[\sum_{r=1}^{R}\left(\frac{\left(freq_{x,L(r),t,j}\right)^2 \xi_{L(r),t}\ AOC_{x,L(r),t,j}}{Tp_{L(r),t}\, \Gamma_{L(r),t}}\right)\right] \leq Q_{x,NTW} \quad (6.23)$$

In some routes, the maximum number of freq is restricted by airport, airlines and government agreements. Equation 6.24 constraints link freq per time t to be less than in the agreement.

$$freq_{x,L(r),t} \leq freq_{max\ L(r),t} \quad (6.24)$$

6.2.5 Financial constraints

The main disadvantage of using the IRR method is when project managers focus on maximizing the IRR rather than the NPV. The problem is the level of risk in companies where the IRR is smaller than the company WACC. Investors will not put money in projects where the IRR is greater than the company WACC. A project is expected to return less money if the project IRR is smaller than the company WACC. In this case, the project is rejected. It represents a constraint in the optimization model (Equation 6.25). This constraint is to consider only routes that maximize profits over invests.

$$\sum_{t=1}^{T}\left(\frac{\sum_{r=1}^{R}\left(Profit_{x,L(r),t,j}\right)-\left(Price_{x,t}\left(NAIR_{x,t,j}-ENAIR_{x,t,j}\right)\right)}{\left(1+IRR_{t,j}\right)^{t}}\right) y_{x,t,j} \leq \sum_{t=1}^{T}\left(\frac{\sum_{r=1}^{R}\left(Profit_{x,L(r),t,j}\right)-\left(Price_{x,t}\left(NAIR_{x,t,j}-ENAIR_{x,t,j}\right)\right)}{\left(1+WACC_{t}\right)^{t}}\right) \quad (6.25)$$

6.2.6 Airport average waiting times

The flying waiting time before landing (WTD) and before takeoff (WTO) depend on landing inter-arrival times, aircraft turnaround processes times, takeoffs inter-event times and number of available gates at an airport.

It is quiet complicated to calculate the waiting times by queuing theory because these queues do not necessarily distribute as a Poisson distribution. For example, in the case of the US airport system, landings and takeoffs waiting times can be deducted from the US airlines on-time database [RITA on-time statistics, 2005-2008]. In the US, WTD and WTO distribute as a G/G/n/K system if it is written down in the Kendall notation [Kleinrock, 1975] [Adan and Resing, 2002]. In this notation, G means that the distribution of inter-arrival times and the distribution of service times are generic distributions. These results conclude that waiting times at US airports do not distribute as Markov or Poisson (M), Erlang-based (E), deterministic (DES) distribution. The second letter is for serving distribution. It is G type for the US WTD and WTO. The number of gates (Ng) at an airport is equal to the number of servers "n" and K represents the maximum length of the queue. A G/G/n/K system is very difficult to solve applying queuing theory. Therefore, fit of a distribution function is used as an easier way to analyze the behaviour of the waiting times at an airport.

Real data allows fitting a distribution that simulates the behaviour of a queue [Adan and Resing, 2002]. It represents the most appropriate approach to calculate airports waiting times for both queues WTD and WTO. In this thesis, Equation 6.26a has been developed by the waiting time behaviour of arrivals (WTD) and departures (WTO) in the US market (Figure 6.3). The advancement and backwardness show an exponential distribution behaviour that is not symmetrical for both arrivals and departures. Thus, the parameters were adjusted for both sides of the distribution, and forced the area under the probability density curve to be equal 1. It is based on the fact that all distributions are between 0 and 1 because the distribution function is the integral of the probability density function. Equation 6.26a is the probability density function that describes the behaviour of the US WTD and WTO airports queue. The parameters of Equation 6.26a have to be estimated for WTD (D(r)) and WTO (O(r)) independently (OD(r)).

$$f(t_1) = C_{3_{OD(r),t}} \exp^{-\lambda_{1_{OD(r),t}} \left|t_1 - t_{0_{OD(r)}}\right|^{\alpha_{1_{OD(r),t}}}} \left(1 - y_{2_{L(r),t}}\right) + C_{3_{OD(r),t}} \exp^{-\lambda_{2_{OD(r),t}} \left|t_1 - t_{0_{OD(r)}}\right|^{\beta_{1_{OD(r),t}}}} \left(y_{2_{L(r),t}}\right) \tag{6.26a}$$

Subject to:

$$y_{2_{L(r),t}} = \begin{cases} 0 & \text{if } t_1 - t_{0_{OD(r)}} < 0 \\ 1 & \text{if } t_1 - t_{0_{OD(r)}} \geq 0 \end{cases} \tag{6.26b}$$

Where:

C_3	= constant factor	[1/min]
t_0	= landing or takeoff time with most probability to happen at an airport	[min]
t_1	= time	[min]
α_1, β_1	= exponent values for landing or takeoff before and after schedule time	[-]
λ_1, λ_2	= probability density function and probability distribution factors for landing and takeoffs before and after schedule time	[-]
y_2	= decision variable {0, 1}	[-]
OD(r)	= the equation is for airport ORI or DES separately (ORI(r) or DES(r))	[-]

The probability distribution function (Equation 6.27) has to be calculated numerically because the analytical expression does not exist. It has to fulfill Equation 6.28.

$$F(t_1) = \int_{-\infty}^{t_1} f(t_1)\, dt \tag{6.27}$$

Subject to:

$$\int_{-\infty}^{\infty} f(t)\,dt = 1 \qquad (6.28)$$

Then,

$$C_3\left\{\int_{-\infty}^{\infty} e^{-\lambda_{1OD(r),t}\left|t_1-t_{0OD(r)}\right|^{\alpha_{1OD(r),t}}}dt + \int_{-\infty}^{\infty} e^{-\lambda_{1OD(r),t}\left|t_1-t_{0OD(r)}\right|^{\beta_{1OD(r),t}}}dt\right\} = 1 \qquad (6.29a)$$

$$C_3 = \frac{1}{\left\{\int_{-\infty}^{\infty} e^{-\lambda_{1OD(r),t}\left|t_1-t_{0OD(r)}\right|^{\alpha_{1OD(r),t}}}dt + \int_{-\infty}^{\infty} e^{-\lambda_{1OD(r),t}\left|t_1-t_{0OD(r)}\right|^{\beta_{1OD(r),t}}}dt\right\}} \qquad (6.29b)$$

The parameters of Equation 6.26 have to be estimated for WTD and WTO independently.

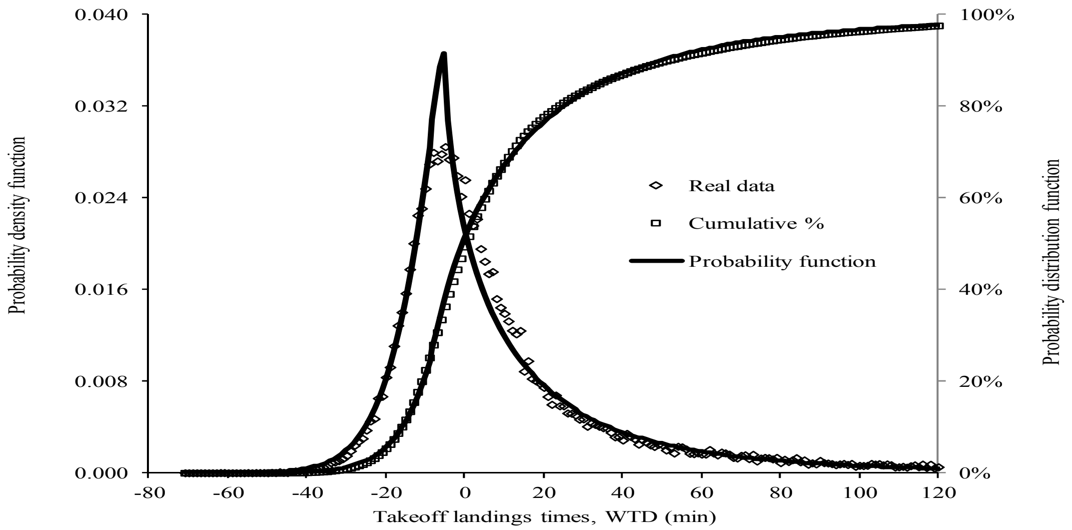


Figure 6.3 American Airlines (AA) landings prob. density function calculations

The parameters in both equations have been calculated by least square method. The results show 99.9% correlation between the data accumulative relative frequency and the estimation accumulative probability distribution. It demonstrates that the probability distribution function can be used to simulate WTD and WTO at different airports in the US. However, providing the probability distribution coefficient for all airports is difficult because of the number of data to gather and process. As an example, Table 6.2 contains the probability distribution function coefficient values for all airports in the US using on-time data from American Airlines (AA). Figure 6.3 shows the probability distribution calculations for WTD and Figure 6.4 shows its calculation for WTO. The coefficient values of the probability density function must be calculated per airport separately.

Table 6.2 Probability distribution function coefficient values all airports

US	*Airport*	α_1	β_1	λ_1	λ_2	t_0	C_3
WTD	DES	1.31	0.67	0.04	0.19	-5.01	0.04
WTO	ORI	0.66	0.28	1.29	1.78	3.14	0.42

The US airlines on-time database is used to study AA waiting times at the US airports operated by this airline (approximately 57,000 flights during December 2005). Figure 6.3 shows that 6% of all flights land after 80 min from their landing schedule time, 27% of all flights land between zero and 20 min after landing schedule time, and 50% of all flights land before their schedule landing time.

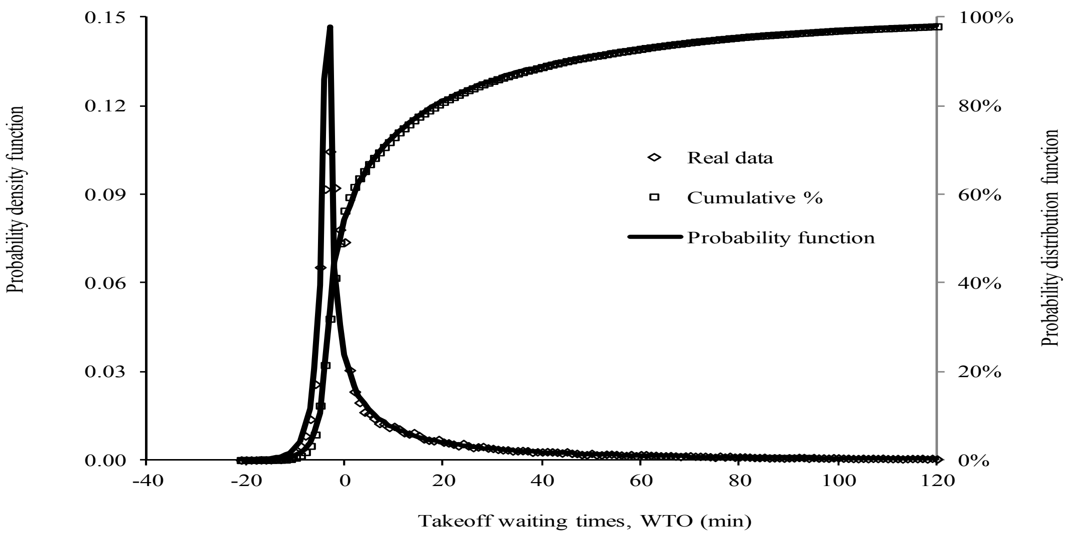


Figure 6.4 American Airlines (AA) takeoffs prob. density function calculations

On the other hand, Figure 6.4 shows that 50% of flights takeoff before the schedule time. AA appears to be very efficient when doing turnaround times or AA turnaround block times are long enough to avoid delays, just 5% of all flights take off after 80 min from the schedule time (Figure 6.4).

Equation 6.26 and Equation 6.27 show that the WTD and WTO distribution are not normally distributed, in the US airports. Equations 6.30 can be used to calculate the average waiting time of a flight for landing (WTD) at airport DES or takeoff (WTO) at airport ORI in time t_1.

$$WTD_{DES(r),t} = t_1 \text{ if } F(t_1) = 0.5 \quad (6.30a)$$
$$WTO_{ORI(r),t} = t_1 \text{ if } F(t_1) = 0.5 \quad (6.30b)$$

For example, the probability of a flight of landing after waiting during 30 min (t_l = 30) is to 1 – F(30) = 1 – 0.89 is equal to 0.11 or 11%. The probability of a flight of landing 5 min before the scheduled time F(-5) = 0.30 = 30%. The probability of a flight to arrive between t_l = -5 and t_l = 5 min is equal to F (5) – F (-5) = 0.60 – 0.30 = 0.30 of 30%. Finally, the average WTD is where F (t_l) = 0.50 = 50%, t_l = -3 min. In the case of AA, its average WTO at all the US airports where it operates is t_l = -0.05 min.

Equations 6.31 expresses the extra flying rout link distance (D_{WTD}) an aircraft needs to fly before being granted for landing by an airport air traffic control. The air traffic control will instruct the pilots to stay at a certain altitude and maintain a certain speed (V_{WTD}). The regulatory bases for reserve fuel establish a maximum WTD of 45 min at normal cruising speed [FAA, 2008a].

$$D_{WTD_{x,DES(r),t}} = \left(V_{WTD_{x,DES(r),t}} \, WTD_{DES(r),t}\right) y_{3\,L(r),t} \quad (6.31a)$$

Subject to:

$$y_{3\,L(r),t} = \begin{cases} 0 & \text{if } WTD_{DES(r),t} \leq 0 \\ 1 & \text{if } WTD_{DES(r),t} > 0 \end{cases} \quad (6.31b)$$

Where:

V_{WTD}	= Aircraft average waiting time cruise speed on the air = V_C	[km/hr]
y_3	= decision variable {0, 1}	[-]

6.2.7 Link distances

Equation 6.32 determines the average flying distance per route link (D_{UF}).

$$D_{UF\,x,L(r),t} = D_r + \left(D_{WTD_{x,DES(r),t}}\right) \quad [km] \quad (6.32)$$

Equation 6.33 expresses the total link distance (D_{UFe}) to fly to an alternative airport in case airport DES is closed. This distance must be considered when flying a route link because it has an influence on the aircraft total weight (W_{TO}) since the extra amount of fuel (UFe) carried by the aircraft must be considered.

$$D_{UFe\,x,L(r)} = D_r + V_{C\,x}\,WTDmax_{DES(r)} + D_{SA_{DES(r)}} \quad [km] \quad (6.33)$$

6.2.8 Aircraft payload, load and cargo capacities

Equation 6.34 expresses an aircraft route link payload (Payload) in tones.

$$Payload_{x,L(r),t} = S_x\left(\frac{WPax+NBags\ WBags}{1000}\right)LF_{x,L(r),t} + Cargo_{x,L(r),t} \quad (6.34)$$

Where:

Payload	= max design zero fuel weight minus OEW	[tons]
WPax	= 89 kg per pax [Peeters, Middel and Hoolhorst, 2005]	[kg/pax]
NBags	= Total number of pax available per pax (LCC's = 1, FSC's = 2)	[bag/pax]
WBags	= 21 kg per bag	[kg/bag]
Cargo	= aircraft amount of cargo capacity per flight haul	[tons]

Equation 6.35 determines an aircraft route link load (Load) in tones.

$$Load_{x,L(r),t} = OEW_x + Payload_{x,L(r),t} \quad (6.35)$$

Where:

Load	= max design zero fuel weight plus OEW	[tons]
OEW	= Aircraft operation empty weight	[tons]

In Chapter 2, one of the LCC's main strategies to reduce turnaround times (Tr) and increase aircraft utilization time is not carrying cargo (Cargo) in short-haul operations. Equation 6.36a constraints the optimization model to not carrying cargo for short-haul operations. Contrary, for long-haul operations Equation 6.36a assumes that an aircraft carries as much cargo as its cargo volume capacity and max takeoff weight design (MTOW) allow it per flight. Equation 6.36b is a decision variable. It decides if a route is a short-haul or a long-haul. The break even distance point where routes change for being short-hauls to long-hauls is calculated by using the CFEM model (Equation 4.8).

$$Cargo_{x,L(r),t} = \left\{y_{4\,x,L(r),t}\left[Cargo_{max\quad x,L(r),t}\right]\right\} \quad (6.36a)$$

Subject to:

$$y_{4\,x,L(r),t} = \begin{cases} 0 \text{ if } D_{L(r)} \leq D^* & \text{"Short} - \text{haul"} \\ 1 \text{ if } D_{L(r)} > D^* & \text{"Long} - \text{haul"} \end{cases} \quad (6.36b)$$

Where:

D*	= Distance point dividing short-haul and long-haul	[km]

Equation 6.37 determines the maximum amount of cargo an aircraft can carry per flight. This equation limits the amount of cargo to be no more than the aircraft max takeoff weight (MTOW). Equation 6.37 expresses the maximum cargo an aircraft can carry on a route link depending on the total jet fuel volume it needs to fly D_{UFe}. Equation 6.37 balances the amount

of cargo with the aircraft jet fuel. This is necessary because as the aircraft weight (W) increases the amount of jet fuel (UF) needed to fly from an airport ORI to an airport destination DES increases too.

$$\mathrm{Cargo}_{\max\ x,L(r),t} = \frac{\mathrm{MTOW}_x - \left[C_0 + C_1(D_{\mathrm{UFe}\ x,L(r)}) + C_2(D_{\mathrm{UFe}\ x,L(r)})^2\right]}{B_0 + B_1(D_{\mathrm{UFe}\ x,L(r)}) + 1} - \left[\mathrm{OEW}_x + S_x\left(\frac{\mathrm{WPax} + \mathrm{NBags\ WBags}}{1000}\right)\mathrm{LF}_{x,L(r),t}\right] \quad (6.37)$$

Where:

MTOW	= aircraft max takeoff weight design	[tons]
B_0	= constant value (Table 3.4)	[-]
B_1	= constant values (Table 3.4)	[km^{-1}]
C_0	= constant value (Table 3.4)	[tons]
C_1, C_2	= constant values (Table 3.4)	[tons/km]

Equation 6.38 constraints the amount of cargo an aircraft can carry per flight to be lighter than its max cargo capacity (CargoVol) in tones.

$$\mathrm{Cargo}_{x,L(r),t}\ y_{x,L(r),t} \leq \mathrm{CargoVol}_x \quad (6.38)$$

6.2.9 Jet fuel volume that maximize aircraft utilization time and profits

In Chapter 3, the aircraft generic jet fuel consumption equation (AGE) (Equation 3.10) calculates the jet fuel volume required to fly a link based on D_r and Load. This equation is particularly useful to calculate an aircraft flying range because it considers the relationship between D_r and Load.

The average UF that an aircraft needs for flying a link, with distance D_r in time t, must include enough fuel to fly D_r and the average WTD at airport DES (Equation 6.30). Equation 6.39 expresses the amount of jet fuel that an aircraft x needs to fly D_{UF} using Equation 3.10.

$$\mathrm{UF}_{x,L(r),t} = \left(B_0 + B_1(D_{\mathrm{UF}x,L(r),t})\right)\ \mathrm{Load}_{x,L(r),t} + \left(C_0 + C_1(D_{\mathrm{UF}x,L(r),t}) + C_2(D_{\mathrm{UF}x,L(r),t})^2\right) \quad (6.39)$$

Equation 6.40 determines the total amount of jet fuel that an aircraft type x needs to fly D_{UFe} using Equation 3.10.

$$\mathrm{UFe}_{x,L(r),t} = \left(B_0 + B_1(D_{\mathrm{UFe}\ x,L(r)})\right)\ \mathrm{Load}_{x,L(r),t} + \left(C_0 + C_1(D_{\mathrm{UFe}\ x,L(r)}) + C_2(D_{\mathrm{UFe}\ x,L(r)})^2\right) \quad (6.40)$$

An aircraft can carry more fuel than the total it needs to fly a certain link. It gives the possibility of reducing turnaround times at en route stations and charge fuel in airports where JFP are cheaper than its next airport on route. It maximizes aircraft utilization times and it reduces jet fuel costs for short-haul routes. On the other hand, turnaround times do not minimize cost, but increase profits in long-haul routes because airlines have time to provide a better service to their passenger than in short-haul routes.

Equation 6.41 determines the maximum amount of jet fuel an aircraft can carry per flight. The calculation of the max amount of jet fuel is different for short-haul routes and long-haul routes. This is because long-haul operations carry cargo but not short-haul (Equation 6.36).

$$\mathrm{UF}_{\max\ x,L(r),t} = \left[\mathrm{MTOW}_x - \mathrm{Load}_{x,L(r),t}\right] \quad (6.41)$$

Where:

UF_{max}	= aircraft max amount of jet fuel volume per flight haul	[tons]

Equations 6.42 determine the jet fuel volume (UFT) that an aircraft must carry per flight depending on haul distance type (short-haul or long-haul) and Cargo strategy.

$$UF_{m\ x,L(r),t} = \left[\left(\left(UFe_{x,L(r-1),t}\, y_{4\ x,L(r-1),t} + \left(1 - y_{4\ x,L(r-1),t}\right) UF_{max,x,L(r-1),t}\right) - UF_{x,L(r-1),t}\right)\left(y_{5\ x,L(r),t}\right)\right] + \left[\left(1 - y_{5\ x,L(r),t}\right)\left(\left(UFe_{x,L(r),t}\, y_{4\ x,L(r-1),t} + \left(1 - y_{4\ x,L(r),t}\right) UF_{max\ \ x,L(r),t}\right)\right)\right] \qquad (6.42a)$$

Subject to:

$$y_{5\ x,L(r),t} = \begin{cases} 1 & \left[\text{if } \left(UFT_{x,L(r-1),t} - UF_{x,L(r-1),t}\right) \geq UF_{e\ x,L(r),t} \text{ AND } JFP_{ORI(r),t} \geq JFP_{DES(r),t}\right] \quad \text{"No"} \\ 0 & \text{Otherwise} \quad \text{"Yes"} \end{cases} \qquad (6.42b)$$

Where:

UF_m	= aircraft amount of jet fuel in its tank after flying link r-1	[tons]
$UFT_{L(r-1)}$	= aircraft amount of jet fuel carried in the previous link	[tons]
$UF_{L(r-1)}$	= aircraft amount of jet fuel to fly the previous link	[tons]
$JFP_{ORI(r)}$	= average jet fuel price at airport origin link r	[usd/ton]
$JFP_{DES(r)}$	= average jet fuel price at airport destination link r	[usd/ton]
y_5	= decision variable {0, 1}	[-]

$$UFT_{x,L(r),t} = UF_{m\ x,L(r),t}\, y_{6\ x,L(r),t} + Tank_{max\ \ x}\left(1 - y_{6\ x,L(r),t}\right) \qquad (6.42c)$$

Subject to:

$$y_{6\ x,L(r),t} = \begin{cases} 1 & \text{if } UF_{m\ x,L(r),t} \leq Tank_{max\ \ x} \\ 0 & \text{if } UF_{m\ x,L(r),t} > Tank_{max\ \ x} \end{cases} \qquad (6.42d)$$

Where:

y_6	= decision variable {0, 1}	[-]

$$AOC_{x,L(r),t} = \left[\left(B_0 + B_1\left(D_{UFx,L(r),t}\right)\right) Load_{x,L(r),t} + \left(C_0 + C_1\left(D_{UFx,L(r),t}\right) + C_2\left(D_{UFx,L(r),t}\right)^2\right)\right]\left(\frac{JFP_{ORI(r-1),t}\, y_{5\ x,L(r),t}}{\%JFC_t}\right) + \left[\left(B_0 + B_1\left(D_{UFx,L(r),t}\right)\right) Load_{x,L(r),t} + \left(C_0 + C_1\left(D_{UFx,L(r),t}\right) + C_2\left(D_{UFx,L(r),t}\right)^2\right)\right]\left(\frac{JFP_{ORI(r),t}\left(1 - y_{5\ x,L(r),t}\right)}{\%JFC_t}\right) \qquad (6.42e)$$

Equation 6.42a determines the amount of jet fuel in an aircraft tanks after flying route link r-1. Equation 6.42b is a decision variable. An aircraft has to charge fuel at an airport during its turnaround if it does not have enough fuel to fly to its next airport on route or if the current JFP at airport ORI is cheaper to the JFP at airport DES. Equation 6.42d is another decision variable. An aircraft tank has to have enough capacity to store UF_m otherwise the max amount of jet fuel to carry is equal to its tank capacity. Finally, Equation 6.42e expresses the airline operating cost per route link.

Equation 6.43 assures that UFT is more or at least equal to UFe. The route link cannot be operated by an aircraft if UFT is fewer than UFe. Aircraft must carry enough jet fuel to travel D_{UFe}.

$$UFT_{x,L(r),t} \geq UFe_{x,L(r),t}\, y_{x,L(r),t} \qquad (6.43)$$

6.2.10 Aircraft performance characteristics related to link flight

This section discusses the main factors affecting the aircraft flying performance related to aircraft maximum flying range, minimum flying range and aircraft weights.

The maximum range (Range) is the longest link distance and aircraft can fly at a certain weight. It determines the number of necessary stops to refuel on a route before reaching its final destination. The minimal flying range (MFR) is the minimum flying distance an aircraft has to fly before landing. The MFR of an aircraft depends on its load. More specifically in the relationship between its takeoff weight (W_{TO}) and its max design landing weight (MLW).

An aircraft range capacity changes based on both factors. The lightest an aircraft takeoffs weight is the longest range it can fly with full aircraft tank volume ($Tank_{max}$). Equations 6.44 express the max flying range and aircraft can fly with a certain Load using the AGE model (Equation 3.10).

$$\text{Range}_{x,L(r),t} = \frac{-(B_1 \text{Load}_{x,L(r),t} + C_1) + \sqrt{(B_1 \text{Load}_{x,L(r),t} + C_1)^2 - 4C_2(B_0 \text{Load}_{x,L(r),t} + C_0 - \text{Tank}_{max\ x})}}{2\,C_2} \quad (6.44a)$$

Subject to:

$$\text{Range}_{x,L(r),t} \geq D_{UFe\ x,L(r)} \quad (6.44b)$$

Where:

Range = aircraft max range carrying a W_{TO} [km]

An aircraft cannot carry more fuel than its tank volume. Equation 6.45 constraints UFT to be less or equal to the aircraft tank fuel storage capacity.

$$D_r \geq \text{Range}_{x,L(r),t}\ y_{x,L(r),t} \quad (6.45)$$

Weight has a high impact on aircraft performance. The ability of an aircraft to fly a route link with distance D_r depends on how long an aircraft can fly under different weights. Each aircraft manual specifies the maximum design weights in which each aircraft must be operated. Any aircraft can be operated over these operation weights. Table 6.3 summarizes the different weights involve in an aircraft operation.

Table 6.3 Aircraft maximum design weights [Boeing manuals]

Weight	*Abbreviation*	*Units*	*Definition*
Max Design Taxi Weight	MTW	Tons	Max weight for ground manoeuvres. It includes taxiing and run-up fuel.
Max Design Takeoff Weight	MTOW	Tons	Max weight for takeoff
Max Design Landing Weight	MLW	Tons	Max weight for landing
Max Design Zero Fuel Weight	MZFW	Tons	Max weight allow before usable fuel and other usable agents
Operating Empty Weight	OEW	Tons	Total aircraft weight without including payload and usable fuel
Max Payload	Payload	Tons	Max design zero fuel weight minus OEW
Usable Fuel	UF	Tons	Fuel available for aircraft propulsion

Equation 6.46 determines an aircraft weight before takeoff (W_{TO}) in tones.

$$W_{TO\ x,L(r),t} = \text{Load}_{x,L(r),t} + \text{UFe}_{x,L(r),t} \quad (6.46)$$

The max load an aircraft can carry before leaving an airport gate has to be less than its MTW:

$$(W_{TO\ x,L(r),t} + \text{ToutF}_{x,L(r),t})\ y_{x,L(r),t} \leq \text{MTW}_x \quad (6.47)$$

The max load an aircraft can carry before taking off has to be less than the MTOW:

$$W_{TO\ x,L(r),t}\ \ y_{x,L(r),t} \leq \text{MTOW}_x \quad (6.48)$$

Equation 6.49 determines an aircraft load before landing (W_{DES}).

$$W_{DES\,x,L(r),t} = W_{TO\,x,L(r),t} - UF_{x,L(r),t} \quad (6.49)$$

The minimal flying range (MFR) for an aircraft depends on the aircraft total weight before landing (W_{DES}). An aircraft cannot land at an airport if its weight before landing is heavier than its max design landing weight (MLW). It has to keep flying until enough jet fuel has been consumed. Thus, an aircraft MFR depends on its MLW, W_{TO} and D_r. Equation 6.50 explains this restriction in its mathematical form.

$$W_{DES\,x,L(r),t}\; y_{x,L(r),t} \leq MLW_x \quad (6.50)$$

6.2.11 The flight cycle of an aircraft

The fly cycle of an aircraft is divided in two times. First, the aircraft is being prepared to initiate the next flight (time on the ground). Second, the time spent during the block time. The time on the ground depends on the time consumed during turnaround activities. The block time is the time aircraft spend during taxi-out, air time and taxi-in (Figure 6.5).

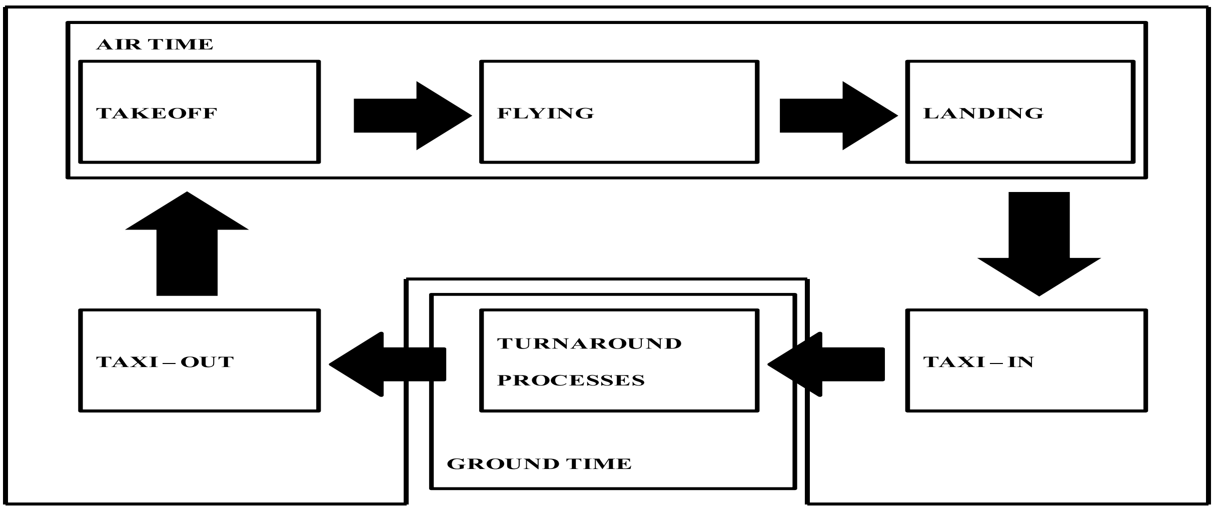


Figure 6.5 The flight cycle of an aircraft

Link Block time (LBT)

The United States Federal Aviation Administration (FAA) and the International Civil Aviation Authority (ICAO) typically name the flight time as the link block time (LBT). The block time starts when the aircraft begins moving with the purpose of taking-off, and it finishes when the aircraft is on-chock after landing [Aviationglossary.com].

Air time (AIRTime)

The air time begins at the moment an aircraft takes off at airport ORI, and it ends at the moment it lands on its airport DES [RITA Glossary]. The air time can be divided by takeoff, flying time and landing. The takeoff is the stage where the aircraft changes from moving on the ground to flying in the air. This process can be divided in two parts. The first part is the ground run. The second part is the distance where the aircraft leaves the ground. It ends until the aircraft is at safety height (15m or 50ft) over the ground. Landing is the stage where the aircraft comes back to the ground. This process can be divided in four parts, the descent, the flare, the touch-down and transition to nose wheel down, and ground run. The total landing distance includes the ground run and the distance where the airplane is located at 15m or 50ft over the ground [Cheng, Grandhi, Hankey, Belcher, 1993]. Flying time occurs between takeoff and landing.

The average takeoff (t_{TO}), flying (t_{flying}) and landing times (t_{DES}) need to be calculated to estimate a link air time (AIRTime). In order to calculate these times, it is necessary to define aircraft stall speed (V_s), liftoff speed or takeoff speed (V_{TO}), cruise speed (V_C) and descent speed (V_{DES}). Stall speed is the minimum flying speed of an aircraft, when flying slower than this speed, aircraft will face a lift reduction, and it will start falling down (Equation 6.51).

$$V_{S\,x,L(r),t} = \sqrt{\frac{W_{TO\,x,L(r),t}\,g}{\frac{1}{2}\rho_{Air}\,S_{W\,x}\,C_{L\,x}}} \qquad (6.51)$$

Where:

V_S	= Stall speed	[km/hr]
g	= gravity	[m/s^2]
S_W	= Wing area, aircraft type x	[m^2]
ρ_{Air}	= air density, the International civil aviation authority (ICAO) standard air density at sea level is 1.22 [ICAO, 1993]	[kg/m^3]
C_L	= Aircraft type x ground lift coefficient	[-]

$$C_{L_{TODES\,x,L(r),t}} = \left[\frac{2\,W_{TODES\,x,L(r),t}\,g}{\rho_{Air}\,V_{C\,x}^2\,S_{W\,x}}\right]\left[\frac{1}{1+\left[\frac{Lift_x}{Drag_x}\right]\tan\alpha_{AT}}\right] = \left[\frac{2\,W_{TODES\,x,L(r),t}\,g}{\rho_{Air}\,V_{C\,x}^2\,S_{W\,x}}\right]\left[\frac{1}{1+\left[4\left(1+\frac{3}{M_x}\right)\right]\tan\alpha_{AT}}\right] \qquad (6.52)$$

[Phillips, 2004]

Where:

α_{AT}	= Aircraft max angle of attack at takeoff or landing	[°]
Lift	= lift force	[N]
Drag	= drag force	[N]
M	= aircraft velocity in match speed	[-]

The safety height is the altitude where aircraft are in the minimum vertical clearance from nearby terrain obstacles and allows appropriate navigation functions. The takeoff or liftoff speed, depending on the aircraft type, is anywhere from 1.05 to 1.25 times the V_s [FAA, 2008b]. In [Cheng et. al, 1993], the V_{TO} speed is set up as 1.2 times V_S (Equation 6.53).

$$V_{TO\,x,L(r),t} = 1.2\,V_{S\,x,L(r),t} \qquad (6.53)$$

Where:

V_{TO} = average takeoff speed [km/hr]

The V_{DES} is 1.3 times the V_S [Cheng et. al, 1993] [FAA, 2008b]:

$$V_{DES\,x,L(r),t} = 1.3\sqrt{\frac{W_{DES\,x,L(r),t}}{\frac{1}{2}\rho_{Air}\,S_{Wx}\,C_L}} \qquad (6.54)$$

Climbing speed is the minimum speed the aircraft must have to pass over the safety height (15m or 50ft) [Cheng, et. al, 1993].

Finally, cruise speed V_C is the velocity in which aircraft fuel consumption is efficient. The aircraft travels at the optimum speed during most of the flying time, but an aircraft optimum speed changes depending on the flight conditions. Many conditions have to be taken into account such as wind, weather, altitude and temperature conditions. However, the average cruise speed and the maximum aircraft speeds are published by the aircraft manufacturer. In Figure 6.6, the average aircraft cruise and max speeds are shown (data in Appendix K).

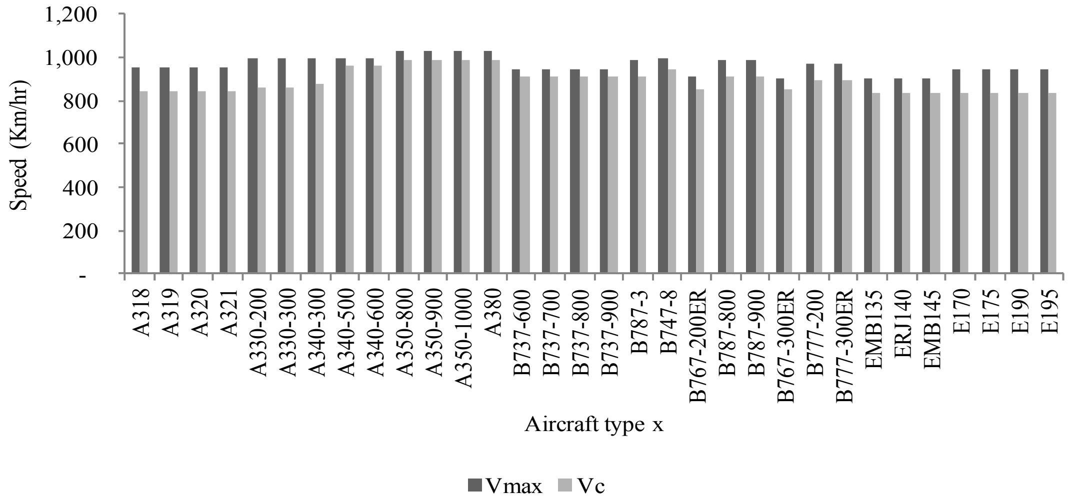


Figure 6.6 Aircraft cruise and max speeds [Airbus, Boeing and Embraer manuals] [Airliners.net]

The wind speed (V_w) must be considered to calculate an aircraft air time, because it affects the performance of the aircraft speed. If the wind blows against an aircraft, the aircraft engines need to inject more power, more fuel will be required to achieve the V_C, V_{TO} or V_{DES}. According with Jenkinson and Marchman III [2003] t_{TO} and t_{DES} are calculated as follow:

$$t_{TODES\,x,L(r),t} = \frac{1}{\sqrt{A_{TODES\,x,L(r),t}\,B_{TODES\,x,L(r),t}}}\left[\tanh^{-1}\left(\sqrt{\frac{B_{TODES\,x,L(r),t}}{A_{TODES\,x,L(r),t}}}\,V_{TODES\,x,L(r),t}\right) - \tanh^{-1}\left(\sqrt{\frac{B_{TODES\,x,L(r),t}}{A_{TODES\,x,L(r),t}}}\,V_{Wr}\right)\right] \quad (6.55a)$$

Where:

t_{TODES}	= takeoff (TO) or landing (DES) time	[hr]
V_w	= average wind speed on route r	[km/hr]
TODES	= aircraft takeoff (TO) or landing (DES) ϵ {TO, DES}	[-]

$$A_{TODES\,x,L(r),t} = \left[\frac{STE_x}{g\,W_{TODES\,x,L(r),t}} - \mu_{1\,x,L(r)}\right] \quad (6.55b)$$

Where:

STE	= aircraft engine static thrust or thrust at zero airspeed	[N]
μ_1	= coefficient of rolling friction	[-]

$$B_{TODES\,x,L(r),t} = \frac{1}{g\,W_{TODES\,x,L(r),t}}\left[\frac{1}{2}\,\rho_{Air}\,S_{Wx}\left(C_{D_{TODES\,x,L(r),t}} - \mu_{1\,x,L(r)}C_{L_{TODES\,x,L(r),t}}\right)\right] \quad (6.55c)$$

Where:

$$C_{D_{TODES\,x,L(r),t}} = \frac{C_{L_{TODES\,x,L(r),t}}}{4\left(1+\frac{3}{M_x}\right)} \quad (6.55d)$$

Equation 6.56 determines routes flying time as a function of route link D_r and aircraft type cruise speed ($V_{C\,x}$) affected by wind flow on route ($V_{w\,r}$).

$$t_{flying\,x,L(r)} = \frac{D_{L(r)}}{V_{C\,x} \mp V_{w\,L(r)}} \quad (6.56)$$

Where:

t_{flying}	= aircraft x flying time	[hr]

Equation 6.57 expresses the air time as the sum of the takeoff, flying and landing times.

$$AIRTime_{x,L(r),t} = t_{TO\,x,L(r),t} + t_{flying\,x,L(r)} + WTD_{DES(r),t} + t_{DES\,x,L(r),t} \quad (6.57)$$

Taxi-in and taxi-out times (Tin and Tout)

Taxiing is an aviation term that refers to the movement of an aircraft from the runway to the apron/gate (taxi-in) and vice versa (taxi-out). It does not include the aircraft ground run before takeoff or after landing. The airports with the longest average taxi-out (Tout) and taxi-in (Tin) times are principally airports with high pax flow. Contrary, airports with decreasing pax flow have shorter taxi times [Goldberg and Chesser, 2008].

Taxi-in and taxi-out times depend on the number of aircraft using the active runways, the distance from the landing runway to the apron/gate (D_{Tin}) and from the apron/gate to the takeoff runway (D_{Tout}). Thus, the min taxi-in and taxi-out times would be the max aircraft underground velocity and the distance between runways to apron/gates. The only queue before being process at the gate is the queue waiting for landing (WTD) if it is not allowed having aircraft waiting on the taxi-in ground run. After the turnaround process, a queue for takeoff at an airport ORI runway (WTO_{ORI}) exists.

Equation 6.58 expresses the taxi-in time at airport DES at a constant velocity.

$$Tin_{DES(r),t} = \frac{D_{Tin_{DES(r),t}}}{V_{taxiing}} \tag{6.58}$$

Where:

Tin	= average taxi-in time operation on route r	[hrs]
D_{Tin}	= Average distance from terminal apron/gate to the runway landings position on route r	[km]
$V_{taxiing}$	= Aircraft taxing constant velocity , 32.18 km/hr [FAA, 2010a]	[km/hr]

Equation 6.59 determines the taxi-out time at airport ORI at constant velocity.

$$Tout_{ORI(r),t} = \frac{D_{Tout_{ORI(r),t}}}{V_{taxiing}} + WTO_{ORI(r),t} \tag{6.59}$$

Where:

Tout	= average taxi-out time operations on route r	[hrs]
D_{TO}	= Average distance from terminal apron/gate to the runway takeoff position on route r	[km]

Finally, Equation 6.60 determines the link BT_x, in hrs, of any aircraft type:

$$LBT_{x,L(r),t} = Tout_{ORI(r),t} + AIRTime_{x,L(r),t} + Tin_{DES(r),t} \tag{6.60}$$

Where:

LBT	= Link block time	[hrs]

Ground time or Turnaround time (Tr)

An aircraft turnaround starts when the aircraft is on-chock and ends when it starts taxing out. These processes are a complex set of sequential and parallel activities. These activities are standardized operations procedures (SOP's) (Figure 6.7) and all have their own processing time. These processes sequence and time limits are explained in each aircraft manual.

The turnaround SOP's can be divided into three categories (Figure 6.7). First, passenger services are those activities related to the transfer of pax onto or off the aircraft and the replenishment of services provided to pax during flight. Second, airplane servicing involves those operations that allow aircraft functioning by itself. Third, cargo and baggage handling category entails the loading and unloading of aircraft [Thorne, Barrett, McFarlane, 2007].

Figure 6.7 shows the common turnaround critical processes path in grey color. In big aircraft service cabin process takes longer than fuelling. In small aircraft such as Embraer, fuelling takes longer time than service cabin. Airlines apply their own SOP's. The embarking and disembarking times depend on the airline load factor, the aircraft seat capacity and the embarking and disembarking rates. These rates are aircraft type specific. Typical values are available in each aircraft SOP manual [Boeing, Airbus manuals]. The turnaround process can be calculated as the sum of the processes that determined the critical path:

$$Tr_{x,ORI(r),t} = TrP_{x,ORI(r),t} + TrD_{x,ORI(r),t} + TrSoF_{x,ORI(r),t} + TrB_{x,ORI(r),t} + TrR_{x,ORI(r),t} + WTr_{x,ORI(r),t} \quad (6.61a)$$

Where:

Tr	= Aircraft turnaround time at an airport in time t	[hr]
TrP	= Aircraft position air bridge or stairs time at an airport in time t	[hr]
TrD	= Aircraft deplane pax time at an airport in time t	[hr]
TrSoF	= Aircraft service galley time at an airport in time t	[hr]
TrB	= Aircraft board pax time at an airport in time t	[hr]
TrR	= Aircraft remove air bridge or stairs time at an airport in time t	[hr]
WTr	= Aircraft turnaround schedule delay/buffer time at an airport in time t	[hr]

$$TrSoF_{x,ORI(r),t} = TrF_{x,ORI(r),t}\left(y_{7_{x,t}}\right) + TrS_{x,ORI(r),t}\left(1 - y_{7_{x,t}}\right) \quad (6.61b)$$

Subject to:

$$y_{7_{x,t}} = \begin{cases} 0 & \text{if } TrF_{x,ORI(r),t} \geq TrS_{x,ORI(r),t} \\ 1 & \text{if } TrF_{x,ORI(r),t} < TrS_{x,ORI(r),t} \end{cases} \quad (6.61c)$$

Where:

TrS	= Aircraft service galley time at an airport	[hr]
TrF	= Aircraft fuelling time at an airport	[hr]
y_7	= aircraft type turnaround decision variable {0, 1}	[-]

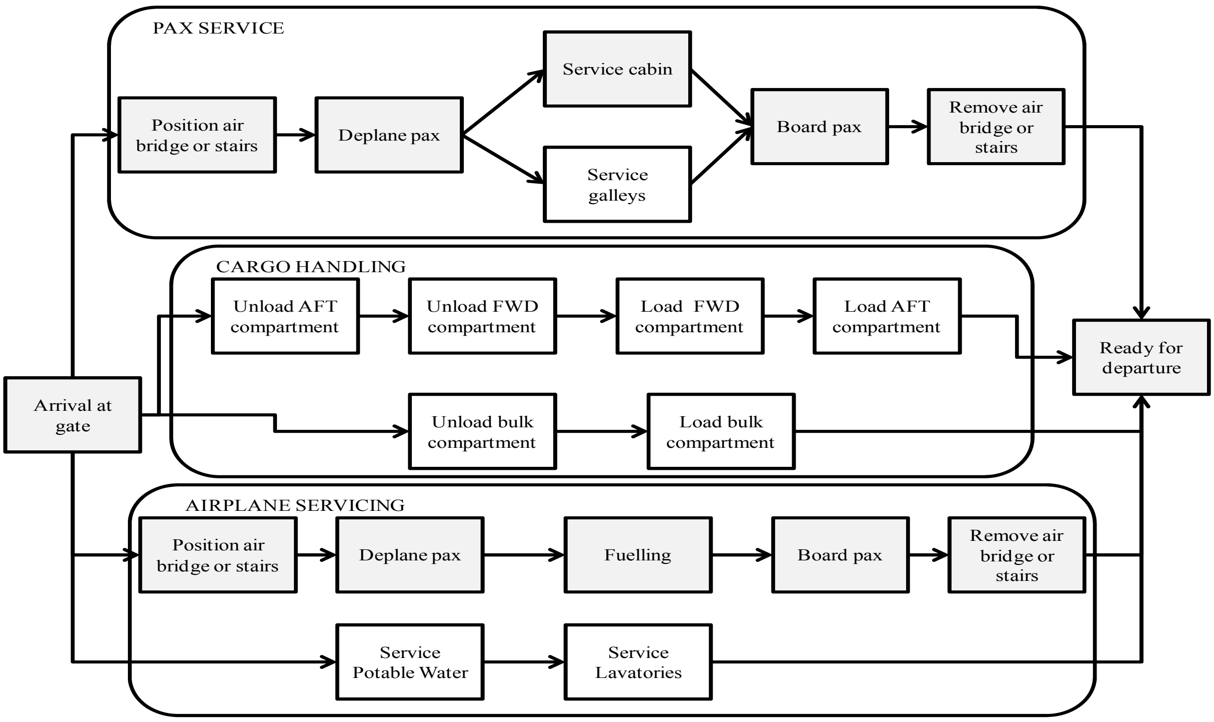


Figure 6.7 Aircraft turnaround common processes diagram

In an aircraft turnaround, some process can be performed simultaneously, such as baggage unloading and pax disembarkation (deplane). Other procedures interfere with each other, such as disembarkation/embarkation with fuelling, boarding pax with load AFT compartment, etc. The aircraft turnaround process is similar for all aircraft. However, Chapter 2 explained that an aircraft turnaround processes may be different between airlines [Bazargan, 2010] and between airports. Minimizing an airline turnaround time process is part of an airline strategy to minimize operating costs by increasing aircraft utilization time per day. For example, variables that are well known to affect the FSC's operations are the seat allocation, number of handled baggage and the use of loading air bridges (not used by LCC's) because they delay the turnaround time of the aircraft [Dennis, 2007].

Whether all operations described by the aircraft manufacturer are executed, depends on the service level the airline provides. Normally, full servicing is performed for a turnaround station (Tr_S) and minimum servicing for an en-route station (Tr_{ES}). In this thesis, an en-route station is an airport where an aircraft stops without charging fuel or major cleaning (Equation 6.61c). An en-route station TrSoF is equal to zero hours, so Tr_{ES} can be calculated as:

$$Tr_{ES_{x,ORI(r),t}} = TrP_{ES_{x,ORI(r),t}} + TrD_{ES_{x,ORI(r),t}} + TrB_{ES_{x,ORI(r),t}} + TrR_{ES_{x,ORI(r),t}} + WTr_{ES_{x,ORI(r),t}} \qquad (6.61d)$$

For simplicity, the Tr is considered as one process. The Tr time is the total time to prepare an aircraft for takeoff. In this thesis, the Tr time provided by the aircraft manufacturers will be used. These times give good approximations for LCC's and FSC's, because the Tr time considered in each aircraft manual [Boeing, Airbus, Embraer manuals] are the minimum Tr times established by the manufacturer. However, it is different for all airlines and airports. Figure 6.8 shows the Tr times according to aircraft manuals (data in Appendix K).

The minimization of an airline operation costs requires charging jet fuel on airports with cheap jet fuel price (JFP). An aircraft charges fuel at an airport for two reasons: first, the aircraft does not have enough fuel to fly its next link. Second, the current JFP at airport ORI is higher than in the next airports where it will stop on its route. Equation 6.62 selects the airports where aircraft must charge fuel on their flying routes.

$$Tr_{x,L(r),t} = Tr_{ST\,x,L(r),t}\; y_{5\,x,L(r),t} + Tr_{ES\,x,L(r),t}\left(1 - y_{5\,x,L(r),t}\right) \qquad (6.62)$$

Link flying time of an aircraft

The total aircraft link time (LTime) is calculated as the sum of the turnaround process time and the link block time from airport ORI to airport DES and vice versa (Equation 6.63):

$$LTime_{x,L(r),t} = Tr_{x,ORI(r),t} + LBT_{x,L(r),t} \qquad [hrs] \qquad (6.63)$$

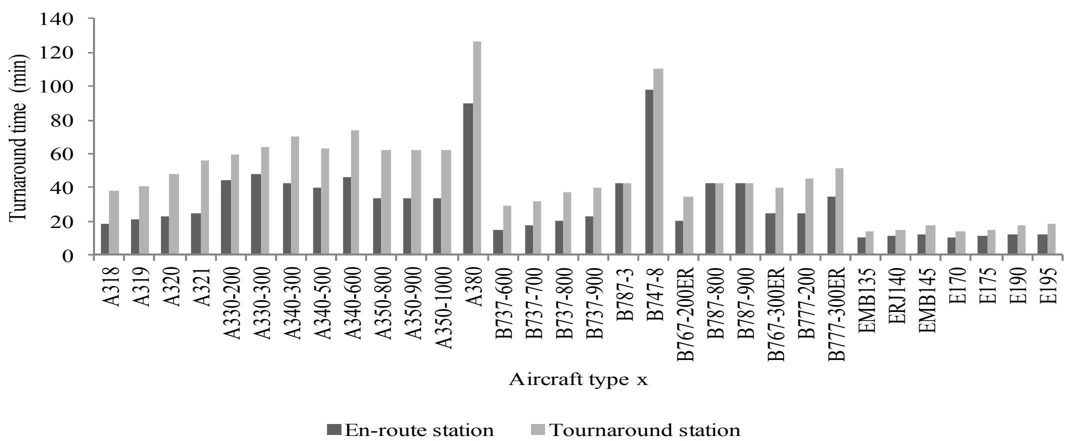


Figure 6.8 Aircraft types turnaround times [Airbus, Boeing and Embraer manuals]

6.2.12 Airport airside and Airport characteristics related to aircraft

Airport characteristics have an important role on airlines aircraft selection. Airport facilities can be divided in airport airside, airport terminal and airport land side [ACRP Report 25, 2010]. On the airside, the runway length and width, the min separation between runways and taxiways, the geometric of taxiways, and the pavement strength determine if an aircraft can operate at a certain airport or not [Gomes de Barros and Wirasinghe, 1997]. On the terminal, the aircraft pax capacity impacts the sizes of pax facilities within the terminal as well as the size of the baggage handling systems at an airport [Gomes de Barros and Wirasinghe, 1997]. On the landside, the accessibility from a region to the airport is determined by different transport modes that influence the passenger airport attractiveness.

Takeoff and landing ground roll

The takeoff distance is divided into ground run and distance from where the plane leaves the ground to until the plane is above 15m (50ft) over the ground. The sum of both distances forms the takeoff distance [Jenkinson and Marchman III, 2003]. The minimum runway takeoff distance is a main concern in the operation of an aircraft [FAA, 2008b]. This distance is normally calculated for max aircraft weight in a standard atmosphere [Jenkinson and Marchman III, 2003]. The worst scenario happens at those airports with high altitude in a hot day with max aircraft weight.

The objective is to calculate the ground roll for takeoff and landing at different airports depending on the aircraft. This is an important restriction when selecting the optimum aircraft type. In reality, the optimum aircraft is constrained to the characteristics of the airports in an airline network such as the characteristics of runways and terminals infrastructures. For example, in case the A380 shows to be the optimum aircraft to operate an airline network, but today few airports have facilities with enough capacities to receive such a big aircraft.

Many variables affect the performance of an aircraft. In concrete, any item affecting the takeoff speed (V_{TO}) during the takeoff roll will increase or decrease the takeoff distance or ground run (S_{TO}). The principal variables affecting the takeoff and landing of an aircraft are aircraft weight, wind, runway slope, and pressure altitude and temperature [FAA, 2008b].

The increase of aircraft W_{TO} requires higher V_{TO}, greater mass to accelerate and increase drag, and ground friction causing the increase of an aircraft S_{TO} [FAA, 2008b]. For example, 10% increase in W_{TO} causes 5% increase in V_{TO}, 9% decrease in rate of acceleration and 21% increase in S_{TO} to support the increment of W_{TO} [FAA, 2008b].

The effect of headwind allows the aircraft to reach the V_{TO} at a lower ground speed. Contrary, the tailwind requires the aircraft to increase the S_{TO} to accomplish the minimum V_{TO}. The effect of wind on landing distance (S_{DES}) is exactly the same to its effect during takeoff [FAA, 2008b]. For example, a headwind of 10% of the V_{TO} will decrease the S_{TO} around 19%. Contrary, a tailwind of 10% of the V_{TO} will increase the S_{TO} around 21% [FAA, 2008b].

The most important factor determining the runway distance in relation to takeoff of an aircraft is the effect of takeoff speed [FAA, 2008b]. The indicated takeoff speed (IAS) at the Airplane flight manual (AFM) and at the Pilot’s Operating Handbook (POH) specified the minimum safe speeds at which the aircraft can fly. Any intent to takeoff under these velocities may not allow the aircraft to climb out the ground effect. For example, 10% airspeed would increase the takeoff 21% [FAA, 2008b].

The effect of pressure altitude and temperature define the density altitude. Aircraft requires the same dynamic pressure to start flying at the takeoff lift coefficient (C_L). The aircraft at any altitude requires the same IAS to takeoff than at the sea level. The reduction of air density at higher altitudes increases the true airspeed (TAS) of an aircraft to takeoff.

The equation that determines the required ground roll for an aircraft to takeoff (for a headwind) is as follows [Jenkinson and Marchman III, 2003]:

$$GR_{TO\ x,L(r),t} = \frac{1}{2\ B_{TO\ x,L(r),t}} \ln\left[\frac{A_{TO\ x,L(r),t} - B_{TO\ x,L(r),t}\,(V_{W\ r})^2}{A_{TO\ x,L(r),t} - B_{TO\ x,L(r),t}\,V^2_{TO\ x,L(r),t}}\right] - V_{W\ r} \qquad (6.64)$$

Where:

GR_{TO} = Aircraft ground roll distance require for takeoff at any airport [km]

The minimum S_{DES} changes in direct proportion to the aircraft W_{DES}. For example, 10% increase in W_{DES} would cause 5% increase in V_{DES} and 10% increase in S_{DES}.

Similar to the min V_{TO}, the min V_{DES} is specified in the AFM and POH. An aircraft landing at slower speeds than those indicated in the manuals are at risk for developing high rates of descent. Contrary, if the aircraft is landing at higher speeds that those indicated in the manuals needs longer S_{DES} [FAA, 2008b]. For example, 10% higher V_{DES} needs at least 21% increases in S_{DES} [FAA, 2008b].

The effect on pressure altitude and temperature defines density altitude and its effect on an aircraft landing performance. V_{DES} increase as density altitude increases, aircraft at higher altitudes lands at the same indicated landing speed (IAS) as at sea level but the TAS increases. For example, at 1,500m (5,000ft), the required S_L is 16% larger than the min S_L at sea level. The approximate increase in S_{DES} is equal to three and one-half percent for each 606m (1,000ft) [FAA, 2008b].

The equation that determines the required ground roll for an aircraft to landing (for a headwind) is as follows [Jenkinson and Marchman III, 2003]:

$$GR_{DES\ x,L(r),t} = \frac{1}{2\ B_{DES\ x,L(r),t}} \ln\left[\frac{A_{DES\ x,L(r),t} - B_{DES\ x,L(r),t}\,(V_{W\ r})^2}{A_{DES\ x,L(r),t} - B_{DES\ x,L(r),t}\,V^2_{TO\ x,L(r),t}}\right] - V_{W\ r} \qquad (6.65)$$

Where:

GR_{DES} = Aircraft ground roll distance require for takeoff at any airport [km]

Finally, an aircraft is allowed to operate and airport only if both S_{TO} and S_{DES} are smaller than the runway length. Equation 6.66 determines if an aircraft can take off at an airport plus a safety distance in case the aircraft needs to stop during the takeoff. Equation 6.66 determines if an aircraft can land at an airport plus a safety distance in case of an emergency.

$$\left(GR_{TODES\ x,L(r),t} + GRs_{TODES\ x,L(r),t}\right) y_{x,L(r),t} \leq RL_{OD(r),t} \qquad (6.66)$$

Where:

GRs = Aircraft ground roll safety distance require during takeoff to allow maneuvering in case of any emergency [km]

RL = Airport runway ORI(r) or DES(r) (OD(r)) length in time t (airport ORI and airport DES can increase the runways lengths in future years if enough space exist to do so) [km]

Runway and taxiway widths and separation between those ways

The wheel track and wingspan relation with runways and taxiways widths, and the separation between them, determine the availability of an aircraft to operate in at an airport [Gomes de Barros and Wirasinghe, 1997].

The size of airports runways and taxiways and the distances between runways is defined by the size of the larger aircraft to which the airport was designed [Gomes de Barros and Wirasinghe, 1997]. The smallest the aircraft the shortest the requirements for separations and its runways and taxiways dimensions, and vice versa. In Table Appendix L. 1, aircraft have been classified according with the FAA airport code (Table 6.4) [FAA, 1989] [ACC, 2008].

Table 6.4 FAA Aircraft approach and design categories [FAA, 1989] [ACC, 2008]

Aircraft approach category	*Aircraft approach speed, V_{DES} (km/hr)*	*Airplane design group*	*Tail Height (m)*	*Wingspan (m)*
A	< 168.53	I	< 6.1	< 14.94
B	168.53 ≤ 224.09	II	6.1 ≤ 9.14	14.94 ≤ 24.08
C	224.09 ≤ 261.13	III	9.14 ≤ 13.72	24.08 ≤ 35.97
D	261.13 ≤ 307.43	IV	13.72 ≤ 18.29	35.97 ≤ 52.12
E	≥ 307.43	V	18.29 ≤ 20.12	52.12 ≤ 65.23
		VI	20.12 ≤ 24.38	65.23 ≤ 79.86

The airside facility dimensions determine an airport classification depending on its smallest airside facility capacity. The aircraft facilities are based on airport geometry, runway design, taxiway and taxi lane designs. Table Appendix L. 2, Table Appendix L. 3, Table Appendix L. 4, Table Appendix L. 5, Table Appendix L. 6, Table Appendix L. 7, Table Appendix L. 8, Table Appendix L. 9 and Table Appendix L. 10 present airport facilities and dimensions required to operate each different aircraft based on its approach category and airplane design group. The dimensions specified on these tables were determined by the US FAA. These tables are used for airport design. Airports are classified into one of the categories in Table 6.4. The classification is made according with airside facilities dimensions (Appendix L). An aircraft is allowed to fly to an airport only if its airplane design group is lower or equal to the airport design group.

In the optimization model, whether airports and aircraft are classified according with the tables presented in Appendix L. Equation 6.67 represents a constraint that allows or not an aircraft to operate at an airport. This is a constraint for routes links selection because not all aircraft are capable to operate at all airports. The airside dimensions of an airport represent an important constraint especially for large or big aircraft.

$$\mathrm{AMI}_x \, y_{x,L(r),t} \leq \mathrm{AIRSIDE}_{OD(r),t} \tag{6.67}$$

Where:

AMI = Aircraft FAA dimensions and designations code (Table Appendix L. 1) [-]

AIRSIDE = Airport FAA code based on runways and taxiways dimensions and separations [-]

Runway capacity

The capacity of an airport is constrained by its maximum number of aircraft movements. The maximum number of aircraft movements at an airport is affected by weather conditions, number of landings, number of takeoffs, aircraft types, airport Air Traffic Control (ATC) and airport facilities in specific the total number of aircraft gates and stands (N_g).

An airport air traffic control (ATC) represents the first part of the air traffic management processes that determine and organize the number of aircraft movements in the air and on the ground. The ATC is responsible for maximizing the number of aircraft landings and takeoffs during time t. Airports ATC's controls the separation between aircraft to prevent collisions based on aircraft wake vortex separation rules on approaches.

Wake vortex effects are related to aircraft weights [Horojneff and McKelvey, 1994]. The lighter the follower aircraft (x_j) is to the leader aircraft (x_i), the more distance is needed. This avoids the leader aircraft wake vortex (Table 6.5). Then, an airport runway capacity (λ) decreases as the mix between different aircraft sizes increases. Airports averages minimal inter-arrival times (IET) decrease if the mix between different aircraft sizes increases.

Table 6.5 FAA Aircraft wake vortex separation rules on approach [FAA, 2010b]

Leader	*Follower (x_j)*				*Aircraft weight type*
(x_i)	*Small (km)*	*Large (km)*	*Heavy (km)*	*Super (km)*	*MTOW (tones)*
Small	7.41	7.41	7.41	7.41	≤ 18.6
Large	7.41	7.41	7.41	7.41	18.6 < 140
Heavy	9.26	9.26	7.41	7.41	≥ 136
Super	14.82	12.96	9.26	7.41	Airbus A380

Equations 6.68 calculate an airport runway average minimal inter-arrival times (IET_t). The equation calculates the minimal inter-arrivals times between leader's aircraft (x_i) and follower's aircraft (x_j) in the airport approaching series. Equation 6.68a also considers the proportions of aircraft type's x_i (p_{xi}) and aircraft types' x_j (p_{xj}) at the airport traffic [Janic and Tosic, 1982] [Janic, 2000]. The required distances between the leader aircraft ($x_{i's}$) and the follower aircraft ($x_{j's}$) approaching an airport are equal to the minimal separation distance (WVS_{xij}).

$$IET_{OD(r),t} = \sum_{xij}\left\{\left(\left[p_{xi,OD(r),t}\left(t_{DES\,x,L(r),t}\right) p_{xj,OD(r),t}\right]\left(1-y_{8_{x,L(r)}}\right)+\left[p_{xi,OD(r),t}\left(\frac{WVS_{xij}}{V_{DES\,xj,L(r)}}\right) p_{xj,OD(r),t}\right]\left(y_{8_{x,L(r)}}\right)\right)\left(1-y_{9_{x,L(r)}}\right)+\left(\left[p_{xi,OD(r),t}\left(\frac{WVS_{xij}}{V_{DES\,xj,L(r)}}+\mathfrak{l}\left[\frac{1}{V_{DES\,xj,L(r)}}+\frac{1}{V_{DES\,xi,L(r)}}\right]\right) p_{xj,OD(r),t}\right]\right)\left(y_{9_{x,L(r)}}\right)\right\} \quad (6.68a)$$

Subject to:

$$y_{8_{x,L(r)}} = \begin{cases} 0 & \text{if } \left(t_{DES\,x,L(r),t} \geq \frac{WVS_{xij}}{V_{DES\,xj,L(r)}}\right) \\ 1 & \text{if } \left(t_{DES\,x,L(r),t} < \frac{WVS_{xij}}{V_{DES\,xj,L(r)}}\right) \end{cases} \quad (6.68b)$$

$$y_{9_{x,L(r)}} = \begin{cases} 0 & \text{if } V_{DES\,xi,L(r)} \leq V_{DES\,xj,L(r)} \\ 1 & \text{if } V_{DES\,xi,L(r)} > V_{DES\,xj,L(r)} \end{cases} \quad (6.68c)$$

Where:

IET = average minimal inter-arrival time at an airport in time t, a route link consist on an airport ORI or takeoff airport (TO) and an airport DES or landing airport DES [mov/hrs]
V_{DESxi}, V_{DESxj} = aircraft type x_i and x_j landing speed [km/hr]
$\mathfrak{l}$ = length of all aircraft approaching path at an airport [km]
WVS_{xij} = wake vortex separation between aircraft type x_i and x_j [km]
p_{xi}, p_{xj} = proportions of aircraft types x_i and x_j at the airport traffic in time t [km]
y_8 = aircraft type turnaround decision variable {0, 1} [-]
y_9 = aircraft type turnaround decision variable {0, 1} [-]

An airport runway landing capacity (λ_{DES}) has to assure the minimum separation between consecutive aircraft approaches or landings. An airport λ_{DES} in time t is calculated as follows:

$$\lambda_{DES_{OD(r),t}} = \frac{Ђ_{OD(r),t}}{IET_{OD(r),t}} \quad (6.69)$$

Where:

λ_{DES} = airport runway landing capacity in an airport, a route link consist on an airport ORI or takeoff airport and an airport DES or landing airport [mov]

Ђ = total number of hours an airport is open for services during time t [hrs]

A runway can be used for landing and takeoff operations at time t. Airports ATC's apply different strategies to control the traffic flow according with the demand of aircraft movements. Equation 6.70 determines the output of airports ATC's applying different landings and takeoffs strategies [Janic, 2000].

$$\lambda_{OD(r),t} = \left(1 + p_{d_{OD(r),t}}\right) \lambda_{DES_{OD(r),t}} \quad (6.70a)$$

Subject to:

$$tgap_{xij,OD(r),t} \geq t_{DES\ xj,OD(r),t} + \frac{d_{x_{jk}}}{V_{DES\ xj,L(r),t}} \quad (6.70b)$$

Where:

λ = airport runway landing and takeoffs capacity in time t, a route link consist on an airport ORI or takeoff airport and an airport DES or landing airport [mov]

$tgap_{xij}$ = airport minimal time gaps allowing aircraft x_k takeoffs between aircraft x_i and x_j landings [hrs]

$p_{d,t}$ = probability of having any gap between aircraft type x_i and x_j movements at airport in time t [-]

d_{xjk} = min distance required between aircraft x_j and takeoff of aircraft x_k [km]

Two ATC extreme scenarios can be studied using Equations 6.70. The first scenario is consecutive aircraft movements. If an airport runway is used only for landings during time t, the runway capacity is equal to λ_{DES} in time t. If an airport runway is used only for takeoffs during time t, the runway capacity is equal to λ_{TO} in time t. The second scenario is alternating landings and takeoffs. This is the ideal ATC strategy because it duplicates the capacity of an airport runway. This scenario happens when the probability of achieving minimal gaps ($tgap_{xij}$) between aircraft movements (landing and takeoffs) is 1. This scenario calculates the runway maximum capacity (λ_{max}) in time t [Janic, 2000]:

$$\lambda_{max_{OD(r),t}} = 2\,\lambda_{DES_{OD(r),t}} \quad (6.71)$$

Where:

λ_{max} = airport maximum runway landing and takeoffs capacity per time t, a route link consist on an airport ORI or takeoff airport and an airport DES or landing airport [mov]

The total number of aircraft movements (landings and takeoffs) at an airport in time t (Mov) is equal to the number of landings M_{DES} plus the number of aircraft takeoffs M_{TO} in time t:

$$Mov_{OD(r),t} = \sum_{a=1}^{A} Mov_{DES_{OD(r),t,a}} + \sum_{a=1}^{A} Mov_{TO_{OD(r),t,a}} \quad (6.72)$$

Where:

Mov = total number of aircraft movements at an airport in time t, a route link consist on an airport ORI or takeoff airport and an airport DES or landing airport [mov]

a = airline operating a link ϵ {United Airlines = 1, American Airlines = 2, etc.} [-]

The max number of aircraft movements available at an airport in time t (Ma_t) can be equal to its λ_{max} minus Mov in time t:

$$Ma_{OD(r),t} = \lambda_{max_{OD(r),t}} - Mov_{OD(r),t} \quad (6.73)$$

Airlines are constrained to the Ma at both airports connecting a route link where they want to open new services. The total number of airlines movements ($freq_r$) at an airport must be less or equal to the airport Ma. An airline route link $freq_r$ must be less or equal to the airport ORI Ma_{ORI} and airport DES Ma_{DES}. Equations 6.74 constraint the max number of $freq_r$ an airline can operate at an airport.

$$freq_{x,L(r),t} \leq Ma_{ORI(r),t} \tag{6.74a}$$

Equation 6.74a refers to those links connecting an airport ORI with all airports DES's. Equation 6.74b refers to all links connecting an airport DES with all airports ORI's. The total number of frequencies that can be opened in an airport must be less than the runways aircraft movement's capacities at the airport.

$$freq_{x,L(r),t} \leq Ma_{DES(r),t} \tag{6.74b}$$

Where:

Ma_D = Aircraft type x available gates at airport DES in time t [mov]

Apron Area and Number of Gates/Stands

This is the area of an airport dedicated for the allocation of aircraft. This area is around the hangars and airports terminals buildings. Aircraft park in the apron area, in front of a gate or in an aircraft parking stand, during the turnaround processes. The apron area where an aircraft is designated for parking most provided enough space to allocate an aircraft. An aircraft apron area is related to its size. Large or big aircraft require more apron space than small aircraft. Thus, an airport that has a restricted apron area can allocate larger aircraft at the cost of using more space where small aircraft could park at the same time.

Airport terminals apron gates are classified into four types according with the FAA [1988] and into six types according with the International Civil Aviation Organization (ICAO) [ICAO, 1993]. FAA [1988] does not have a letter for the largest aircraft apron gates (group VI). Apron gates are classified depending on the wing spans and fuselage lengths of the aircraft which they accommodate [FAA, 1988] and wing spans and outer main gear wheel span [ICAO, 1993]. The wings span measures for classifications of airplane design according with the FAA and ICAO are the same but with different letters. The classification measures for large aircraft are exactly the same for both agencies. ICAO F code can be designated for large aircraft such as the A380 (Table 6.6).

Table 6.6 explains that aircraft cannot park at all stands/gates at an airport. An airport has a different number of stand/gates for different aircraft parking per time t (Ng). It is a constraint that airlines must consider when choosing their aircraft fleets. The number of gates for parking an aircraft type x at an airport is variable. At some airports, gates/stands for parking big aircraft are adapted to park two small aircraft. For example, a gate/stand for parking a B777 can be adapted for parking two B737 at the same time. Thus, the total number of gates/stands for parking an aircraft type x is different depending on aircraft type and dimensions of airports gates/stands facilities.

The capacity of an airport apron area and terminal gates/stands per aircraft type (ω_{max}) can be defined as the max number of aircraft that can be accommodated on a given number of parking stands during some period of time [Janic, 2000]. The max capacity of an airport runway (λ_{max}), its number of gates for parking aircraft type x (Ng) and types of aircraft operating at the airport are related. Airports cannot attend or receive flights when all its gates/stands are occupied, even if airports ATC's or runway system capacity movements allow receiving flights. Airports apron/gates capacities are limited for each aircraft type.

Airports cannot serve all type of aircraft. Airports have more gates/stands for parking a certain aircraft type than for other kinds. Thus, airlines $freq_r$ are constrained to the available number of airports gates/stands where their aircraft can park in time t.

Table 6.6 FAA Apron categories and ICAO aerodromes code [FAA, 1988] [ICAO, 1993]

Airplane design group FAA	*Terminal apron gate FAA types*	*Wingspan (m)*	*Fuselage (m)*	*Aerodromes code (ICAO)*	*Wingspan (m)*	*Outer main gear wheel span*
I		< 14.94	-	A	< 15	< 4.5
II		14.94 ≤ 24.08	-	B	15 < 24	4.5 < 6
III	A	24.08 ≤ 35.97	-	C	24 < 36	6 < 9
IV	B	35.97 ≤ 52.12	≤ 49	D	36 < 52	9 < 14
	C		> 49			
V	D	52.12 ≤ 65.23	52 ≤ 213	E	52 < 65	9 < 14
VI		65.23 ≤ 79.86	≤ 80	F	65 ≤ 80	14 < 16

Equation 6.75 determines the maximum capacity of an airport apron area and terminal gates/stands where aircraft type x can park in time t (Ꝏ_{max}). An airport apron area is not exclusive for a certain aircraft type x. All aircraft with equal airplane design code can park at the same apron category code (Table 6.6).

$$\text{Ꝏ}_{max_{x,OD(r),t}} = \text{rounddown}\left[\left(\frac{Ng_{x,OD(r),t}}{\sum_a \sum_x (Tr_{x,OD(r),ta}\, p_{x,OD(r),t,a})}\right) \text{Ѣ}_{OD(r),t}\right] \quad (6.75)$$

Where:

Ꝏ_{max} = capacity of an airport apron area and terminal gates/stands for aircraft type x in time t [mov]
Ng = Number of gates where an aircraft type x can park at an airport in time t [mov]
p_x = proportion of aircraft type x serving an airport in time t [-]

The total number of gates/stands occupied (Pg) at an airport, where an aircraft type x can park in time t, is equal to the total number of aircraft type x landings M_{DES}:

$$Pg_{x,OD(r),t} = \sum_{a=1}^{A} Mov_{DES_{OD(r),t,a}} \quad (6.76)$$

Where:

Pg = number of gates/stands occupied at an airport in time t [mov]

The available number of gates/stands at an airport (G), where aircraft type x can park in time t, is equal to the total number of airport gates/stands (Ꝏ_{max}), where aircraft type x can park in time t, minus Pg (Equation 6.77). This assumes that aircraft are not allowed to embark or disembark pax in other areas different to aircraft stands/gates.

$$G_{x,OD(r),t} = \text{Ꝏ}_{max_{x,OD(r),t}} - Pg_{x,OD(r),t} \quad (6.77)$$

The total number of flights connecting an airport ORI with its airports destination, in an airline route network, must be less or equal to G per airport. This constraints the number of airlines routes links connecting airports between each other. Equations 6.78 constraint the optimum number of airline $freq_r$ connecting an airport with other airports.

$$freq_{x,L(r),t} \leq G_{x,ORI(r),t} \quad (6.78a)$$

Where:

G = Aircraft type x available gates at an airport in time t [mov]

Equation 6.78a refers to those links connecting an airport ORI with all airports DES's. Equation 6.78b refers to all links connecting an airport DES with all airports ORI's. An airline total number of frequencies from an airport ORI to airport DES must be less than the available number of gates where an aircraft type x can park at airport ORI and airport DES in time t.

$$freq_{x,L(r),t} \leq G_{x,DES(r),t} \quad (6.78b)$$

Equation 6.79 is a constraint that forbids an airport to operate more aircraft movements than its maximum apron/gate/stand capacity.

$$\sum_{x=1}^{X} \mathbb{Q}_{max_{x,OD(r),t}} \geq \frac{\lambda_{max_{OD(r),t}}}{2} \geq \lambda_{DES_{OD(r),t}} \quad (6.79)$$

6.2.13 Airport terminal side, land side and characteristics related to pax capacity

On one hand, airside infrastructure dimensions determine airports capacities to serve different aircraft types and a maximum number of aircraft movements in time t. On the other hand, airports pax and handling baggage capacities are determined by airports terminals infrastructure. According with Janic [2000] the capacity of an airport can be measured by the maximum number of aircraft landings and takeoffs, explained in Chapter 6.3.12, maximum number of pax arriving and departing, their number of baggage's, and total cargo tonnes transported in time t.

Airports terminals facilities areas are ticketing/check-in, passenger screening, hold rooms, concessions, baggage claim, circulation, airlines office and operations areas, baggage handling, baggage screening system, international facilities or federal inspection services and support areas [ACRP Report 25, 2010]. Airport terminal facilities areas that are related to pax service are check-in queue area, wait/circulate, hold room, baggage claim and government inspection services. Airports service facilities areas are tickets/check-in counters, security checking desks, gates desks and baggage handling systems.

The most important aspects in an airport terminal side or building infrastructure components are its level of service (LOS), its total pax flow demand and pax flow capacity [ACRP Report 25, 2010]. Airports facilities have limited capacities. Airports capacities are constrained to the level of service (LOS) they want to provide to pax. The LOS concept mainly speaks about the level of pax congestion at each of the airport facilities (Table 6.7). It depends on the capacity of each terminal facility space, and how many pax can stand in this area at the same time. It also speaks about the queue service rates in checking counters, security and government inspection services (GIS), desks, departure gates desks and baggage claim system.

LOS standards only exist for the principal airport terminal facilities. The numbers of square meters per person determine the minimum for each LOS (Table 6.7). An airport facility area with less square meters per pax than LOS E is considered as an unacceptable level of service. It is where system breakdown and unacceptable delays exist [ACRP Report 25, 2010].

An airport terminal facility capacity is a measure of pax throughput. Each facility is determined by its space, where pax and companions wait for being served, and its server's average services times. The LOS allows quantifying waiting times and processing times. The capacity of an airport facility area is calculated as a static capacity (Equation 6.80) whiles the capacity of an airport server is calculated as a dynamic capacity (Equation 6.81) [Janic, 2000].

$$\mathrm{CapS}_{\mathrm{af}_{\mathrm{OD(r),t}}} = \frac{\mathrm{Å}_{\mathrm{af}_{\mathrm{OD(r),t}}}}{\mathrm{Å}_{\mathrm{0af}_{\mathrm{OD(r),t}}}} \quad (6.80)$$

Where:

$CapS_{af}$ = number of pax in airport facility f (static capacity) [pax]

$Å_{af}$ = area of airport facility af [m^2]

$Å_{0af}$ = square meter per pax allowed at each airport facility depending on the LOS it wants to provide to pax using the airport (Table 6.7) [m^2/pax]

af ϵ {check-in, wait/circulate, hold room, baggage claim, GIS} [-]

$$\mathrm{CapD}_{\mathrm{sf}_{\mathrm{OD(r),t}}} = \mathrm{u}_{\mathrm{sf}_{\mathrm{OD(r),t}}} \frac{\mathrm{T_{dhp}}}{\mathrm{st}_{\mathrm{sf}_{\mathrm{OD(r),t}}}} \quad (6.81)$$

Where:

$CapD_{sf}$ = number of pax served (dynamic capacity) [pax]

u = facility f number of servers [-]

T_{dhp} = design hour period, normally 15 minutes [ACRP Report 25, 2010] [hrs]

st_{sf} = average service time per pax [hrs/pax]

sf ϵ {checking counters, security and GIS, desks, departure gates desks, baggage claim system} [-]

Table 6.7 IATA LOS standards [ACRP Report 25, 2010]

Airport facility level of Service (LOS)							
Terminal facility		*Checking-in Queue area*	*Wait /Circulate*	*Hold Room*	*Baggage Claim*	*GIS*	*Definition*
		(m^2/pax)					
A	Excellent	1.8	1.6	1.4	1.2	1.0	Conditions of free flow; no delays; excellent level of comfort
B	High	2.7	2.3	1.9	1.5	1.0	Conditions of stable flow; very few delays; high level of comfort
C	Good	1.4	1.2	1.0	0.8	0.6	Conditions of stable flow; acceptable brief delays; good level of comfort
D	Adequate	2.0	1.8	1.6	1.4	1.2	Condition of unstable flow; acceptable delays for short periods of time; adequate level of comfort
E	Un-acceptable	1.4	1.2	1.0	0.8	0.6	Condition of unstable flow; unacceptable delays; inadequate level of comfort

Capacity must be always related to the LOS an airport wants to provide to pax. Normally, airport terminal LOS "C" is considered as a design objective because it represents a good service level at a reasonable infrastructure cost [ACRP Report 25, 2010]. The delays and level of comfort are reasonable and acceptable at this level of service (Table 6.7).

The design hour period (T_{dhp}) is known as the 15 minutes rule. This rule explains that if an airport facility designed to operate at a certain LOS value exceeds its pax capacity for longer than 15 minutes, this facility most be considered as the next lower LOS value. For example, an airport terminal facility was designed to be a LOS "C" facility, but it operates at LOS "D" during more than 15 minutes, this facility is considered as a LOS "D" rather than "C".

Equation 6.82 determines the maximum number of pax that an airport can serve depending on the LOS it wants to provide to pax during a T_{dhp}, 15 minutes.

$$\mathrm{AC}_{\mathrm{OD(r),t}} = \begin{cases} \min\left[\mathrm{CapS}_{\mathrm{af}_{\mathrm{OD(r),t}}}\right] & \text{for } \mathrm{CapS}_{\mathrm{af}_{\mathrm{OD(r),t}}} \leq \mathrm{CapD}_{\mathrm{sf}_{\mathrm{OD(r),t}}} \\ \min\left[\mathrm{CapD}_{\mathrm{af}_{\mathrm{OD(r),t}}}\right] & \text{for } \mathrm{CapS}_{\mathrm{af}_{\mathrm{OD(r),t}}} > \mathrm{CapD}_{\mathrm{sf}_{\mathrm{OD(r),t}}} \end{cases} \quad (6.82)$$

Where:
AC = Airport max number of pax during a T_{dhp} depending on its LOS [pax]

An airport level of service depends on its airport terminal facility with the minimum number of pax flow capacity during a T_{dhp}.

Airports passenger's capacities are constrained to a maximum number of passengers and a maximum numbers of bags that can be handle by their facility with the minimum space or by their terminal service with the highest pax processing time. Equation 6.83 calculates the total number of pax transported in an airport in time t.

$$PAX_{OD(r),t} = \sum_{a=1}^{A} \sum_{x=1}^{X} \left(\mathrm{Ѡ}_{max\,x,OD(r),t}\, S_{x,a}\, p_{x,OD(r),t,a} \right) = \sum_{a=1}^{A} \sum_{x=1}^{X} \left(Pg_{x,OD(r),t}\, S_{x,t,a1}\, p_{x,OD(r),t,a} \right) + S_{x,t}\, freq_{x,L(r),t} \tag{6.83}$$

Where:
PAX = airport total number of pax in time t [pax]
p_x = proportion of aircraft type x serving an airport in time t [-]
A = total number of airlines serving an airport [-]

The total number of pax that can be transported per route link is constrained to be less or equal than both airports maximum number of pax flow determined by their service facilities and space facilities LOS (Equation 6.84) during time t.

$$\left(S_x\, freq_{x,L(r),t} \right) \leq AC_{ORI(r),t} \left(\frac{\mathrm{Ђ}_{ORI(r),t}}{T_{dhp}} \right) - \sum_{a=1}^{A} \sum_{x=1}^{X} \left(Pg_{x,ORI(r),t}\, S_{x,t,a}\, p_{x,ORI(r),t,a} \right) \tag{6.84a}$$

$$\left(S_x\, freq_{x,L(r),t} \right) \leq AC_{DES(r),t} \left(\frac{\mathrm{Ђ}_{DES(r),t}}{T_{dhp}} \right) - \sum_{a=1}^{A} \sum_{x=1}^{X} \left(Pg_{x,DES(r),t}\, S_{x,t,a}\, p_{x,DES(r),t,a} \right) \tag{6.84b}$$

The optimum number of frequencies that maximize the net present value of an airline network must be always positive:

$$freq_{x,L(r),t} \geq 0 \quad \epsilon\ \text{int} \tag{6.85}$$

Airport landside

Airport landside determines and represents the accessibility from a region to an airport. Passengers access airports by using different modes of transportation systems such as road and rail. In particular, pedestrian and automobile movements can be affected by congestion at peaks of demand times. Pax can access in an airport terminal by using different transport modes such as pedestrian facilities, vehicles lanes, parking, entry/exit roadways, private vehicles, transit staging areas, and rail transit facilities [ACRP Report 25, 2010]. In this thesis, the airport landside accessibility is not considered in the optimization model.

6.2.14 The optimum number of aircraft to invest

Equation 6.86 calculates the time that an aircraft type x needs to fly a link both ways. It assures that the same number of frequencies connecting airport ORI with airport DES is connecting airport DES with airport ORI.

$$Time_{x,L(r),t} = 2LTime_{x,L(r),t} \tag{6.86}$$

An aircraft cannot fly longer time than its block or maximum utilization time per week. Equation 6.87 constraints the optimization model to estimate the optimum number of aircraft's based on the optimum number of frequencies that minimize operation cost and maximize the net present value of each route. It allows the NAIR variable to be dependent on the frequency variable.

$$\left(\mathrm{U}_{x,t,j} - \mathrm{maintenance}_{x,t,j}\right) \geq \sum_{r=1}^{R}\left(\mathrm{Time}_{x,L(r),t}\; y_{x,L(r),t}\right) \quad (6.87)$$

Where:

U = Aircraft maximum utilization time equal to 24*7=156 hrs [hrs/week]

maintenance = aircraft maintenance time per week [hrs/week]

Equation 6.88 calculates the number of aircraft's needed to operate a route in the network.

$$\mathrm{NAIR}_{x,t,j} = \mathrm{roundup}\left[\frac{\sum_{r=1}^{R}\left(\mathrm{Time}_{x,L(r)}\; \mathrm{freq}_{x,L(r),t}\; y_{x,L(r),t}\right)}{\left(\mathrm{U}_{x,t,j} - \mathrm{maintenance}_{x,t,j}\right)}\right] \quad (6.88)$$

The total route time must be shorter than the total route fleet utilization time:

$$\sum_{t=1}^{T}\left[\mathrm{NAIR}_{x,t,j}\left(\mathrm{U}_{x,t,j} - \mathrm{maintenance}_{x,t,j}\right)\right] \geq \sum_{t=1}^{T}\left[\sum_{r=1}^{R}\left(\mathrm{Time}_{x,L(r),t}\; \mathrm{freq}_{x,L(r),t}\; y_{x,L(r),t}\right)\right] \quad (6.89)$$

Equation 6.90 calculates the total number of aircraft's in the airline fleet.

$$\mathrm{NAIR}_{x,NTW} = \sum_{j=1}^{J}\sum_{t=1}^{T}\mathrm{NAIR}_{x,t,j} \quad (6.90)$$

The total number of aircraft to invest per year must be higher than the actual number of aircraft in fleet (Equation 6.79). The airline does not need to buy aircraft's if it is equal.

$$\mathrm{NAIR}_{x,t,j} \geq \mathrm{ENAIR}_{x,t,j}\; y_{10_{x,t,j}} \quad (6.91)$$

Where:

y_{10} = decision variable {0, 1} [-]

The total number of aircraft operating an airline network must be always positive:

$$\mathrm{NAIR}_{x,t,j} > 0 \;\; \epsilon\; int \quad (6.92)$$

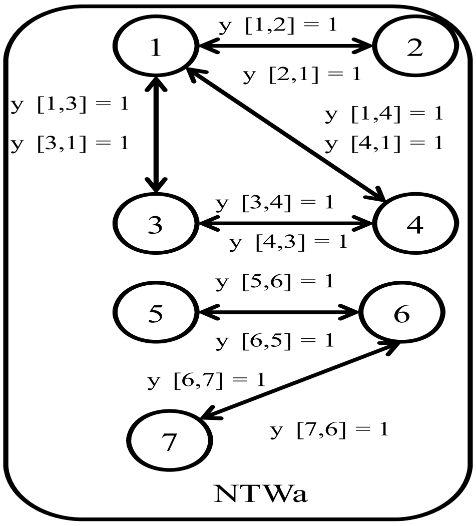
6.3 Route Generation Algorithm

Since this research project focuses on the optimization of a new airline network, it is necessary to incorporate a route generator algorithm. The model has been extended with a route generation program enabling the program to find an optimal rotation planning as well as an optimal optimized fleet assignment strategy.

A matrix of route links ($MAT_{x,t,0}$) is generated after the CFEM and PEM models have selected the links that may represent an opportunity to open services. $MAT_{x,t,0}$ is a symmetric matrix with values zero for links that were not selected by the CFEM and PEM models, and value one for the links selected by both models. Figure 6.9 shows an example of an airline network. The $MAT_{x,t,0}$ has two routes in this example. The first route connects 8 links and the second route connects 4 links.

The optimization model has to know the number of routes to which each link belongs and the number of link. This is necessary because the model needs to recognize aircraft path flows.

For example, the network in Figure 6.9 does not allow aircraft flying from airport 2 to airport 3, 4, 5, 6, and 7. It means that aircraft need to fly from airport 2 to airport 1 after flying from airport 1 to airport 2. The algorithm has to identify the links that are interconnected. The optimization model needs to know the route number ($j \in J$) and routes links numbers in a consecutive order to optimize the network.



MAT x,t,0		Airports Destination						
		1	2	3	4	5	6	7
Airports Origin	1	0	1	1	1	0	0	0
	2	1	0	0	0	0	0	0
	3	1	0	0	1	0	0	0
	4	1	0	1	0	0	0	0
	5	0	0	0	0	0	1	0
	6	0	0	0	0	1	0	1
	7	0	0	0	0	0	1	0

Figure 6.9 Route Generation Algorithm, matrix $MAT_{x,t,0}$

The algorithm identifies the number of routes in a network. It also assigns a number to each link in each route determining aircraft path flow. It ends the iteration process when the number of routes and links do not change before and after optimization. Then, the algorithm and the optimization model select the optimum routes, links and aircraft flying path. The algorithm is explained by steps 1 to 10.

STEP 1: The $MAT_{x,t,0}$ matrix is formed by those links previously selected by the CFEM and PEM models. The decision variable $y_{x,i,k,t,0}$ indicates what airports in the origin links were chosen by both models. The routes that were not selected have a $y_{x,i,k,t,0}$ equal zero. The routes that were selected have $y_{x,i,k,t,0}$ value equal one (Figure 6.9).

STEP 2: Equation 6.93a counts the number of links that are operated before optimization (SumB). Equation 6.93b assigns the number of airport origin to each link in the network matrix, $MAT_{x,t,0}$.

SumB = 0
For i = 1, …, N_{ORI} do
For k = 1, …, N_{DES} do

$$\text{SumB} = \text{SumB} + y_{x,i,k,,t,0} \quad (6.93a)$$

$$MAT_{x,i,k\,t,0} = y_{x,i,k,,t,0} \times i \quad (6.93b)$$

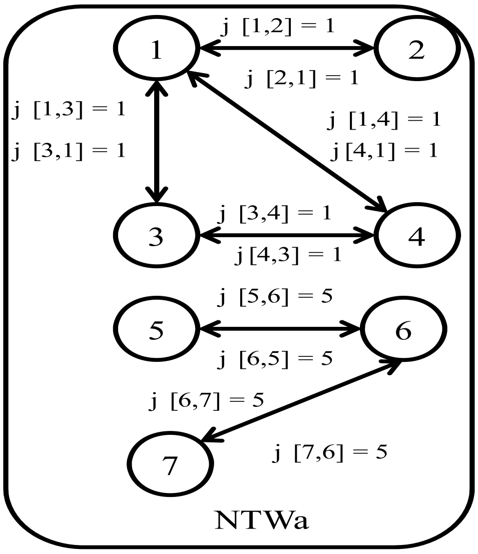
Where:

$y_{x,i,k,t,0}$	= Decision variable {1, 0}	[-]
N_{ORI}	= number of airports origin	[-]
N_{DES}	= number of airports destination	[-]
i, k	= integer counters	[-]

STEP 3: Each link has to be associated to an aircraft route. This association is made by assigning the number of the route to each of their links. For example, the link from airport 1 to 2 is identified by the same number as links 1 to 3 or 1 to 4 but not 5 to 6 or 6 to 7 (Figure

6.9). This step assigns the number of route origin airport/city to each link per route (Figure 6.10). Equation 6.93c transform the matrix $MAT_{x,t,0}$ into a symmetric matrix.

For i = 1, …, N_{ORI} – 1 do
  For k = i + 1, …, N_{DES} do
    $MAT_{x,k,i,t,0} = MAT_{x,i,k,t,0}$ (6.93c)
For i = 1, …, N_{ORI} do
  w = 100,000,000 ("Maximum integer possible number")
  For k = 1, …, N_{DES} do
    If $(MAT_{x,k,i,t,0} > 0 \; and \; MAT_{x,i,k,t,0} < w)$
      $w = MAT_{x,k,i,t,0}$
  For k = 1, …, N_{DES} do
    If $(MAT_{x,k,i,t,0} > 0)$
      $MAT_{x,k,i,t,0} = w$



MAT x,t,0	Airports Destination						
	1	2	3	4	5	6	7
Airports Origin 1	0	1	1	1	0	0	0
2	1	0	0	0	0	0	0
3	1	0	0	1	0	0	0
4	1	0	1	0	0	0	0
5	0	0	0	0	0	5	0
6	0	0	0	0	5	0	5
7	0	0	0	0	0	5	0

Figure 6.10 Route Generation Algorithm by route airport origin number $MAT_{x,t,0}$

STEP 4: In the optimization, each link has to be part of one route in the network. This number is j ϵ J. The algorithm identifies routes following $MAT_{x,t,0}$ values after step 3. In step 4, each $MAT_{x,i,k,t,0}$ value will be equal to the number of the network they belong in a consecutive order (Figure 6.11). This number is not related to the airport where an aircraft starts its journey. It is the j value assigned to each route link.

An identical matrix to $MAT_{x,t,0}$ is generated and named $MAT2_{x,t,0}$ (Equation 6.93d). The reason is that $MAT2_{x,t,0}$ has to be modified during the process. It will indicate when to stop the iteration process. It will stop until $MAT2_{x,t,0}$ becomes a null matrix. In this process each route matrix ($MAT_{x,t,j}$) will be generated. The original matrix $MAT_{x,t,0}$ contains the number of route associated to each link. The matrix of each route will contain a letter A to indicate what links form each route j (Figure 6.11).

For i = 1, …, N_{ORI} do
  For k = 1, …, N_{DES} do
    $MAT2_{x,i,k,t,0} = MAT_{x,i,k,t,0}$ (6.93d)
w = 1
Do
  For i = 1, …, N_{ORI} do
    For k = 1, …, N_{DES} do

If $(MAT_{x,i,k,t,0} = 1 \text{ do})$
$MAT_{x,i,k,t,w} = \text{"A"}$
$MAT_{x,i,k,t,w} = w$
$MAT2_{x,i,k,t,0} = MAT2_{x,i,k,t,0} - 1$
Num1 = 0 (Integer counter)
Num2 = 0 (Integer counter)
For i = 1, …, N_{ORI} do
For k = 1, …, N_{DES} do
$Num1 = Num1 + MAT2_{x,i,k,t,0}$
If $(MAT_{x,i,k,t,w} = \text{"A"})$
$Num2 = Num2 + 1$
If $(Num2 > 0)$
w = w + 1
While (Num1 > 0)

STEP 5: The number of routes in the model (J) is equal to w-1.
J = w – 1

MAT x,t,0	Airports Destination 1	2	3	4	5	6	7
Airports Origin 1	0	1	1	1	0	0	0
2	1	0	0	0	0	0	0
3	1	0	0	1	0	0	0
4	1	0	1	0	0	0	0
5	0	0	0	0	0	2	0
6	0	0	0	0	2	0	2
7	0	0	0	0	0	2	0

MAT2 x,t,0	Airports Destination 1	2	3	4	5	6	7
Airports Origin 1	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0
7	0	0	0	0	0	0	0

MAT x,t,1	Airports Destination 1	2	3	4	5	6	7
Airports Origin 1	0	A	A	A	0	0	0
2	A	0	0	0	0	0	0
3	A	0	0	A	0	0	0
4	A	0	A	0	0	0	0
5	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0
7	0	0	0	0	0	0	0

MAT x,t,2	Airports Destination 1	2	3	4	5	6	7
Airports Origin 1	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0
5	0	0	0	0	0	A	0
6	0	0	0	0	A	0	A
7	0	0	0	0	0	A	0

Figure 6.11 Route Generation Algorithm, matrix MAT, matrix MAT2 and routes matrix

STEP 6: Now that each route matrix has been generated, the routes links have to have a unique number (r). In step 6, the algorithm assigns a consecutive number to each route link. This is an important step because the model needs to mark each route link with the correct number in such a way that an aircraft can travel on the route without being stop or blocked. It has to have the sequence that allows aircraft to come back when they cannot fly further, and the only option is going back to the airport origin in r-1 (Figure 6.12).

In this step, all vectors L(r) = [ORI(r), DES(r)] are formed after giving a number r to each link in each route matrix.

```
For j = 1, …, J
 w = 0
 For k = 1, …, N_ORI do
  If MAT_x,i,k,t,j = "A" do
   w = w + 1
   ORI(w) = i
   DES(w) = k
   MAT_x,i,k,t,j = w
   ki = k
   ik = i
   Do
    p = 0
    ik = ik + 1
    If MAT_x,ki,ik,t,j = "A" do
     w = w + 1
     ORI(w) = ki
     DES(w) = ik
     MAT_x,ki,ik,t,j = w
     p = ki
     ki = ik
     ik = p
   Until (ik ≥ N_DES)
  p = w
  Do
   If p > 0 do
    w = w + 1
    ORI(w) = DES(p)
    DES(w) = ORI(p)
    MAT_x,ORI(w),DES(w),t,j = w
    p = p – 1
  Until (DES(w) = i)
 R_j = w ("The number of links (R) per route J")
```

STEP 7: Optimization of the airline network routes matrix's $MAT_{x,t,j}$ (Figure 6.12) using the mathematical model (Section 6.4).

MAT x,t,1	Airports Destination							MAT x,t,2	Airports Destination						
	1	2	3	4	5	6	7		1	2	3	4	5	6	7
Airports Origin 1	0	1	3	7	0	0	0	Airports Origin 1	0	0	0	0	0	0	0
2	2	0	0	0	0	0	0	2	0	0	0	0	0	0	0
3	6	0	0	4	0	0	0	3	0	0	0	0	0	0	0
4	8	0	5	0	0	0	0	4	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	5	0	0	0	0	0	1	0
6	0	0	0	0	0	0	0	6	0	0	0	0	4	0	2
7	0	0	0	0	0	0	0	7	0	0	0	0	0	3	0

Figure 6.12 Route Generation Algorithm, routes matrix $MAT_{x,t,j}$

STEP 8: The main objective is selecting routes that represent a possibility to open services. It means the model must find all the routes that can be operated, and from those routes find the maximum NPV. In order to grow, airlines need to operate as much links as they can because they will get stronger as they increase pax transported during time t. Then, the first link (r = 1) and all links (r) where the aircraft flying path indicates that the airport ORI in r is the same as the airport DES in r + 1 must be eliminated only if the NPV of a route j is negative. In these cases, Equation 6.8 could be applicable because these links do not break routes flying paths.

```
For j = 1, …, J do
 If (NPV_{x,t,j} < 0) do
  For i = 1, …, N_ORI do
   w = 0
   For k = 1, …, N_DES do
    If MAT_{x,i,k,t,k} > 0 do
    w = w + 1
   For k = 1, …, N_DES do
    If Profit_{x,i,k,t,0} < 0 do
     y_{x,i,k,t,0} = 0
     y_{x,k,i,t,0} = 0
```

STEP 9: The network matrix $MAT_{x,t,0}$ has to be generated always after each optimization. It is formed by the routes links variable $y_{x,L(r),t,j}$ values because this decision variable indicates what links are operated.

```
SumA = 0
For i = 1, …, N_ORI do
 For k = 1, …, N_DES do
      SumA = SumA + y_{x,i,k,,t,0}
      MAT_{x,i,k t,0} = y_{x,i,k,,t,0} × i
```

STEP 10: The algorithm that generates the network routes and their links must be computed as an iterative process. It has to be run at least once. Step 10 decides when the algorithm stops. It depends on the sum (SumA) of the links decision variables $y_{x,L(r),t}$ values. The algorithm will stop when the values of the sum of each route links decision variables $y_{x,L(r),t}$ is equal before and after the optimization. This happens when no link has been cancelled, and no route has been broken in the network.

```
If SumA < SumB
      Go to Step 2 “Route generator and optimization"
```

6.4 Model that maximize the net present value of an airline network by assigning the optimum aircraft type under competition

The optimization model includes just one objective function, which is defined with based on multiple variables relations. The optimization model determines what routes to flight, what aircraft type and how many of them to buy, number of frequencies per route and number of passengers to attend when there are other airlines supplying service. This model aims to maximize the net present value and the network number of passenger, as a tool to design airlines networks. In this section, the summary of the optimization model is given taking into account the competition between airlines operating same links.

In order to consider the competition between airlines the relationship between market share and capacity share needs to be added to the optimization model. The relationship between market share and capacity share may explain the reaction of passengers when an airline enters or increase the number of flights in a route link. Teodorovi and Krcmar-nozic [1989] use the relation between market share and frequency share on competitive routes. This is the proportion between the number of frequencies operated by an airline and the total number of frequencies operated by all airlines. Janic [2000] used that relationship between market share and capacity share. He defined it as the proportion between the total number of seats supply by an airline and the total number of seats supply by all airlines operating the route link.

Contrary to Teodorovi and Krcmar-Nozic [1989] and Janic [2000] the market share (MS) of an airline is determined as the ratio between the number of pax transported by the airline and the total number of pax transported on the link. In this thesis, the market share of an airline is calculated using Equation 6.6. This equation considers that each airline operating a link provides services to its optimum number of pax flow depending on their aircraft flight cost (AOC), airline optimum number of frequencies (freq) and the empirical constant value (§). The empirical constant value (§) explains the degree to which pax react to a change in the number of flights supply by an airline on a link. In Teodorovi and Krcmar-Nozic [1989] and Janic [2000], this value is in the range 1 < § < 2. The optimum market share can be calculated as follows:

$$MS_{L(r),t,a1}{}^{*} = \left(\frac{Q_{L(r),t,a1}{}^{*}}{TQ_{L(r),t}}\right)^{\S} = \left[\frac{\left[\sum_{x=1}^{X}\left(\left(freq_{x,L(r),t,a1}\right)^{2} AOC_{x,L(r),t,a1}\right)\right]}{\left[\sum_{a=1}^{A}\sum_{x=1}^{X}\left(\left(freq_{x,L(r),t,a}\right)^{2} AOC_{x,L(r),t,a}\right)\right]}\right]^{\S} \qquad (6.94a)$$

Where:

MS = airline a1 market share [-]

§ = is an empirical constant (1 < § < 2) [-]

$$TQ_{L(r),t} = \sum_{a=1}^{A} Q_{L(r),t,a}{}^{*} \qquad (6.94b)$$

Where:

TQ = airlines total route pax flow [-]

Equation 6.94a assumes that all airlines operating the link transport their optimum number of passengers which is determined by Equation 6.6. In this section, the numbers of the equations are the same as in Chapter 6.2 because each equation determines the same, but this time considering the effects of the competition between airlines.

$$NPV_{NTW\,x} = \sum_{j=1}^{J}\sum_{t=0}^{T}\left(\frac{\left[\sum_{r=1}^{R}\left(F_{L(r),t,j,a1} TQ_{L(r),t}\left(\frac{Q_{L(r),t,a1}{}^{*}}{TQ_{L(r),t}}\right)^{\S} - AOC_{x,L(r),t,j,a1} freq_{x,L(r),t,a1}\right)\right] - \left(Price_{x,t,a1}\left(NAIR_{x,t,j,a1} - ENAIR_{x,t,j,a1}\right)\right)}{\left(1+WACC_{t,a1}\right)^{t}}\right) \qquad (6.12a)$$

Equation 6.95 is the objective function that maximizes the number of passengers to serve on an airline network [Teodorovi and Krcmar-nozic, 1989].

$$MAX\ Q_{x,NTW,a} = \sum_{j=1}^{J}\sum_{t=0}^{T}\left[\sum_{r=1}^{R}\left(TQ_{L(r),t}\left(\frac{Q_{L(r),t,a1}{}^{*}}{TQ_{L(r),t}}\right)^{\S}\right)\right] \qquad (6.95)$$

Subject to:

$$REV_{x,t,j,a1} = \sum_{r=1}^{R}\left[\left(F_{L(r),t,a1} TQ_{L(r),t}\left(\frac{Q_{L(r),t,a1}{}^{*}}{TQ_{L(r),t}}\right)^{\S}\right) y_{x,L(r),t,a1}\right] \qquad (6.15)$$

$$CT_{x,t,j,a1} = \sum_{r=1}^{R}\left[\left(AOC_{x,L(r),t,a1}\ freq_{x,L(r),t,a1}\right) y_{x,L(r),t,a1}\right] \qquad (6.16)$$

$$\sum_{r=1}^{R}\left(F_{L(r),t,a1} TQ_{L(r),t}\left(\frac{Q_{L(r),t,a1}{}^{*}}{TQ_{L(r),t}}\right)^{\S}\right) \geq \left[\sum_{r=1}^{R}\left(AOC_{x,L(r),t,a1} freq_{x,L(r),t,a1}\right)\right] y1_{x,t,j,a1} \qquad (6.17)$$

$$S_{x,a1} \sum_{r=1}^{R} \left(freq_{x,L(r),t,a1}\, y_{x,L(r),t,a1} \right) \geq \sum_{r=1}^{R} \left(\frac{\left(freq_{x,L(r),t,a1} \right)^2 \xi_{L(r),t}\ AOC_{x,L(r),t,a1}}{Tp_{L(r),t}\, \Gamma_{L(r),t}} \right) \quad (6.18)$$

$$FREQ_{x,t,j,a1} = \sum_{r=1}^{R} \left(freq_{x,L(r),t,a1}\, y_{x,L(r),t,a1} \right) \quad (6.19)$$

$$\frac{\left(freq_{x,L(r),t,a1} \right)^2 \xi_{L(r),t,a1}\ AOC_{x,L(r),t,a1}}{Tp_{L(r),t}\, \Gamma_{L(r),t}} \leq TQ_{L(r),t} \left(\frac{Q_{L(r),t,a1}{}^{*}}{TQ_{L(r),t}} \right)^{\S} \quad (6.20)$$

$$\sum_{r=1}^{R} \left(\frac{\left(freq_{x,L(r),t,a1} \right)^2 \xi_{L(r),t,a1}\ AOC_{x,L(r),t,a1}}{Tp_{L(r),t}\, \Gamma_{L(r),t}} \right) \leq \sum_{r=1}^{R} \left(TQ_{L(r),t} \left(\frac{Q_{L(r),t,a1}{}^{*}}{TQ_{L(r),t}} \right)^{\S} \right) \quad (6.21)$$

$$\sum_{t=1}^{T} \left[\sum_{r=1}^{R} \left(\frac{\left(freq_{x,L(r),t} \right)^2 \xi_{L(r),t,a1}\ AOC_{x,L(r),t}}{Tp_{L(r),t}\, \Gamma_{L(r),t}} \right) \right] \leq \sum_{t=1}^{T} \left[\sum_{r=1}^{R} TQ_{L(r),t} \left(\frac{Q_{L(r),t,a1}{}^{*}}{TQ_{L(r),t}} \right)^{\S} \right] \quad (6.22)$$

$$\sum_{j=1}^{J} \sum_{t=1}^{T} \left[\sum_{r=1}^{R} \left(\frac{\left(freq_{x,L(r),t,j} \right)^2 \xi_{L(r),t,a1,j}\ AOC_{x,L(r),t,j}}{Tp_{L(r),t,j}\, \Gamma_{L(r),t,j}} \right) \right] \leq \sum_{j=1}^{J} \sum_{t=1}^{T} \left[\sum_{r=1}^{R} TQ_{L(r),t} \left(\frac{Q_{L(r),t,j,a1}{}^{*}}{TQ_{L(r),t,j}} \right)^{\S} \right] \quad (6.23)$$

$$\sum_{j=1}^{J} \sum_{t=1}^{T} \left[\sum_{r=1}^{R} \left(\frac{\left(freq_{x,L(r),t} \right)^2 \xi_{L(r),t,a1}\ AOC_{x,L(r),t}}{Tp_{L(r),t}\, \Gamma_{L(r),t}} \right) \right] \leq \sum_{j=1}^{J} \sum_{t=1}^{T} \left[\sum_{r=1}^{R} TQ_{L(r),t} \left(\frac{Q_{L(r),t,a1}{}^{*}}{TQ_{L(r),t}} \right)^{\S} \right] \quad (6.23)$$

$$freq_{x,L(r),t,a1} \leq freq_{max\quad L(r),t,a1} \quad (6.24)$$

Financial constraints

$$\sum_{t=1}^{T} \left(\frac{\sum_{r=1}^{R} \left(F_{L(r),t,a1} TQ_{L(r),t,a1} \left(\frac{Q_{L(r),t,a1}{}^{*}}{TQ_{L(r),t}} \right)^{\S} - AOC_{x,L(r),t,a1}\, freq_{x,L(r),t,a1} \right) - \left(Price_{x,t,a1} \left(NAIR_{x,t,j,a1} - ENAIR_{x,t,j,a1} \right) \right)}{\left(1 + IRR_{t,j,a1} \right)^{t}} \right) = 0 \quad (6.13)$$

$$\sum_{t=1}^{T} \left(\frac{\sum_{r=1}^{R} \left(F_{L(r),t,a1} TQ_{L(r),t,a1} \left(\frac{Q_{L(r),t,a1}{}^{*}}{TQ_{L(r),t}} \right)^{\S} - AOC_{x,L(r),t,a1}\, freq_{x,L(r),t,a1} \right) - \left(Price_{x,t,a1} \left(NAIR_{x,t,j,a1} - ENAIR_{x,t,j,a1} \right) \right)}{\left(1 + IRR_{t,a1} \right)^{t}} \right) y_{1\, x,t,j,a1} \leq$$

$$\sum_{t=1}^{T} \left(\frac{\sum_{r=1}^{R} \left(F_{L(r),t,a1} TQ_{L(r),t,a1} \left(\frac{Q_{L(r),t,a1}{}^{*}}{TQ_{L(r),t}} \right)^{\S} - AOC_{x,L(r),t,a1}\, freq_{x,L(r),t,a1} \right) - \left(Price_{x,t,a1} \left(NAIR_{x,t,j,a1} - ENAIR_{x,t,j,a1} \right) \right)}{\left(1 + WACC_{t,a1} \right)^{t}} \right) \quad (6.25)$$

Airport average waiting times

$$y_{2_{L(r),t}} = \begin{cases} 0 & \text{if } t_1 - t_0 < 0 \\ 1 & \text{if } t_1 - t_0 \geq 0 \end{cases} \quad (6.26b)$$

$$f(t_1) =$$
$$C_{3_{DES(r),t}} \exp^{-\lambda_{1_{DES(r),t}} \left| t_1 - t_{0_{DES(r)}} \right|^{\alpha_{1_{DES(r),t}}}} \left(1 - y_{2_{L(r),t}} \right) + C_{3_{DES(r),t}} \exp^{-\lambda_{1_{DES(r),t}} \left| t_1 - t_{0_{DES(r)}} \right|^{\beta_{1_{DES(r),t}}}} \left(y_{2_{L(r),t}} \right) \quad (6.26a)$$

$$F(t_1) = \int_{-\infty}^{t_1} f(t_1)\, dt \quad (6.27)$$

$$F(t_1) = \int_{-\infty}^{\infty} f(t_1)\, dt = 1 \quad (6.28)$$

$$C_3 \left\{ \int_{-\infty}^{\infty} e^{-\lambda_{1_{DES(r),t}} \left| t_1 - t_{0_{DES(r)}} \right|^{\alpha_{1_{DES(r),t}}}} dt + \int_{-\infty}^{\infty} e^{-\lambda_{1_{DES(r),t}} \left| t_1 - t_{0_{DES(r)}} \right|^{\beta_{1_{DES(r),t}}}} dt \right\} = 1 \quad (6.29a)$$

$$C_3 = \frac{1}{\left\{ \int_{-\infty}^{\infty} e^{-\lambda_{1_{DES(r),t}} \left| t_1 - t_{0_{DES(r)}} \right|^{\alpha_{1_{DES(r),t}}}} dt + \int_{-\infty}^{\infty} e^{-\lambda_{1_{DES(r),t}} \left| t_1 - t_{0_{DES(r)}} \right|^{\beta_{1_{DES(r),t}}}} dt \right\}} \quad (6.29b)$$

$$WTD_{DES(r),t} = t_1 \text{ if } F(t_1) = 0.5 \quad (6.30a)$$

$$y_{2_{L(r),t}} = \begin{cases} 0 & \text{if } t_1 - t_{0_{DES(r)}} < 0 \\ 1 & \text{if } t_1 - t_{0_{DES(r)}} \geq 0 \end{cases} \quad (6.26b)$$

$$f(t_1) = C_{3_{ORI(r),t}} \exp^{-\lambda_{1_{ORI(r),t}} \left|t_1 - t_{0_{ORI(r)}}\right|^{\alpha_{1_{ORI(r),t}}}} \left(1 - y_{2_{L(r),t}}\right) + C_{3_{ORI(r),t}} \exp^{-\lambda_{1_{ORI(r),t}} \left|t_1 - t_{0_{ORI(r)}}\right|^{\beta_{1_{ORI(r),t}}}} \left(y_{2_{L(r),t}}\right) \quad (6.26a)$$

$$F(t_1) = \int_{-\infty}^{t_1} f(t_1)\, dt \quad (6.27)$$

$$F(t_1) = \int_{-\infty}^{\infty} f(t_1)\, dt = 1 \quad (6.28)$$

$$C_3 \left\{ \int_{-\infty}^{\infty} e^{-\lambda_{1_{ORI(r),t}} \left|t_1 - t_{0_{ORI(r)}}\right|^{\alpha_{1_{ORI(r),t}}}} dt + \int_{-\infty}^{\infty} e^{-\lambda_{1_{ORI(r),t}} \left|t_1 - t_{0_{ORI(r)}}\right|^{\beta_{1_{ORI(r),t}}}} dt \right\} = 1 \quad (6.29a)$$

$$C_3 = \frac{1}{\left\{ \int_{-\infty}^{\infty} e^{-\lambda_{1_{ORI(r),t}} \left|t_1 - t_{0_{ORI(r)}}\right|^{\alpha_{1_{ORI(r),t}}}} dt + \int_{-\infty}^{\infty} e^{-\lambda_{1_{ORI(r),t}} \left|t_1 - t_{0_{ORI(r)}}\right|^{\beta_{1_{ORI(r),t}}}} dt \right\}} \quad (6.29b)$$

$$WTD_{ORI(r),t} = t_1 \text{ if } F(t_1) = 0.5 \quad (6.30a)$$

$$y_{3\,L(r),t} = \begin{cases} 0 & \text{if } WTD_{DES(r),t} \leq 0 \\ 1 & \text{if } WTD_{DES(r),t} > 0 \end{cases} \quad (6.31b)$$

$$D_{WTD_{x,DES(r),t}} = \left(V_{WTD_{x,DES(r),t}}\, WTD_{DES(r),t}\right) y_{3\,L(r),t} \quad (6.31a)$$

$$D_{UF\,x,L(r),t} = D_r + \left(D_{WTD_{x,DES(r),t}}\right) \quad (6.32)$$

$$D_{UFe\,x,L(r)} = D_r + V_{C\,x}\, WTDmax_{DES(r)} + D_{SA} \quad (6.33)$$

Aircraft payload, load and cargo capacities

$$Payload_{x,L(r),t,a1} = S_{x,a1} \left(\frac{WPax_{a1} + NBags_{a1}\, WBags_{a1}}{1000}\right) LF_{x,L(r),t,a1} + Cargo_{x,L(r),t,a1} \quad (6.34)$$

$$Load_{x,L(r),t,a1} = OEW_x + Payload_{x,L(r),t,a1} \quad (6.35)$$

$$y_{4\,x,L(r),t,a1} = \begin{cases} 0 \text{ if } D_r \leq D^* & \text{"Short - haul"} \\ 1 \text{ if } D_r > D^* & \text{"Long - haul"} \end{cases} \quad (6.36b)$$

$$Cargo_{x,L(r),t,a1} = \left\{y_{4\,x,L(r),t,a1} \left[Cargo_{max\ x,L(r),t,a1}\right]\right\} \quad (6.36a)$$

$$Cargo_{max\,x,L(r),t,a1} = \frac{MTOW_x - \left[C_0 + C_1\left(D_{UFe\,x,L(r)}\right) + C_2\left(D_{UFe\,x,L(r)}\right)^2\right]}{B_0 + B_1\left(D_{UFe\,x,L(r)}\right) + 1} - \left[OEW_x + S_{x,a1}\left(\frac{WPax_{a1} + NBags_{a1} WBags_{a1}}{1000}\right) LF_{x,L(r),t,a1}\right] \quad (6.37)$$

$$Cargo_{x,L(r),t,a1}\ y_{x,L(r),t,a1} \leq CargoVol_{x,a1} \quad (6.38)$$

Jet fuel volume that max aircraft utilization time and profits

$$UF_{x,L(r),t,a1} = \left(B_0 + B_1\left(D_{UFx,L(r),t}\right)\right) Load_{x,L(r),t,a1} + \left(C_0 + C_1\left(D_{UFx,L(r),t}\right) + C_2\left(D_{UFx,L(r),t}\right)^2\right) \quad (6.39)$$

$$UFe_{x,L(r),t,a1} = \left(B_0 + B_1\left(D_{UFe\,x,L(r)}\right)\right) Load_{x,L(r),t,a1} + \left(C_0 + C_1\left(D_{UFe\,x,L(r)}\right) + C_2\left(D_{UFe\,x,L(r)}\right)^2\right) \quad (6.40)$$

$$UF_{max\ x,L(r),t,a1} = \left[MTOW_x - \left(Cargo_{x,L(r),t,a1} + S_x\left(\frac{WPax_{a1} + NBags_{a1}\, WBags_{a1}}{1000}\right) LF_{x,L(r),t,a1}\right)\right] \quad (6.41)$$

$$y_{5\,x,L(r),t,a1} = \begin{cases} 1 & \left[\text{if } \left(UFT_{x,L(r-1),t,a1} - UF_{x,L(r-1),t,a1}\right) \geq UF_{e\,x,L(r),t,a1} \text{ AND } JFP_{ORI(r),t} \geq JFP_{DES(r),t}\right] \quad \text{"No"} \\ 0 & \text{Otherwise} \quad \text{"Yes"} \end{cases} \quad (6.42b)$$

$$UF_{m\,x,L(r),t,a1} = \left[\left(\left(UFe_{x,L(r-1),t,a1}\, y_{4\,x,L(r-1),t,a1} + \left(1 - y_{4\,x,L(r-1),t,a1}\right) UF_{max,x,L(r-1),t,a1}\right) - UF_{x,L(r-1),t,a1}\right)\left(y_{5\,x,L(r),t,a1}\right)\right] + \left[\left(1 - y_{5\,x,L(r),t,a1}\right)\left(\left(UFe_{x,L(r),t,a1}\, y_{4\,x,L(r-1),t,a1} + \left(1 - y_{4\,x,L(r),t,a1}\right) UF_{max\ x,L(r),t,a1}\right)\right)\right] \quad (6.42a)$$

$$y_{6\,x,L(r),t,a1} = \begin{cases} 1 & \text{if } UF_{m\,x,L(r),t,a1} \leq Tank_{max\ x,a1} \\ 0 & \text{if } UF_{m\,x,L(r),t,a1} > Tank_{max\ x,a1} \end{cases} \quad (6.42d)$$

$$UFT_{x,L(r),t,a1} = UF_{m\,x,L(r),t,a1}\ y_{6\,x,L(r),t,a1} + Tank_{max\ x,a1}\left(1 - y_{6\,x,L(r),t,a1}\right) \quad (6.42c)$$

$$AOC_{x,L(r),t,a1} = \left[\left(B_0 + B_1\left(D_{UFx,L(r),t}\right)\right) Load_{x,L(r),t,a1} + \left(C_0 + C_1\left(D_{UFx,L(r),t}\right) + C_2\left(D_{UFx,L(r),t}\right)^2\right)\right]\left(\frac{JFP_{ORI(r-1),t}\ y_{5\,x,L(r),t}}{\%JFC_t}\right) + \left[\left(B_0 + B_1\left(D_{UFx,L(r),t}\right)\right) Load_{x,L(r),t,a1} + \left(C_0 + C_1\left(D_{UFx,L(r),t}\right) + C_2\left(D_{UFx,L(r),t}\right)^2\right)\right]\left(\frac{JFP_{ORI(r),t}\left(1 - y_{5\,x,L(r),t}\right)}{\%JFC_t}\right) \quad (6.42e)$$

$$UFT_{x,L(r),t,a1} \geq UFe_{x,L(r),t,a1}\, y_{x,L(r),t,a1} \tag{6.43}$$

Aircraft maximum range

$$Range_{x,t,a1} \geq D_{UFe\ x,L(r),a1} \tag{6.44b}$$

$$Range_{x,L(r),t,a1} = \frac{-(B_1 Load_{x,L(r),t,a1} + C_1) + \sqrt{(B_1 Load_{x,L(r),t,a1} + C_1)^2 - 4C_2 (B_0 Load_{x,L(r),t,a1} + C_0 - Tank_{max\ \ x,a1})}}{2\, C_2} \tag{6.44a}$$

$$Tank_{max\ x,a1} \geq UFT_{x,L(r),t,a1}\, y_{x,L(r),t,a1} \tag{6.45}$$

Weights calculations

$$W_{TO\ x,L(r),t,a1} = Load_{x,L(r),t,a1} + UFe_{x,L(r),t,a1} \tag{6.46}$$

$$\left(W_{TO\ x,L(r),t,a1} + ToutF_{x,ORI(r),t,a1}\right) y_{x,L(r),t,a1} \leq MTW_x \tag{6.47}$$

$$W_{TO\ x,L(r),t,a1}\ \ y_{x,L(r),t,a1} \leq MTOW_x \tag{6.48}$$

$$W_{DES\ x,L(r),t,a1} = W_{TO\ x,L(r),t,a1} - UF_{x,L(r),t,a1} \tag{6.49}$$

$$W_{DES\ x,L(r),t,a1}\ y_{x,L(r),t,a1} \leq MLW_x \tag{6.50}$$

Flying times

$$V_{S\ x,L(r),t} = \sqrt{\frac{W_{TO\ x,L(r),t,a1}\, g}{\frac{1}{2}\rho_{Air}\, S_{W\ x}\, C_{Lmax\ x}}} \tag{6.51}$$

$$C_{L_{TO\ x,L(r),t,a1}} = \left[\frac{2\, W_{TO\ x,L(r),t}\, g}{\rho_{Air}\, V_{C\ x}^2\, S_{W\ x}}\right]\left[\frac{1}{1+\left[4\left(1+\frac{3}{M_x}\right)\right]\tan\alpha_{AT}}\right] \tag{6.52}$$

$$C_{L_{DES\ x,L(r),t,a1}} = \left[\frac{2\, W_{DES\ x,L(r),t}\, g}{\rho_{Air}\, V_{C\ x}^2\, S_{W\ x}}\right]\left[\frac{1}{1+\left[4\left(1+\frac{3}{M_x}\right)\right]\tan\alpha_{AT}}\right] \tag{6.52}$$

$$V_{TO\ x,L(r),t,a1} = 1.2\, V_{S\ x,L(r),t,a1} \tag{6.53}$$

$$V_{DES\ x,L(r),t,a1} = 1.3\sqrt{\frac{W_{DES\ x,L(r),t,a1}}{\frac{1}{2}\rho_{Air}\, S_{W\ x}\, C_L}} \tag{6.54}$$

$$A_{TO\ x,L(r),t,a1} = \left[\frac{STE_x}{g\, W_{TO\ x,L(r),t,a1}} - \mu_{1\,x,L(r)}\right] \tag{6.55b}$$

$$A_{DES\ x,L(r),t,a1} = \left[\frac{STE_x}{g\, W_{DES\ x,L(r),t,a1}} - \mu_{1\,x,L(r)}\right] \tag{6.55b}$$

$$B_{TO\ x,L(r),t,a1} = \frac{1}{g\, W_{TO\ x,L(r),t,a1}}\left[\frac{1}{2}\,\rho_{Air}\, S_{Wx}\left(C_{D_{TO\ x,L(r),t,a1}} - \mu_{1\,x,L(r)}\, C_{L_{TO\ x,L(r),t,a1}}\right)\right] \tag{6.55c}$$

$$B_{DES\ x,L(r),t,a1} = \frac{1}{g\, W_{DES\ x,L(r),t,a1}}\left[\frac{1}{2}\,\rho_{Air}\, S_{Wx}\left(C_{D_{DES\ x,L(r),t,a1}} - \mu_{1\,x,L(r)}\, C_{L_{DES\ x,L(r),t,a1}}\right)\right] \tag{6.55c}$$

$$C_{D_{TO\ x,L(r),t,a1}} = \frac{C_{L_{TO\ x,L(r),t,a1}}}{4\left(1+\frac{3}{M_x}\right)} \tag{6.55d}$$

$$C_{D_{DES\ x,L(r),t,a1}} = \frac{C_{L_{DES\ x,L(r),t,a1}}}{4\left(1+\frac{3}{M_x}\right)} \tag{6.55d}$$

$$t_{TO\ x,L(r),t,a1} = \frac{1}{\sqrt{A_{TO\ x,L(r),t,a1}\, B_{TO\ x,L(r),t,a1}}}\left[\tanh^{-1}\left(\sqrt{\frac{B_{TO\ x,L(r),t,a1}}{A_{TO\ x,L(r),t,a1}}}\, V_{TO\ x,L(r),t,a1}\right) - \tanh^{-1}\left(\sqrt{\frac{B_{TO\ x,L(r),t,a1}}{A_{TO\ x,L(r),t,a1}}}\, V_{W\ r}\right)\right] \tag{6.55a}$$

$$t_{DES\ x,L(r),t,a1} = \frac{1}{\sqrt{A_{DES\ x,L(r),t,a1}\, B_{DES\ x,L(r),t,a1}}}\left[\tanh^{-1}\left(\sqrt{\frac{B_{DES\ x,L(r),t,a1}}{A_{DES\ x,L(r),t,a1}}}\, V_{DES\ x,L(r),t,a1}\right) - \tanh^{-1}\left(\sqrt{\frac{B_{DES\ x,L(r),t,a1}}{A_{DES\ x,L(r),t,a1}}}\, V_{W\ r}\right)\right] \tag{6.55a}$$

$$t_{flying\ x,L(r)} = \frac{D_{L(r)}}{V_{C\ x} \mp V_{W\ L(r)}} \tag{6.56}$$

Airtime

$$AIRTime_{x,L(r),t,a1} = t_{TO\ x,L(r),t,a1} + t_{flying\ x,L(r)} + WTD_{DES(r),t} + t_{DES\ x,L(r),t,a1} \tag{6.57}$$

Taxi times

$$\mathrm{Tin}_{\mathrm{DES(r),t}} = \frac{\mathrm{D}_{\mathrm{Tin}_{\mathrm{DES(r),t}}}}{\mathrm{V}_{\mathrm{taxiing}}} \quad (6.58)$$

$$\mathrm{Tout}_{\mathrm{ORI(r),t}} = \frac{\mathrm{D}_{\mathrm{Tout}_{\mathrm{ORI(r),t}}}}{\mathrm{V}_{\mathrm{taxiing}}} + \mathrm{WTO}_{\mathrm{ORI(r),t}} \quad (6.59)$$

Link block time

$$\mathrm{LBT}_{\mathrm{x,L(r),t,a1}} = \mathrm{Tout}_{\mathrm{ORI(r),t}} + \mathrm{AIRTime}_{\mathrm{x,L(r),t,a1}} + \mathrm{Tin}_{\mathrm{DES(r),t}} \quad (6.60)$$

Turnaround times

$$\mathrm{y}_{7_{\mathrm{x,t,a1}}} = \begin{cases} 0 & \text{if } \mathrm{TrF}_{\mathrm{x,ORI(r),t,a1}} \geq \mathrm{TrS}_{\mathrm{x,ORI(r),t,a1}} \\ 1 & \text{if } \mathrm{TrF}_{\mathrm{x,ORI(r),t,a1}} < \mathrm{TrS}_{\mathrm{x,ORI(r),t,a1}} \end{cases} \quad (6.61c)$$

$$\mathrm{TrSoF}_{\mathrm{x,ORI(r),t,a1}} = \mathrm{TrF}_{\mathrm{x,ORI(r),t,a1}} \left(\mathrm{y}_{7_{\mathrm{x,t,a1}}}\right) + \mathrm{TrS}_{\mathrm{x,ORI(r),t,a1}}\left(1 - \mathrm{y}_{7\ \mathrm{x,t,a1}}\right) \quad (6.61b)$$

$$\mathrm{Tr}_{\mathrm{x,ORI(r),t,a1}} = \mathrm{TrP}_{\mathrm{x,ORI(r),t,a1}} + \mathrm{TrD}_{\mathrm{x,ORI(r),t,a1}} + \mathrm{TrSoF}_{\mathrm{x,ORI(r),t,a1}} + \mathrm{TrB}_{\mathrm{x,ORI(r),t,a1}} + \mathrm{TrR}_{\mathrm{x,ORI(r),t,a1}} + \mathrm{WTr}_{\mathrm{x,ORI(r),t,a1}} \quad (6.61a)$$

$$\mathrm{Tr}_{\mathrm{ES}_{\mathrm{x,ORI(r),t,a1}}} = \mathrm{TrP}_{\mathrm{ES}_{\mathrm{x,ORI(r),t,a1}}} + \mathrm{TrD}_{\mathrm{ES}_{\mathrm{x,ORI(r),t,a1}}} + \mathrm{TrB}_{\mathrm{ES}_{\mathrm{x,ORI(r),t,a1}}} + \mathrm{TrR}_{\mathrm{ES}_{\mathrm{x,ORI(r),t,a1}}} + \mathrm{WTr}_{\mathrm{ES}_{\mathrm{x,ORI(r),t,a1}}} \quad (6.61d)$$

$$\mathrm{Tr}_{\mathrm{x,L(r),t,a1}} = \mathrm{Tr}_{\mathrm{ST\ x,L(r),t,a1}}\ \mathrm{y}_{5\ \mathrm{x,L(r),t,a1}} + \mathrm{Tr}_{\mathrm{ES\ x,L(r),t,a1}} \left(1 - \mathrm{y}_{5\ \mathrm{x,L(r),t,a1}}\right) \quad (6.62)$$

Link flying time of an aircraft

$$\mathrm{LTime}_{\mathrm{x,L(r),t,a1}} = \mathrm{Tr}_{\mathrm{x,ORI(r),t,a1}} + \mathrm{LBT}_{\mathrm{x,L(r),t,a1}} \quad (6.63)$$

Airside runway length constraints

$$\mathrm{GR}_{\mathrm{TO\ x,L(r),t,a1}} = \frac{1}{2\ \mathrm{B}_{\mathrm{TO\ x,L(r),t,a1}}} \ln\left[\frac{\mathrm{A}_{\mathrm{TO\ x,L(r),t,a1}} - \mathrm{B}_{\mathrm{TO\ x,L(r),t,a1}} (\mathrm{V}_{\mathrm{W\ r}})^2}{\mathrm{A}_{\mathrm{TO\ x,L(r),t,a1}} - \mathrm{B}_{\mathrm{TO\ x,L(r),t,a1}}\ \mathrm{V}^2_{\mathrm{TO\ x,L(r),t,a1}}}\right] - \mathrm{V}_{\mathrm{W\ r}} \quad (6.64)$$

$$\mathrm{GR}_{\mathrm{DES\ x,L(r),t,a1}} = \frac{1}{2\ \mathrm{B}_{\mathrm{DES\ x,L(r),t,a1}}} \ln\left[\frac{\mathrm{A}_{\mathrm{DES\ x,L(r),t,a1}} - \mathrm{B}_{\mathrm{DES\ x,L(r),t,a1}} (\mathrm{V}_{\mathrm{W\ r}})^2}{\mathrm{A}_{\mathrm{DES\ x,L(r),t,a1}} - \mathrm{B}_{\mathrm{DES\ x,L(r),t,a1}}\ \mathrm{V}^2_{\mathrm{TO\ x,L(r),t,a1}}}\right] - \mathrm{V}_{\mathrm{W\ r}} \quad (6.65)$$

$$\left(\mathrm{GR}_{\mathrm{TO\ x,L(r),t,a1}} + \mathrm{GRs}_{\mathrm{TO\ x,L(r),t,a1}}\right) \mathrm{y}_{\mathrm{x,L(r),t,a1}} \leq \mathrm{RL}_{\mathrm{ORI(r),t}} \quad (6.66)$$

$$\left(\mathrm{GR}_{\mathrm{DES\ x,L(r),t,a1}} + \mathrm{GRs}_{\mathrm{DES\ x,L(r),t,a1}}\right) \mathrm{y}_{\mathrm{x,L(r),t,a1}} \leq \mathrm{RL}_{\mathrm{DES(r),t}} \quad (6.66)$$

Airside aircraft constraints

$$\mathrm{AMI}_{\mathrm{x}}\ \mathrm{y}_{\mathrm{x,L(r),t,a1}} \leq \mathrm{AIRSIDE}_{\mathrm{ORI(r),t}} \quad (6.67)$$

$$\mathrm{AMI}_{\mathrm{x}}\ \mathrm{y}_{\mathrm{x,L(r),t,a1}} \leq \mathrm{AIRSIDE}_{\mathrm{DES(r),t}} \quad (6.67)$$

Airport runway length capacities

$$\mathrm{y}_{8_{\mathrm{x,L(r)}}} = \begin{cases} 0 & \text{if } \left(\mathrm{t}_{\mathrm{DES\ x,L(r),t}} \geq \frac{\mathrm{wvs}_{\mathrm{xij}}}{\mathrm{V}_{\mathrm{DES\ xj,L(r)}}}\right) \\ 1 & \text{if } \left(\mathrm{t}_{\mathrm{DES\ x,L(r),t}} < \frac{\mathrm{wvs}_{\mathrm{xij}}}{\mathrm{V}_{\mathrm{DES\ xj,L(r)}}}\right) \end{cases} \quad (6.68b)$$

$$\mathrm{y}_{9_{\mathrm{x,L(r)}}} = \begin{cases} 0 & \text{if } \mathrm{V}_{\mathrm{DES\ xi,L(r)}} \leq \mathrm{V}_{\mathrm{DES\ xj,L(r)}} \\ 1 & \text{if } \mathrm{V}_{\mathrm{DES\ xi,L(r)}} > \mathrm{V}_{\mathrm{DES\ xj,L(r)}} \end{cases} \quad (6.68c)$$

$$\mathrm{IET}_{\mathrm{DES(r),t}} = \sum_{\mathrm{xij}} \left\{ \left(\left[p_{\mathrm{xi,DES(r),t}} \left(t_{\mathrm{DES\ x,L(r),t,a1}} \right) p_{\mathrm{xj,DES(r),t}} \right] \left(1 - y_{8_{\mathrm{x,L(r)}}} \right) + \left[p_{\mathrm{xi,DES(r),t}} \left(\frac{\mathrm{WVS_{xij}}}{V_{\mathrm{DES\ xj,L(r)}}} \right) p_{\mathrm{xj,DES(r),t}} \right] \left(y_{8_{\mathrm{x,L(r)}}} \right) \right) \left(1 - y_{9_{\mathrm{x,L(r)}}} \right) + \left(\left[p_{\mathrm{xi,DES(r),t}} \left(\frac{\mathrm{WVS_{xij}}}{V_{\mathrm{DES\ xj,L(r)}}} + \iota \left[\frac{1}{V_{\mathrm{DES\ xj,L(r)}}} + \frac{1}{V_{\mathrm{DES\ xi,L(r)}}} \right] \right) p_{\mathrm{xj,DES(r),t}} \right] \right) \left(y_{9_{\mathrm{x,L(r)}}} \right) \right\} \quad (6.68a)$$

$$y_{8_{\mathrm{x,L(r)}}} = \begin{cases} 0 & \text{if } \left(t_{\mathrm{DES\ x,L(r),t}} \geq \frac{\mathrm{WVS_{xij}}}{V_{\mathrm{DES\ xj,L(r)}}} \right) \\ 1 & \text{if } \left(t_{\mathrm{DES\ x,L(r),t}} < \frac{\mathrm{WVS_{xij}}}{V_{\mathrm{DES\ xj,L(r)}}} \right) \end{cases} \quad (6.68b)$$

$$y_{9_{\mathrm{x,L(r)}}} = \begin{cases} 0 & \text{if } V_{\mathrm{DES\ xi,L(r)}} \leq V_{\mathrm{DES\ xj,L(r)}} \\ 1 & \text{if } V_{\mathrm{DES\ xi,L(r)}} > V_{\mathrm{DES\ xj,L(r)}} \end{cases} \quad (6.68c)$$

$$\mathrm{IET}_{\mathrm{ORI(r),t}} = \sum_{\mathrm{xij}} \left\{ \left(\left[p_{\mathrm{xi,ORI(r),t}} \left(t_{\mathrm{DES\ x,L(r),t,a1}} \right) p_{\mathrm{xj,ORI(r),t}} \right] \left(1 - y_{8_{\mathrm{x,L(r)}}} \right) + \left[p_{\mathrm{xi,ORI(r),t}} \left(\frac{\mathrm{WVS_{xij}}}{V_{\mathrm{DES\ xj,L(r)}}} \right) p_{\mathrm{xj,ORI(r),t}} \right] \left(y_{8_{\mathrm{x,L(r)}}} \right) \right) \left(1 - y_{9_{\mathrm{x,L(r)}}} \right) + \left(\left[p_{\mathrm{xi,ORI(r),t}} \left(\frac{\mathrm{WVS_{xij}}}{V_{\mathrm{DES\ xj,L(r)}}} + \iota \left[\frac{1}{V_{\mathrm{DES\ xj,L(r)}}} + \frac{1}{V_{\mathrm{DES\ xi,L(r)}}} \right] \right) p_{\mathrm{xj,ORI(r),t}} \right] \right) \left(y_{9_{\mathrm{x,L(r)}}} \right) \right\} \quad (6.68a)$$

$$\lambda_{\mathrm{DES_{ORI(r),t}}} = \frac{Ђ_{\mathrm{ORI(r),t}}}{\mathrm{IET_{ORI(r),t}}} \quad (6.69)$$

$$\lambda_{\mathrm{DES_{DES(r),t}}} = \frac{Ђ_{\mathrm{DES(r),t}}}{\mathrm{IET_{DES(r),t}}} \quad (6.69)$$

$$\lambda_{\mathrm{max_{ORI(r),t}}} = 2\,\lambda_{\mathrm{DES_{ORI(r),t}}} \quad (6.71)$$

$$\lambda_{\mathrm{max_{DES(r),t}}} = 2\,\lambda_{\mathrm{DES_{DES(r),t}}} \quad (6.71)$$

$$\mathrm{Mov_{ORI(r),t}} = \sum_{a=1}^{A} \mathrm{Mov_{DES_{ORI(r),t,a}}} + \sum_{a=1}^{A} \mathrm{Mov_{TO_{O\ RI(r),t,a}}} \quad (6.72)$$

$$\mathrm{Mov_{DES(r),t}} = \sum_{a=1}^{A} \mathrm{Mov_{DES_{DES(r),t,a}}} + \sum_{a=1}^{A} \mathrm{Mov_{TO_{DES(r),t,a}}} \quad (6.72)$$

$$\mathrm{Ma_{ORI(r),t}} = \lambda_{\mathrm{max_{ORI(r),t}}} - \mathrm{Mov_{ORI(r),t}} \quad (6.73)$$

$$\mathrm{Ma_{DES(r),t}} = \lambda_{\mathrm{max_{DES(r),t}}} - \mathrm{Mov_{DES(r),t}} \quad (6.73)$$

$$\mathrm{freq_{x,L(r),t}} \leq \mathrm{Ma_{ORI(r),t}} \quad (6.74a)$$

$$\mathrm{freq_{x,L(r),t}} \leq \mathrm{Ma_{DES(r),t}} \quad (6.74b)$$

Apron Area and Number of Gates/Stands

$$Ꝋ_{\mathrm{max_{x,DES(r),t}}} = \mathrm{rounddown}\left[\left(\frac{\mathrm{Ng_{x,DES(r),t}}}{\sum_a \sum_x \left(\mathrm{Tr_{x,DES(r),t,a}}\ p_{\mathrm{x,DES(r),t,a}} \right)} \right) Ђ_{\mathrm{DES(r),t}} \right] \quad (6.75)$$

$$Ꝋ_{\mathrm{max_{x,ORI(r),t}}} = \mathrm{rounddown}\left[\left(\frac{\mathrm{Ng_{O\ x,L(r),t}}}{\sum_a \sum_x \left(\mathrm{Tr_{x,ORI(r),t,a}}\ p_{\mathrm{x,ORI(r),t,a}} \right)} \right) Ђ_{\mathrm{ORI(r),t}} \right] \quad (6.75)$$

$$\mathrm{Pg_{x,ORI(r),t}} = \sum_{a=1}^{A} \mathrm{Mov_{DES_{ORI(r),t,a}}} \quad (6.76)$$

$$\mathrm{Pg_{x,DES(r),t}} = \sum_{a=1}^{A} \mathrm{Mov_{DES_{DES(r),t,a}}} \quad (6.76)$$

$$\mathrm{G_{x,ORI(r),t}} = Ꝋ_{\mathrm{max_{x,ORI(r),t}}} - \mathrm{Pg_{x,ORI(r),t}} \quad (6.77)$$

$$\mathrm{G_{x,DES(r),t}} = Ꝋ_{\mathrm{max_{x,DES(r),t}}} - \mathrm{Pg_{x,DES(r),t}} \quad (6.77)$$

$$\mathrm{freq_{x,L(r),t}} \leq \mathrm{G_{x,ORI(r),t}} \quad (6.78a)$$

$$\mathrm{freq_{x,L(r),t}} \leq \mathrm{G_{x,DES(r),t}} \quad (6.78b)$$

Airport terminal facilities spaces and service rates

$$\sum_{x=1}^{X} Ꝋ_{\mathrm{max_{x,ORI(r),t}}} \geq \frac{\lambda_{\mathrm{max_{ORI(r),t}}}}{2} \geq \lambda_{\mathrm{DES_{ORI(r),t}}} \quad (6.79)$$

$$\sum_{x=1}^{X} Ꝋ_{\mathrm{max_{x,DES(r),t}}} \geq \frac{\lambda_{\mathrm{max_{DES(r),t}}}}{2} \geq \lambda_{\mathrm{DES_{DES(r),t}}} \quad (6.79)$$

$$\mathrm{CapS_{af_{ORI(r),t}}} = \frac{\mathrm{Å_{af_{ORI(r),t}}}}{\mathrm{Å_{0,af_{ORI(r),t}}}} \quad (6.80)$$

$$\mathrm{CapS}_{af_{DES(r),t}} = \frac{Å_{af_{DES(r),t}}}{Å_{0,af_{DES(r),t}}} \quad (6.80)$$

$$\mathrm{CapD}_{sf_{ORI(r),t}} = u_{sf_{ORI(r),t}} \frac{T_{dhp}}{st_{sf_{ORI(r),t}}} \quad (6.81)$$

$$\mathrm{CapD}_{sf_{DES(r),t}} = u_{sf_{DES(r),t}} \frac{T_{dhp}}{st_{s_{DES(r),t}}} \quad (6.81)$$

$$AC_{ORI(r),t} = \begin{cases} \min\left[\mathrm{CapS}_{af_{ORI(r),t}}\right] & \text{for } \mathrm{CapS}_{af_{ORI(r),t}} \leq \mathrm{CapD}_{sf_{ORI(r),t}} \\ \min\left[\mathrm{CapD}_{af_{ORI(r),t}}\right] & \text{for } \mathrm{CapS}_{af_{ORI(r),t}} > \mathrm{CapD}_{sf_{ORI(r),t}} \end{cases} \quad (6.82)$$

$$AC_{DES(r),t} = \begin{cases} \min\left[\mathrm{CapS}_{af_{DES(r),t}}\right] & \text{for } \mathrm{CapS}_{af_{DES(r),t}} \leq \mathrm{CapD}_{sf_{DES(r),t}} \\ \min\left[\mathrm{CapD}_{af_{DES(r),t}}\right] & \text{for } \mathrm{CapS}_{af_{DES(r),t}} > \mathrm{CapD}_{sf_{DES(r),t}} \end{cases} \quad (6.82)$$

$$\left(S_x\, freq_{x,L(r),t}\right) \leq AC_{ORI(r),t} \left(\frac{Ђ_{ORI(r),t}}{T_{dhp}}\right) - \sum_{a=1}^{A} \sum_{x=1}^{X} \left(Pg_{x,ORI(r),t}\, S_{x,a}\, p_{x,ORI(r),t,a}\right) \quad (6.84a)$$

$$\left(S_x\, freq_{x,L(r),t}\right) \leq AC_{DES(r),t} \left(\frac{Ђ_{DES(r),t}}{T_{dhp}}\right) - \sum_{a=1}^{A} \sum_{x=1}^{X} \left(Pg_{x,DES(r),t}\, S_{x,a}\, p_{x,DES(r),t,a}\right) \quad (6.84b)$$

<u>The optimum number of frequencies must be always positive</u>

$$freq_{x,L(r),t,a1} \geq 0 \quad \epsilon \text{ int} \quad (6.85)$$

<u>Optimum number of aircraft to invest</u>

$$Time_{x,L(r),t,a1} = LTime_{x,L(r),t,a1} + LTime_{x,L(r),t,a1} \quad (6.86)$$

$$\left(U_{x,t,j} - maintenance_{x,t,j,a1}\right) \geq \sum_{r=1}^{R} \left(Time_{x,L(r),t,a1}\, y_{x,L(r),t,a1}\right) \quad (6.87)$$

$$NAIR_{x,t,j,a1} = \mathrm{roundup}\left[\frac{\sum_{r=1}^{R}\left(Time_{x,L(r),t,a1}\, freq_{x,L(r),t,a1}\, y_{x,L(r),t,a1}\right)}{\left(U_{x,t,j} - maintenance_{x,t,j,a1}\right)}\right] \quad (6.88)$$

$$\sum_{t=1}^{T}\left[NAIR_{x,t,j,a1}\left(U_{x,t,j,a1} - maintenance_{x,t,j,a1}\right)\right] \geq \sum_{t=1}^{T}\left[\sum_{r=1}^{R}\left(Time_{x,L(r),t,a1}\, freq_{x,L(r),t,a1}\, y_{x,L(r),t,a1}\right)\right] \quad (6.89)$$

$$NAIR_{x,NTW} = \sum_{j=1}^{J} \sum_{t=1}^{T} NAIR_{x,t,j,a1} \quad (6.90)$$

$$NAIR_{x,t,j,a1} \geq ENAIR_{x,t,j,a1}\, y_{10_{x,t,j,a1}} \quad (6.91)$$

<u>The optimum number of aircraft must be always positive</u>

$$NAIR_{x,t,j,a1} \geq 0 \quad \epsilon \text{ int} \quad (6.92)$$

<u>The optimum number of seats must be always positive</u>

$$S_{x,a1} \geq 0 \quad \epsilon \text{ int} \quad (6.96)$$

<u>Decision variables</u>

$$y_{x,L(r),t,a1} \in [0,1] \quad (6.97)$$

$$y_{1\,x,L(r),t,a1} \in [0,1] \quad (6.98)$$

$$y_{2_{x,L(r),t}} \in [0,1] \quad (6.99)$$

$$y_{3\,L(r),t} \in [0,1] \quad (6.100)$$

$$y_{4\,x,L(r),t,a1} \in [0,1] \quad (6.101)$$

$$y_{5\,x,L(r),t,a1} \in [0,1] \quad (6.102)$$

$$y_{6\,x,L(r),t,a1} \in [0,1] \quad (6.103)$$

$$y_{7_{L(r),t,a1}} \in [0,1] \quad (6.104)$$

$$y_{8_{L(r),t,a1}} \in [0,1] \quad (6.105)$$

$$y_{9_{L(r),t,a1}} \in [0,1] \quad (6.106)$$

$$y_{10_{x,t,j,a1}} \in [0,1] \quad (6.107)$$

Total network and Sub-networks Return on investment (ROI)

$$ROI_{x,t,j,a1} = \frac{\left(\sum_{t=0}^{T}\frac{\sum_{r=1}^{R}\left(F_{L(r),t,j,a1}\, Q_{x,L(r),t,j,a1}{}^{*} - AOC_{x,L(r),t,j,a1}\, freq_{x,L(r),t,j,a1}\right) - \left(Price_{x,t,a1}\left(NAIR_{x,t,j,a1} - ENAIR_{x,t,j,a1}\right)\right)}{(1+WACC)^{t}}\right) + \frac{VA_{x,T,j,a1}}{(1+WACC)^{T}}}{\sum_{t=0}^{T}\frac{\left(Price_{x,t}\left(NAIR_{x,t,j,a1} - ENAIR_{x,t,j,a1}\right)\right)}{(1+WACC_{a1})^{t}}}$$

(6.14a)

$$ROI_{x,t,NTW,a1} = \frac{\left(\sum_{j=1}^{J}\sum_{t=0}^{T}\left(\frac{\sum_{r=1}^{R}\left(F_{L(r),t,j}\, Q_{x,L(r),t,j,a1}{}^{*} - AOC_{x,L(r),t,j,a1}\, freq_{x,L(r),t,j,a1}\right) - Price_{x,t,a1}\left(NAIR_{x,t,j,a1} - ENAIR_{x,t,j,a1}\right)}{(1+IRR_{a})^{t}}\right)\right) + \frac{VA_{x,T,j,a1}}{(1+WACC_{a1})^{T}}}{\sum_{j=1}^{J}\sum_{t=0}^{T}\left(\frac{Price_{x,t}\left(NAIR_{x,t,j} - ENAIR_{x,t,j}\right)}{(1+WACC_{a1})^{t}}\right)}$$

(6.14b)

6.5 Social Impact

The benefits of opening more airline transport services are directly reflected on the society. The social benefit can be measured as the number of jobs that would be created as a consequence of opening new airlines transport services.

Airlines employ thousands of people and contribute to the direct economy of any country. Indirectly, airlines provide services and purchase goods and services from other companies increasing the number of jobs for other industries. It also helps to increase the gross domestic product (GDP) of any country as it is explained in Chapter 1.

In general, airlines numbers of employers are highly correlated with the number of pax the airlines transported during a year (Figure 6.13). Figure 6.13 shows the correlation between total pax transported and the total number of employees for 14 airlines in the US. In Figure 6.13, the total number of employees for an airline increase as its number of pax transported increases too. FSC's hires one person to attend 1375 pax per year. Southwest Airlines (WN) and Frontier (F9) hire one person to attended 3028 pax per year. FSC's hires more than two times the employees than LCC's to transport the same number of pax.

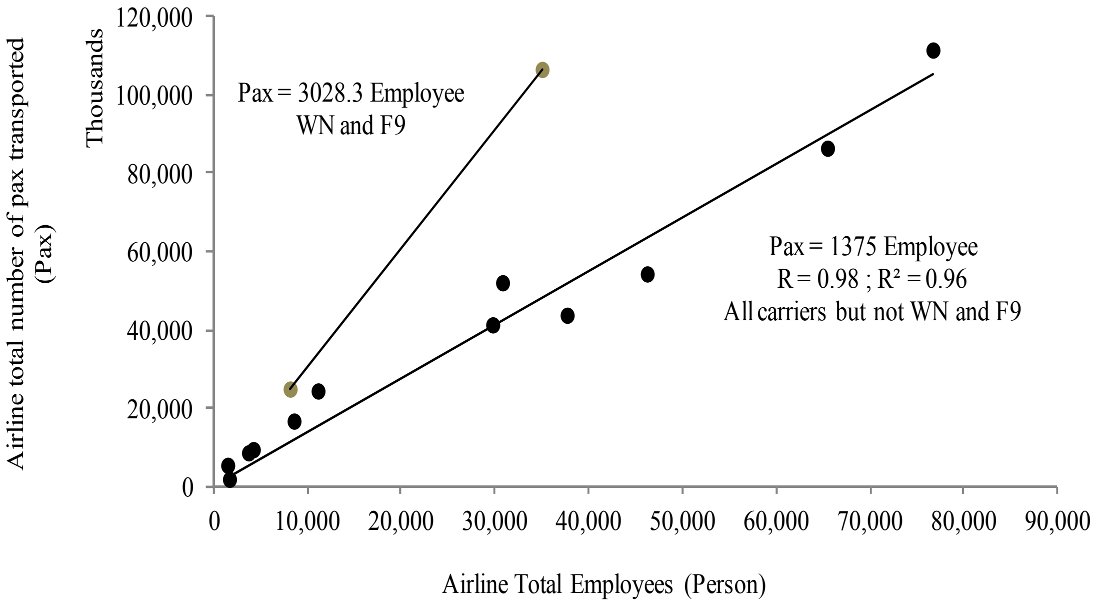


Figure 6.13 Airlines total number of employers for FSC's and LCC's

Equation 6.109 calculates the total number of employees an airline may need to operate the selected network after optimization. The constant factor (C_4) is the only parameter that changes its value to calculate the number of employees needed for each airline employee type.

$$\text{Employee} = C_4^{-1} Q^{*}_{NTW} \tag{6.109}$$

Where:

Employee = number of employees required to operate the network [person]
C_4 = employee type constant factor [pax/person]
Q_{NTW} = optimum number of passengers to serve in the designed network [pax]

Table 6.8 shows the value of the constant factor C_4 for each airline employee type. It also shows the correlation between each airline employee type and the total number of pax transported by 14 airlines shown in Table Appendix M. 1 and Table Appendix M. 2, during 2010. For more information, Table Appendix M. 1 and Table Appendix M. 2 contains the number of pax transported by the 14 airlines for 2010 year [MIT]. It also contains the total number of employee per airline employee type.

Table 6.8 Employee type constant factor (C_4) for FSC's and LCC's

Airline business type	*FSC*			*LCC*[17]
Type	*C_4*	*R*	*R^2*	*C_4*
Management	257,203	0.73	0.54	106,652
Pilots	10,617	0.96	0.92	16,472
General Services	5,702	0.89	0.80	12,149
Maintenance	9,841	0.70	0.49	64,688
Handling	16,502	0.65	0.42	17,494
Aircraft control	68,654	0.30	0.09	373,475
Pax Handling	5,095	0.78	0.61	14,755
Cargo Handling	9,811	0.42	0.17	284,244
Trainees and Instructors	227,255	0.69	0.47	1,170,959
Stats	13,963	0.44	0.20	123,043
Traffic Solicitors	72,781	0.48	0.23	1,656,250
Other	8,336	0.54	0.30	41,259
Employees	1,368	0.90	0.80	3,028

6.6 Discussion

Even when one route has been selected by the CFEM and PEM models, it does not mean that they represent an opportunity to open services. The routes selection of an airline network have more constraints than just finding routes that are very expensive and have a high number of induced passenger demand. Aircraft and airport capacities, characteristics, and economic conditions are main constraints to consider when selecting routes that represent an investment. Airlines invest a lot of money before opening new pax transportation services, for this reason, airlines have to analyze if their profits will exceed their investment when opening new services. The optimization model based on the maximization of the net present value (NPV) allows airlines to make sure that a set of routes and links forming new networks represent and investment.

The optimization model designs airlines network by joining links previously selected by the CFEM and PEM models. The links form aircraft flying paths known as routes in this chapter.

[17] Only WN and F9 provided data about the total number of employees.

All the routes form the network. The model integrates aircraft performance with two financial methods: the NPV and the internal rate of return (IRR) to evaluate if a route in a network is an opportunity to open services. The model considers human desires and preferences for flying different links, financial constraints, average waiting times, aircraft characteristics, weights, flying times, ground times, airport-aircraft constraints, and airports characteristics and infrastructure. The model is based on short-haul and long-haul strategies. It distinguishes the differences between long-haul and short-haul operations. The final model is a one objective function model which is defined with base on multiple variable relations. This model maximizes the NPV and the network pax flow. At the same time, the model considers the competition between airlines operating the same link.

The competitiveness between airlines is measured by the relationship between market share and the number of frequencies that determine the optimal number of passengers to serve by each airline operating the same link. In this thesis, the market share is determined by the ratio between the multiplication of airline operating costs by frequency and the sum of the multiplication of the airline operating costs by frequency for all airlines operating the same link. This is contrary to other researchers who have determined the market share using the total number of seats. Equation 6.94 determines the number of passengers carried on each link for each airline operating the same link. The relationship between market share and capacity share was introduced to explain the reaction of passengers when an airline enters or increase the number of flights in a link. It allows the model to assess the reaction that passengers have when airlines increase the supply of frequencies on links.

While discussing the model results, it was evident that the model considers the parameters that are involved in the simulation of an airline. The main advantage of the model is the capacity to connect aircraft characteristics and capacities with airports airside, terminal side, and level of services (LOS). For this reason, the model is considered to be able to design a large scale airline network.

The optimization model designs large scale airline networks considering aircraft performance, aircraft characteristics, airport airsides and terminals sides' infrastructure. However, collecting all the data required to make the optimization analysis of an airline network can be quiet difficult. Therefore, the optimization model can easily be modified to reduce the number of parameters, especially when not sufficient data is available. Equations 6.12 to 6.50, 6.56 to 6.63, 6.85 to 6.104, and 6.107 are the model's main equations if the optimization model is used with the purpose of designing an airline network by assigning an aircraft type. It does not mean that part of the optimization model is not needed. A trustable design of an airline network must be done by considering all the optimization model parameters and constraints.

The optimization model turnaround (Tr) parameters allow doing simulations for different Tr. This thesis does not propose a Tr process to minimize times, but it gives the possibility for an airline to simulate a new Tr process sequence. If an airline is interested in assessing the advantages and disadvantages of a new Tr, the airlines just need to adjust parameters that determine the Tr critical path and the processes time will have an impact on the Tr process time as a whole. Then, airlines can analyze if a new Tr process is beneficial to the maximization of their NPV's and the maximization of the total number of pax to transport. This can happen on short-haul routes networks, but in long-haul, minimizing the Tr does not matter because the flying time is not enough to offer another flight. However, the optimization model can be set up for different Tr processes for any type of haul.

During the development of the model, it was understood that a route generation algorithm was necessary to determine the flying paths that aircraft can follow. The route generation algorithm is based on the idea that airlines have to operate networks that provide good profits over investment. However, they also have to increase their number of routes and pax flow, because the way to compete is to be as big as they can. For this reason, the route generation algorithm does not generate all possible routes between cities/airports in an airline network by purpose. The objective of the route generation algorithm is to design airline networks that represent a good opportunity to open services by computing the maximum network NPV for most of the links selected by the CFEM and PEM models. It means the algorithm was designed to include most of the links selected by the CFEM and PEM model and from those routes, the optimization model finds the maximum NPV. Networks with fewer routes than the best combination are not optimized because the algorithm stops the process after the maximum NPV values has been found for the maximum possible number of route links. It is better for an airline to operate big networks with high pax flow and good NPV than operating small networks with small pax flow and high NPV. The number of passengers and number of links is also important for growth and to be competitive. The route generation algorithm takes this into account by stopping the process after it has found a good solution for largest possible network.

Based on the model characteristics, parameters, and constraints it is possible to conclude that a design and an analysis of the feasibility of an airline network can be done by using this optimization model. It is also possible to conclude that the optimization model finally identifies routes that are opportunities to open services, based on airline operating costs, passenger demand, aircraft and airport capacities and constraints.

Finally, it is important for an airline to calculate the number of employees it will need to operate the network designed, because the feasible network cannot be feasible if the total number of high skilled employers such as pilots does not exist. An equation that determines the total number of employees an airline needs in order to operate the selected network after optimization has been developed. The results of this equation are shown to be accurate. For this reason, it can be used to determine the total number of employees needed to operate an airline network for each type of job required by an airline.

7 Short-haul and Long-haul optimization cases

This chapter presents one short-haul low-cost network and one long-haul low-cost network as cases studies. This chapter also proposes a long-haul low-cost business model. The first study case is based on the United States domestic market, DOT US Consumer Report [2005]. Figure 7.1 shows the routes selected by the CFEM and PEM models. These routes form the short-haul low-cost network case before optimization. The second case is the analysis of a long-haul low-cost business model which will be proposed in this chapter. It is a hypothetical study case. In the long-haul hypothetical case, three studies are performed. First, all airports in the network are connected by direct flights. Second, airports are connected through hubs. Third, complete deregulation of the market. This will simulate the connection between short-haul low-cost airlines in different regions by a long-haul low-cost carrier. This network data is also created using the mathematical models presented in the previous chapters (AOC, FEM, and PEM models). An algorithm will be developed to allow pax connection through hubs.

The constant value of the parameter that expresses the passenger perception of travelling in cost unit or the desire for passengers to fly (Γ) is a main parameter in the calculation of the optimum number of passengers to serve (Q_r*) and the optimum number of frequencies to operate ($freq_r$*) per link (Equation 6.5). This is an important parameter that is used to analyze and prove the optimization model. The analyses of different values of the parameter Γ are to compare between LCC's and FSC's market conditions.

Γ has been calculated by equalizing each link frequency to Equation 6.5 for all routes in the DOT US Consumer report [2005] database. The FSC's links average value of Γ is 78 [usd/hour/pax]. The LCC's links average value of Γ is 71 [usd/hour/pax]. A link operated only by LCC's average value of Γ is 54 [usd/hour/pax]. However, these are average values but the dispersion indicates that FSC's and LCC's can operate routes with higher and lower values of Γ than their averages. For the 81 routes selected by the CFEM and PEM models as possible routes to open service, the analysis of the value of Γ is 94.10 [usd/hour/pax]. These routes have a high value of Γ because the passengers travelling in these routes are FSC's, and their perception of travelling is higher than in other routes. These values of Γ suggest that routes under 50 [usd/hour/pax] can be mainly interest for LCC's. Values of Γ between 50 and 100 [usd/hour/pax] are an interest for LCC's and FSC's, and values of Γ higher than 100 [usd/hour/pax] are probably more interested for FSC operations because in these routes links passengers are willing to pay a lot of money for travelling, and they demand better services than low cost services.

The values of Γ are logical. For example, today a pax willing to travel from Mexico City to Amsterdam is paying between 1000 and 1600 usd in economy class. The pax buying fares in this route pay a value of Γ between 77 and 123 [usd/hour/pax] because it is an approximately 13 hour's complete journey.

In Chapter 3, it was concluded that the AGE model (Equation 3.10) values of coefficients (Table 3.4) calibrated for Airbus aircraft are not accurate because Airbus fuel consumption diagrams do not show enough data points as they do for Boeing and Embraer fuel consumption diagrams. The results for airbus using Table 3.4 for the values of the coefficients calculate high volumes of fuel consumption. For this reason, the AGE model values of the coefficients for Airbus aircraft have to be calibrated with more data points. In this chapter, Airbus aircraft fuel consumption AGE model (Equation 3.10) coefficient values (Table 3.4) are taken equal to Boeing AGE model values of coefficients. It allows a comparison between Boeing and Airbus aircraft. Otherwise, the optimizations for Airbus planes calculate small net present values (NPV) and little number of links to operate, which is not realistic.

The aim of this chapter is to illustrate how the optimization model works for short-haul and long-haul cases. This chapter presents one short-haul low-cost network study case in Section 7.1. In Section 7.2, the long-haul low-cost model is proposed and analyzed with a hypothetical case. Finally, a discussion on the optimization model results is presented in Section 7.3 as a conclusion to this chapter.

7.1 Short-haul low-cost United States Domestic market case

Figure 7.1 shows the short-haul low-cost US Domestic market network before optimization. These routes are the result from the selection of routes made by the CFEM and PEM models as a study case in Chapter 4 and Chapter 5. This network was previously selected by the FEM model and the PEM model (Chapter 4 and Chapter 5). Figure 7.1 shows 81 links that after being joined form three routes. Route 1 is formed by 76 links (Figure 7.1, red color). Route 2 is formed by 3 links (Figure 7.1, green color), and Route 3 is formed by 3 links (Figure 7.1, blue color).

7.1.1 Short-haul low-cost case non-limited number of frequencies

First short-haul study case: the optimization is performed without assuming a maximum number of frequencies per link. The value of Γ has been calculated from the airlines already operating each link with real data [DOT US Consumer report, 2005].

Figure 7.1 contains the results of the optimization per aircraft type. In case of non limited $freq_r$, the best aircraft type is the E195 because it yields the highest network NPV. According to the optimization results (Figure 7.1) using an E195, in T = 20 years, the NPV is equal to 2.51 billion usd earning 6.14 billion in profits. This aircraft operates 4 routes serving a total of 39 links with 12 aircraft attracting 83,325 pax per week.

Figure 7.2 shows the short-haul low-cost US Domestic market network after optimization with non limited number of flights between airports/cities. Figure 7.2 shows the network designed after optimization for the E195 plane. The total number of links that do not represent an opportunity to open services is 42 links (Figure 7.2, yellow). Now, route 1 is formed by 31 links (Figure 7.2, red color). Route 2 is formed by 5 links (Figure 7.2, blue). Route 3 is formed by 2 links (Figure 7.2, black), and Route 4 is formed by 1 link (Figure 7.2, green). The total network return on investment ($ROI_{NTW,E195}$) is equal to 498%. Route 1 $ROI_{NTW,E195}$ = 679% with an $IRR_{NTW,E195}$ = 79% (Figure 7.2, red color). Route 2 $ROI_{NTW,E195}$ = 185% with an $IRR_{NTW,E195}$ = 29% (Figure 7.2, blue color). Route 3 $ROI_{NTW,E195}$ = 131% with an $IRR_{NTW,E195}$ = 23% (Figure 7.2, black color). Route 4 $ROI_{NTW,E195}$ = 50% with an $IRR_{NTW,E195}$ = 14% (Figure 7.2, green color).

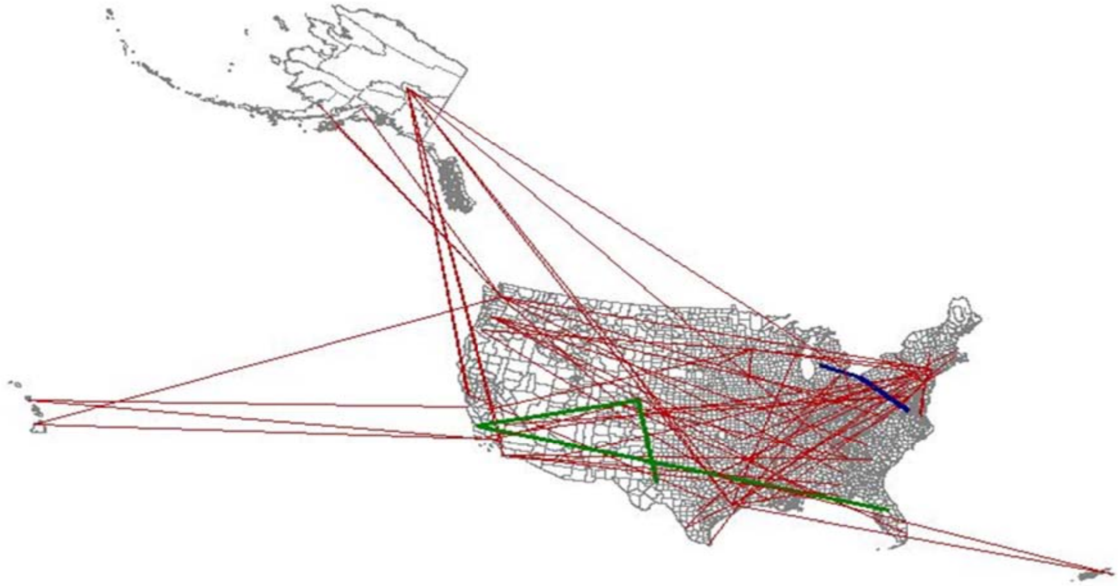


Figure 7.1 Short-haul network case before optimization

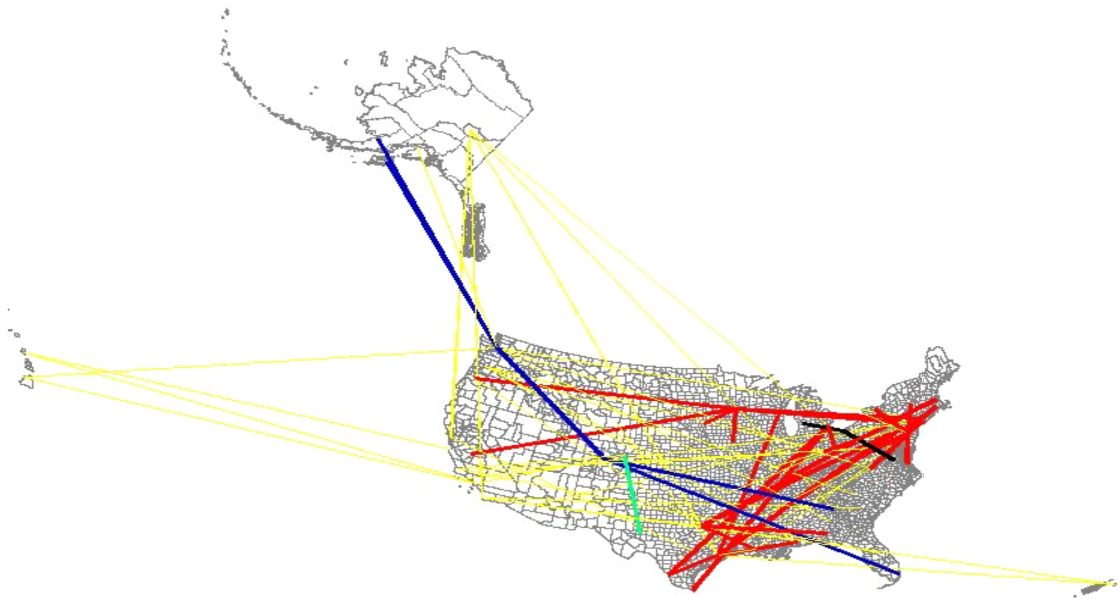


Figure 7.2 Short-haul network case after optimization non limited frequency, E195

The calculations of the NPV's per aircraft type show these values to be high, what is logical because this study case is not constrained to a limited number of $freq_r$. The optimum number of passengers (Q_r*) to serve per week is determined by the optimization model. It can be observed because the total number of passengers per aircraft type is not similar, what confirms the capacity of the model to determine Q_r* for the networks designed for different aircraft types.

Table 7.1 Short-haul network case after optimization non-limited frequency results

First case Real Γ and non limited Freq	*NPV (mill)*	*Num of routes*	*Num of links*	*NAIR*	*Q per week*	*Freq per week*	*Total Profits (mill)*	*S*	*LF*
E195	2,512	4	39	12	83,325	1,082	6,143	105	0.73
E190	2,363	4	39	12	80,190	1,100	5,778	94	0.78
E175	2,313	4	39	12	36,673	1,158	5,580	78	0.41
E170	2,143	4	39	12	72,659	1,172	5,172	70	0.89
B737-800	1,977	3	45	12	96,515	772	6,001	186	0.67
B737-600	1,889	2	50	13	93,209	914	5,354	132	0.77
B737-700	1,884	3	48	14	95,310	866	5,774	150	0.73
B737-900	1,803	4	43	13	95,211	738	5,945	200	0.65
A319	1,776	2	46	12	92,923	814	5,517	156	0.73
A320	1,645	2	43	12	89,908	768	5,428	161	0.73
A321	1,529	3	37	11	89,536	660	5,350	220	0.62
EMB145	1,461	4	41	14	30,598	1,436	3,676	45	0.47
A318	1,347	3	48	13	85,189	882	4,471	117	0.83
ERJ140	1,075	5	35	12	22,557	1,294	2,727	39	0.45
EMB135	791	4	33	11	18,315	1,400	2,038	34	0.38
A330-300	680	1	15	3	55,260	186	2,985	440	0.68
A350-1000	536	1	18	3	58,285	244	2,924	350	0.68
A340-300	504	1	15	4	55,260	190	2,966	440	0.66
B767-200ER	408	1	20	4	47,193	306	2,006	181	0.85
B767-300ER	361	1	21	4	51,674	308	2,074	200	0.84
A350-900	305	1	21	4	60,394	270	2,802	314	0.71
A350-800	280	1	21	4	57,263	276	2,498	270	0.77
B787-800	168	1	21	4	52,904	274	1,852	237	0.81
B777-200	134	1	9	2	31,708	126	1,220	301	0.84
A340-500	88	1	14	3	44,874	138	1,778	375	0.87
B787-900	53	1	20	4	53,288	264	1,885	250	0.81
A330-200	-	-	-	-	-	-	-	209	-
A380	-	-	-	-	-	-	-	553	-
B747-8	-	-	-	-	-	-	-	467	-
B777-300ER	-	-	-	-	-	-	-	365	-

The optimum number of frequencies ($freq_r$*) is high, it is not only because this study case do not have a maximum limit of $freq_r$. It is also because the values of Γ are high. In the first and second study cases, the values of the parameter Γ were calculated using the DOT US Consumer Report [2005] data. These links were selected using the CFEM and PEM models in routes without LCC operations. In FSC's routes, the values of the parameter Γ are expected to be high because FSC's passengers are willing to pay more to get more frequent services, at pick time hours, and spend less time on the journey.

The results show the capacity of the model for designing different airline networks depending on the aircraft type with the objective of maximize the designed network NPV. The number of aircraft (NAIR) to buy, and what links to operate according to the links that aircraft can fly are also determined by using the model. The model resolves the Q_r*, load factor per link (LF_r), and the network average LF.

The values of the LF determined by the model per aircraft type (Figure 7.1) prove that the model works since they are not equal 1. If these values would be equal 1, it would be difficult to affirm that the model is optimizing, because the model would be providing an amount of NS_r that 100% fulfill the amount of passengers, what would not be consistent with the results show in the analyses of the demand function model (Equation 5.1) studied in Chapter 5. In that chapter, the demand function model was used to estimate Q_r. Equation 5.1 contains parameters that represent the supply of NS_r and the average number of aircraft seats (S_a) per airline affected by an exponent parameter per airline type (π_a). In short-haul routes, LF's cannot be equal 1 because the correlation between NS_r and Q_r is not 1 for the real data.

It is important to clarify that the financial constraints and the maximization of the network NPV are actually working. In this case, the network with the maximum profit without financial constraints is designed for the A321. The profit of the network designed for the A321 is 5.84 billion usd without financial constraints, whilst the profit of the network designed for the E195 is 5.61 billion usd without financial constraints. In these networks, some routes have negative NPV's. These routes increase profits if they are not canceled. The results demonstrate the importance of the financial constraints, and why the objective function must be to maximize the NPV of the networks rather than the profit of the network.

The estimated number of employees to operate the network (Figure 7.2) is 646. Table 7.2 shows the total number of employees per employment type. The numbers are calculated using Equation 6.109 with the LCC constant C_4 values show in Table 6.8.

Table 7.2 The total number of employees to operate the network E195 (Figure 7.2)

Employee concept	*Number*	*Employee concept*	*Number*	*Employee concept*	*Number*
Management	19	Pax Handling	131	Handling	110
Pilots	117	Cargo Handling	7	Aircraft Control	6
General Services	159	Trainees and Instructors	2	Traffic Solicitors	2
Maintenance	30	Stats	16	Other	47

7.1.2 Short-haul low-cost case limited number of frequencies

Second short-haul study case: the optimization is performed constraining to 14 as a maximum number of frequencies per link per week.

Table 7.3 contains the results of the optimization per aircraft type. The results indicate that the NPV value is higher for medium size aircraft, with a capacity of 186 pax, than for larger or small aircraft. In this study case, the maximum number of $freq_r$ is equal 14 freq per week. The best aircraft is the B737-800. According to the optimization results (Table 7.3) using a B737-800, in T = 20 years, the NPV is equal to 1.40 billion usd earning 4.49 billion in profits. This aircraft operates 3 routes serving a total of 45 links with 10 aircraft attending 69,993 pax per week.

Table 7.3 Short-haul network case after optimization max frequency equal 14 results

Second case Real Γ and max Freq equal 14	*NPV (mill)*	*Num of routes*	*Num of links*	*NAIR*	*Q per week*	*Freq per week*	*Total Profits (mill)*	*S*	*LF*
B737-800	1,397	3	45	10	69,993	514	4,492	186	0.73
B737-900	1,312	4	43	11	69,667	486	4,595	200	0.72
B737-700	1,293	3	48	10	65,918	554	4,017	150	0.79
B737-600	1,217	2	50	10	63,986	584	3,638	132	0.83
A319	1,171	3	48	11	68,407	556	4,127	156	0.79
A320	1,163	2	43	9	63,202	496	3,927	161	0.79
A321	1,184	3	37	9	66,431	444	4,239	220	0.68
E195	1,095	3	38	8	40,221	512	2,914	105	0.75
E190	986	3	38	8	37,943	514	2,653	94	0.79
A340-300	841	1	15	3	53,185	166	3,168	440	0.73
E175	839	3	38	7	21,459	516	2,215	78	0.53
A330-300	766	1	15	3	53,249	164	3,161	440	0.74
A318	724	3	48	11	57,377	556	2,937	117	0.88
E170	716	3	38	7	30,329	516	1,929	70	0.84
A350-1000	530	1	18	3	52,043	198	2,911	350	0.75
A350-900	510	1	21	3	53,224	222	2,673	314	0.76
B767-200ER	461	2	27	4	48,939	302	2,113	181	0.90
A350-800	423	1	21	3	49,416	224	2,308	270	0.82
EMB145	331	2	35	6	11,292	486	973	45	0.52
B787-800	310	2	29	4	59,456	294	2,141	237	0.85
ERJ140	243	3	31	5	8,369	426	719	39	0.50
B787-900	217	1	20	3	46,178	216	1,775	250	0.86
B767-300ER	202	1	21	4	41,546	234	1,750	200	0.89
EMB135	148	3	32	5	7,358	440	495	34	0.49
B777-200	117	1	9	2	28,698	110	1,184	301	0.87
A340-500	80	1	14	3	42,866	128	1,763	375	0.89
A330-200	-	-	-	-	-	-	-	209	-
A380	-	-	-	-	-	-	-	553	-
B747-8	-	-	-	-	-	-	-	467	-
B777-300ER	-	-	-	-	-	-	-	365	-

Figure 7.3 shows the short-haul low-cost US Domestic market network after optimization with maximum limited number of flights, freq = 14, between airports/cities. Figure 7.3 shows the network after optimization for the B737-800 aircraft. The total number of links that do not represent an opportunity to open services is 36 links (Figure 7.3, yellow). Route 1 is formed by 24 links (Figure 7.3, red). Route 2 is formed by 19 links (Figure 7.3, blue), and Route 3 is formed by 2 links (Figure 7.3, black). The total network $ROI_{NTW,B737\text{-}800}$ is equal to 173%. Route 1 $ROI_{NTW,B737\text{-}800}$ = 218% with an $IRR_{NTW,B737\text{-}800}$ = 32% (Figure 7.3, red). Route 2 $ROI_{NTW,B737\text{-}800}$ = 158% with an $IRR_{NTW,B737\text{-}800}$ = 26% (Figure 7.3, blue), and Route 3 $ROI_{NTW,B737\text{-}800}$ = 6% with an $IRR_{NTW,B737\text{-}800}$ = 9% (Figure 7.3, black).

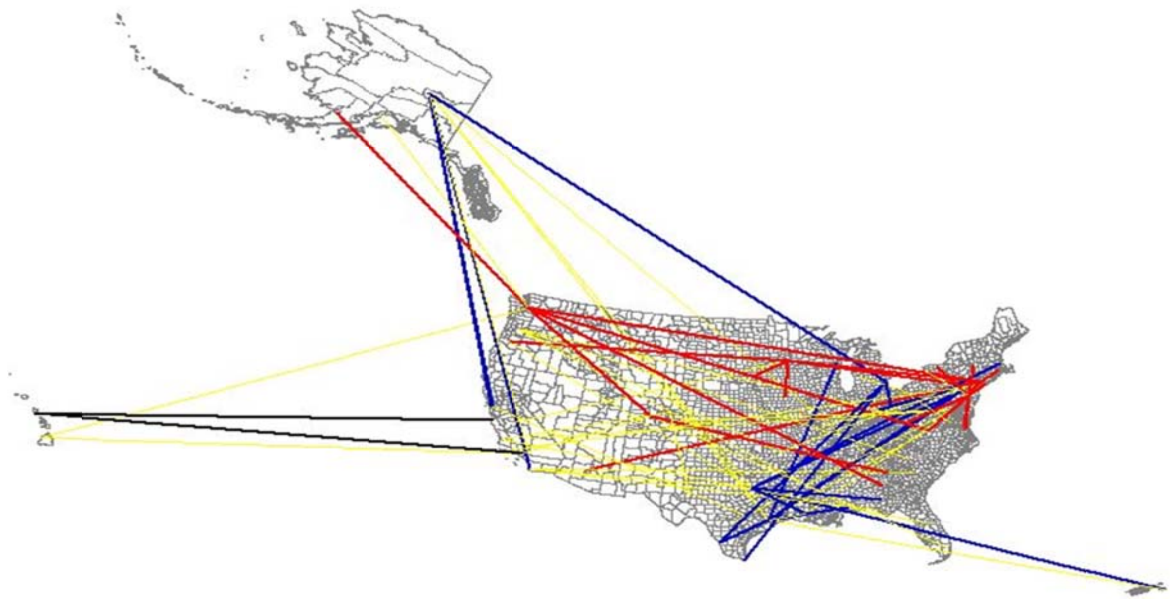


Figure 7.3 Short-haul network case after optimization max link freq equal 14, B737-800

The calculations of the NPV's per aircraft type show the second study case values to be less than in the first study case, what is logical because this study case is constrained to maximum 14 $freq_r$. The optimum number of passengers (Q_r*) to serve per week is less than in the study case 1. The average number of $freq_r$ to serve reduced from 13 flights (first case) to 8 flights. In the first study case, 13 is the average number of $freq_r$ between all routes that form the network, but not the number of $freq_r$ calculated for each link. It means some routes links frequencies are over 14 $freq_r$ per week and others are less than 14 $freq_r$ per week. In the second case, all links has less than 14 flights per week. The results validate the optimization, since the reduction in the average number of $freq_r$ concludes less number of $freq_r$ operated per route link between the first and the second study cases.

The optimization model selected the B737-800 as best option. It is a larger aircraft than the E195. The model is determining more seats (S) per flight in order to increase the NS_r supplied because it is not possible to serve more $freq_r$ than 2 (4 flights) per day. The model is trying to satisfy as much Q_r demand as it can by supplying more S per flight. In this case, the optimization result could be confronted because other aircraft have more seats than the B737-800. The model determines a medium size aircraft because of the value of the parameter Γ per link. Γ's are the same as in the study case 1, and the model tries to satisfy the high demand for flights as well as to provide services to the maximum possible number of pax.

The fact that the model determines more number of links to be operated with medium aircraft, such as the B737-800, than for the cases of small aircraft, such as the E195, point out that the model considers the capacity of aircraft to operate different links. At the same time, networks designed for small aircraft have more routes, with few links, than for networks designed for medium aircraft. It points out that the model considers the capacity of aircraft to fly different routes. The network before optimization (Figure 7.1) has links that are long for the capacities of small aircraft. It is correct that the model determines a higher number of links to be operated by the medium aircraft, and a higher number of routes formed for networks designed for small aircraft. At the same time, it is correct that the model do not find so many routes to be operated by larger aircraft because they satisfy their Q_r* with less flights. Their operating costs are higher than medium aircraft, and revenues are not higher than costs.

The values of the LF_r determined by the model prove that the model optimizes since they are not equal 1. It is a realist study case since it is constrained to a maximum limit of $freq_r$. The model determines the supply of NS_r in the network to be higher than the total number of Q_r transported in the whole network. Then, the optimization model proves to be consistent with the demand function results presented in Chapter 5. The fact that some LF's are very low (Figure 7.1 and Table 7.2) is because these study cases are based on FSC's. The values of the parameter Γ are for FSC's, without competition with LCC's, where fares are higher than fares calculated by the CFEM model, and the data comes from passengers that are willing to pay more demanding more services. LCC's passengers are expected to be lower than these values of the parameter Γ because they are not willing to pay more for more flights, with better services, and at pick hours. If the values of the parameter Γ are low, the optimization model determines low $freq_r$. Then, the best designed network needs to be operated by medium aircraft. It will increase the number of Q_r and the LF_r per flight.

Finally, the results prove that the model optimizes because the model determines different Q_r* to be transported by different aircraft types in order to find the highest NPV. If the model would not be optimizing, all aircraft would provide service to the induced demand (Q_r). Especially in the first study case because there is no limited number of $freq_r$ and the only thing airlines need to do is buying aircraft to provide enough NS_r.

The validation of the model cannot be demonstrated numerically because data is not available to compare. Airlines do not share specific data per each link they operate. They also do not share aircraft flying paths. If data would be available the effect of the optimization can only compare the NPV value of the network, designed by the model using a certain aircraft type, with the NPV value from airline data, for the same network configuration, finding the optimization results to be higher than the airline NPV. It is compulsory that the optimization conditions are the same. For example, duty free and other revenues must be plus to the profits in the optimization data or subtract from real data. Otherwise, the NPV is not calculated in equal conditions. The validation of the model can be assumed by the analyses of the results presented by study case 1 and 2.

Based on the model characteristics, parameters, and constraints it is possible to conclude that the model optimize, design airline network, and identifies routes that are opportunities to open services, based on airline operating costs, passenger demand, aircraft and airport capacities and constraints.

The total number of employees to operate the network is 766. Table 7.4 shows the estimated number of employees per employment type.

Table 7.4 Total number of employees to operate the network B737-800

Employee concept	*Number*	*Employee concept*	*Number*	*Employee concept*	*Number*
Management	22	Pax Handling	155	Handling	131
Pilots	139	Cargo Handling	9	Aircraft Control	7
General Services	188	Trainees and Instructors	2	Traffic Solicitors	2
Maintenance	36	Stats	19	Other	56

7.2 Long-haul low-cost model proposition and hypothetical case of study

After reviewing different business models and strategies, in Chapter 2, a concept of a low-cost long-haul business model has been developed based on literature review. The main objective is to keep the cost down and passenger number up by offering low fares. Thus, fares have been found to be the main parameter or variable that could be actively used to attract long-haul passengers.

The main idea is that long-haul low-cost carriers should concentrate on connecting different LCC's short-haul networks (at least two) Figure 7.4. The low-cost long-haul airline works as a feeder airline for two or more LCC short-haul networks far away. Since LCC's network system is organized in a point-to-point routing system, it is important to identify those airports where the LCC's have more connections, and more passenger flow demand. These airports are selected as connection points for the long-haul low-cost carrier. Thus, the new airline connects different airports with a hub and spoke (HS) routing system, which is essential for long-haul operations. The application of the HS is expected to increase the passenger flow, helping the airline to achieve enough number of passengers required to operate at least one frequency per day using a specific aircraft type. Passengers will have to do the electronic connectivity, passenger and baggage handling by themselves to solve the problem of connecting passengers between LCC's.

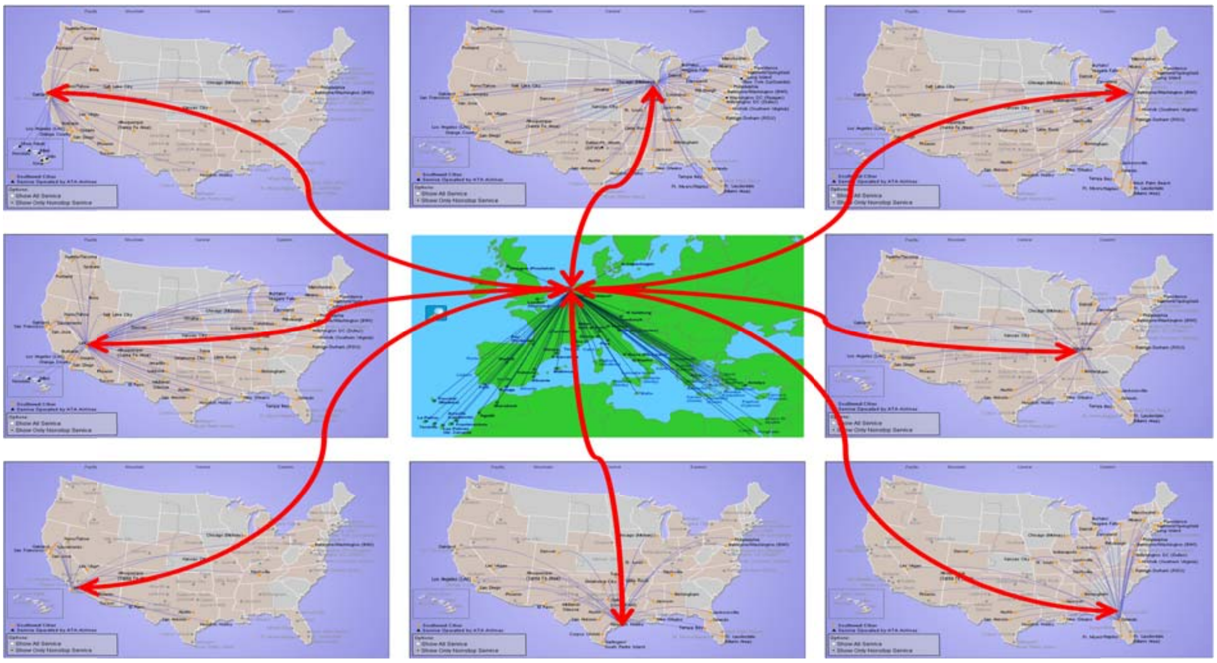


Figure 7.4 Transavia and WN long-haul networks connection [Airlines Routes Maps]

The main strategy is to identify short-haul routes that have enough induced demand and can be served by LCC's, where FSC's are charging high fees. The purpose of the long-haul subsidiary is just to feed and connect LCC's networks. Thus, the long-haul carrier just needs to price equal to operational costs to avoid losses and achieve profitability by selling extra services. The advantage is that FSC's have to keep their quality services what means high costs, less profit. Another advantage is that LCC's achieve higher profits in short-haul markets and the increase of the pax flow in short-haul routes could represent more profits and the possibility to enter in the long-haul market. Table 7.5 summarizes the low-cost model proposition.

Table 7.5 Low-cost long haul model proposition[18]

Long haul low cost characteristics	*Long Haul Low Cost Model Strategies*	*Advantage*
General Strategy	LCC short haul networks connected by a long haul carrier subsidiary	Feeder airline for LCC short haul networks
Scale	As large as the number of point connections and frequencies	That depends on the number of airports to be connected
Model Operations	Multi-hub and spoke	Airports where LCC's have more connections and passenger flow
	Long haul flights	More than 6 hours
	High aircraft capacity utilization	Over 15 hours
	High aircraft load factor	Over 80%
	Uniform aircraft type (Boeing 787, Airbus 350 or Airbus 380)	Selection of the most convenient aircraft that satisfy the network system
	Not necessary hub airports, also secondary airports	Airports will need to have the proper infrastructure to operate big aircraft
	Primary and business classes	Apparently offering just economic class does not provide any advantage
	No need for fast turnarounds	Aircraft already stay longer time on the air but for routes under 7 hours a turnaround operation of less than 1 hour would be important
	Passenger pre allocation	Pre arranged seats
	Crew utilization	Use lower cost labor but leaving other services intact
Market	Offer lower quality frills free	Increase revenues charging for better meals
	Catering extra for	Increase revenues selling duty free
	In-flight entertainment	Increase revenues selling ancilliary services
	Frequent flier schemes	Maybe considered as more valuable
	Cargo	Cargo represents between 20 to 30% total revenues
	Passenger number of baggage's	Sell cargo service and charge per passenger baggage
Inventory management	Electronic tickets, no travel agency and internet booking or direct	The tickets have to be sold through the LCC or LCC's websites

7.2.1 Long-haul low-cost direct flights non hubs

In this section, the long-haul low-cost hypothetical case is optimized for direct flights between all airports in short-haul networks (Figure 7.5). The long-haul connects four airports/cities in Europe (Amsterdam, Berlin, Rome, and Sicilia) with four airports/cities in North America (Mexico City, Guadalajara, Tijuana, and San Francisco) and four airport/cities in South America (Brasilia, Sao Paolo, Buenos Aires, and Santiago). The network is formed by 57 links. Nine links are short-haul (Figure 7.5, red, blue, and green), and 48 links are long-haul (Figure 7.5, black). In this example, open skies are assumed just for long-haul flights as it is explained by the Freedom of the Air number 9th (Appendix A). These examples assumed that a long-haul airline can operate routes from different countries that are not its national country.

In this case, the optimization is performed for 4 different cases. Table 7.6 contains the results of the optimization for the best aircraft to operate the designed long-haul (LH) network and

[18] Table sources: Harbison and McDermott [2009], Humphreys et al [2007], Morrell [2008] and Maertens [2010]

each of the designed short-haul (SH) networks (North America, NA; South America, SA; Europe, EU). Short-haul flights never carry cargo, and aircraft flying in the LH network cannot fly in any of the three SH network.

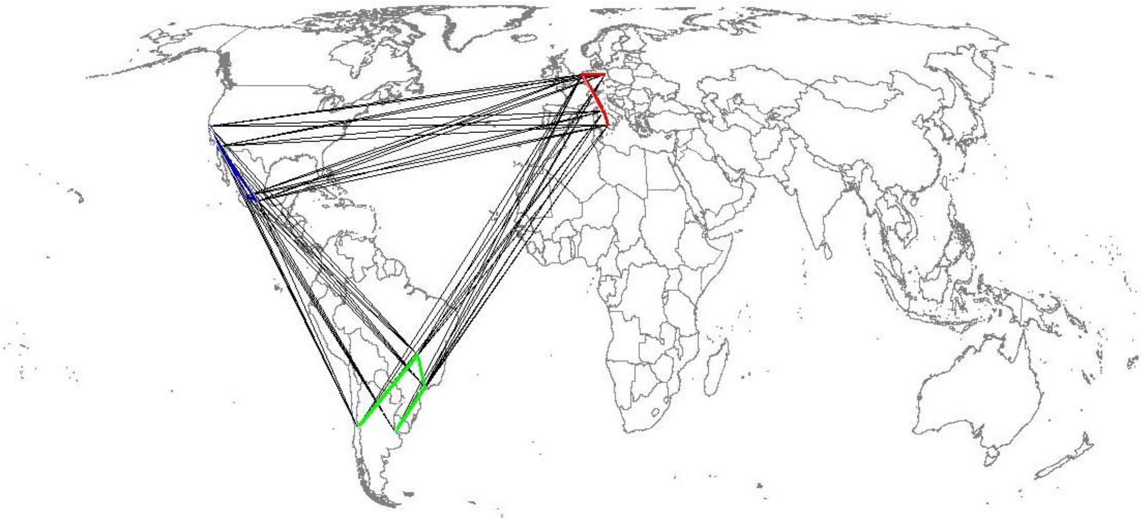


Figure 7.5 Long-haul low-cost hypothetical case, direct flights

Table 7.6 Long-haul low-cost direct connections non hubs results

Aircraft	*NPV (mill)*	*Num of routes*	*Num of links*	*NAIR*	*Q per week*	*Freq per week*	*Total Profits (mill)*	*ROI*	*IRR*	*Haul*	*S*	*LF*
Direct ; Γ = 1 ; without cargo (First long-haul study case)												
B737-900	395.51	1	3	1	10,800	54	980.45	461	57	EU	200	1.00
A321	218.19	1	3	1	7,480	34	647.56	219	32	NA	220	1.00
B737-900	271.45	1	3	1	8,400	42	727.74	316	42	SA	200	1.00
A380	203.24	1	48	4	27,650	50	3,472.01	14	10	LH	553	1.00
Direct ; Γ = 1 ; with cargo (Second long-haul study case)												
B737-900	395.51	1	3	1	10,800	54	980.45	461	57	EU	200	1.00
A321	218.19	1	3	1	7,480	34	647.56	219	32	NA	220	1.00
B737-900	271.45	1	3	1	8,400	42	727.74	316	42	SA	200	1.00
A350-1000	22,034.81	1	48	6	17,160	66	48,548.89	1,225	135	LH	350	0.74
Direct ; Γ = 200 ; without cargo (Third long-haul study case)												
E195	4,194.06	1	3	9	103,835	1,050	9,313.49	1,110	123	EU	105	0.94
E195	2,127.00	1	3	8	64,566	690	5,017.24	633	75	NA	105	0.89
B737-900	3,185.01	1	3	9	96,668	519	8,061.02	412	52	SA	200	0.93
										LH		
Direct ; Γ = 200 ; with cargo (Fourth long-haul study case)												
E195	4,194.06	1	3	9	103,835	1,050	9,313.49	1,110	123	EU	105	0.94
E195	2,127.00	1	3	8	64,566	690	5,017.24	633	75	NA	105	0.89
B737-900	3,045.28	1	3	9	94,588	525	7,776.38	412	52	SA	200	0.90
A350-1000	18,972.53	1	48	6	6,050	75	42,310.90	1,055	118	LH	350	0.23

First long-haul study case: long-haul flights do not carry cargo and the pax perception of travelling in cost unit (Γ) is equal 1 for all routes in all networks, direct flights.

In this case, the airline network designed is shown by Figure 7.5. The network did not change because all LH and SH routes are operated. The optimization model selected the airbus A380 for the designed LH network (Figure 7.5, black). The optimization model selected the A321 for the designed NA SH network (Figure 7.5, blue). The optimization model selected the B737-900 for designed EU and SA SH networks (Figure 7.5, red and green). According to the optimization results (Table 7.6) using an A380, in T = 20 years, the NPV for the LH is equal to 0.40 billion usd earning 3.47 billion in profits. This aircraft operates 48 routes serving a total of 48 links with 4 aircraft attending 27,650 pax per week. The LH network $ROI_{NTW,A380}$ = 14% with an $IRR_{NTW,A380}$ = 10%. The EU network $ROI_{NTW,B737\text{-}900}$ = 461% with an $IRR_{NTW,B737\text{-}900}$ = 57%. The NA network $ROI_{NTW,A321}$ = 219% with an $IRR_{NTW,B737\text{-}900}$ = 32%. The SA network $ROI_{NTW,B737\text{-}900}$ = 316% with an $IRR_{NTW,B737\text{-}900}$ = 42%.

Second long-haul study case: long-haul flights carry cargo and the pax perception of travelling in cost unit (Γ) is equal 1 for all routes in all networks. Short-haul flights never carry cargo, direct flights.

In this case, the airline network designed is also shown by Figure 7.5. The network did not change because all LH and SH routes are operated. However, this network NPV, profits, pax to attend, frequencies to supply and number of aircraft to operate increased in comparison with LH case 1. The optimization model selected the airbus A380 for the designed LH network (Figure 7.5, black). The optimization model selected the A321 for the designed NA SH network (Figure 7.5, blue). The optimization model selected the B737-900 for the designed EU and SA SH networks (Figure 7.5, red and green). According to the optimization results (Table 7.6) using an A350-1000, in T = 20 years, the NPV for LH network is equal to 22.03 billion usd earning 48.55 billion in profits. This aircraft operates 48 routes serving a total of 48 links with 6 aircraft attending 17,160 pax per week. The LH network $ROI_{NTW,A350\text{-}1000}$ = 1,225% with an $IRR_{NTW,A350\text{-}1000}$ = 135%. In this case, short-haul network results are the same as in the first case because the conditions stay the same, what it has to be because the SH networks did not change, the only difference between this study case and the first case is in the LH network.

Third long-haul study case: long-haul flights do not carry cargo and the pax perception of travelling in cost unit (Γ) is equal 200 for all routes in all networks. Short-haul flights never carry cargo, direct flights.

In this case, the airline network designed is shown by Figure 7.6. The network changes because all the routes in the LH network do not represent opportunities to open services. The results indicate that it is better not to operate the LH network than operate it. It is because pax are willing to pay higher fares and airlines needs to provide more frequencies. In this case, a long-haul low-cost company is not needed since pax are not demanding low fares. In short-hauls, the network NPV, profits, pax to attend, frequencies to supply and number of aircraft to operate increased, in comparison with LH study cases 1 and 2, because the demand for more frequencies increase as Γ increases. In short-haul, the model selected the E195 aircraft for the designed EU and NA networks, and the B787-900 for the designed SA network. Route EU $ROI_{NTW,E195}$ = 1,110% with an $IRR_{NTW,E195}$ = 123% (Figure 7.6, red). Route NA $ROI_{NTW,E195}$ = 633% with an $IRR_{NTW,E195}$ = 75% (Figure 7.6, blue), and Route SA $ROI_{NTW,B737\text{-}900}$ = 412% with an $IRR_{NTW,B737\text{-}900}$ = 52% (Figure 7.6, green).

Figure 7.6 shows the airline network designed for the third case. The total number of links that do not represent an opportunity to open services is 48 links (Figure 7.6, yellow). The EU network is formed by 3 links (Figure 7.6, red). The NA network is formed by 3 links (Figure 7.6, blue), and the SA network is formed by 3 links (Figure 7.6, green).

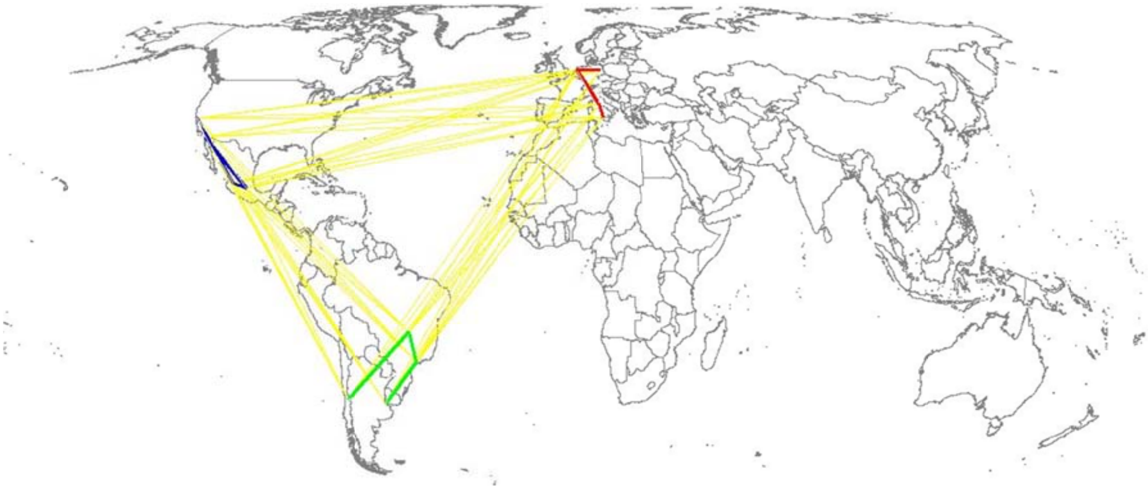


Figure 7.6 Long-haul low-cost hypothetical case, direct flights

Fourth long-haul study case: long-haul flights carry cargo and the pax perception of travelling in cost unit (Γ) is equal 200 for all routes in all networks. Short-haul flights never carry cargo, direct flights.

In this case, the airline network designed is also shown by Figure 7.5. The network did not change because all LH and SH routes are operated. However, the increase of the value of the parameter Γ in the case of the LH network in respect to the second case, the NPV, profits, and pax to attend decrease, the number of frequencies to supply increased, and the number of aircraft to operate stays the same. The optimization model selected the airbus A350-1000 for the designed LH links (Figure 7.5, black). The optimization model selected the E195 for the designed EU and NA links (Figure 7.5, red and blue), and the optimization model selected the airbus B737-900 for the designed SA network (Figure 7.5, green). According to the optimization results (Table 7.6) using an A350-1000, in T = 20 years, the NPV for LH network is equal to 18.97 billion usd earning 42.31 billion in profits. This aircraft operates 48 routes serving a total of 48 links with 6 aircraft attending 6,050 pax per week. The LH network $ROI_{NTW,A350-1000}$ = 1,225% with an $IRR_{NTW,A350-1000}$ = 37%. In this case, short-haul network results are the same as in the first case because the conditions stay the same, what it has to be because the SH networks did not change, the only difference between this study case and the last one is in the LH network by carrying cargo.

Study cases long-haul non hubs direct flights non hubs analysis of the results

The calculations of the short-haul networks NPV's per aircraft type show lower NPV's than in the short-haul cases study cases (Chapter 7.1). It is because the demand of $freq_r$ is low, since Γ = 1. The values of the parameter Γ determine that the desire of passengers for buying tickets is low. It has a direct effect on the Q_r*. Whether the values of the parameter Γ are low, the interest of an airline for operating links in these kinds of networks must be low. The results are consistent with Equation 6.5. This equation determines $freq_r$* to operate according to aircraft operating costs, demand of air transport services, and the desire of passengers for buying tickets. The results point out that airlines are willing to provide more $freq_r$ as Γ increases, and the increment of Γ means passengers are willing to buy tickets and pay more. Since the results of the optimization show low NPV's, it suggests that low fares do not achieve high revenues. It forces airlines to increase revenues selling other products or minimize operating costs what has been explained to be very complicated for long-haul flights (Chapter 2).

Analyzing the results from the passenger's point of view (Equation 6.6) if the average value of Γ increases because they are demanding more $freq_r$ and willing to pay high fares, at some point, the demand will cause fares to increase because the supply of seats will be less than the Q_r* demand. Then, Γ will start decreasing Q_r*. The results are very important because it demonstrates the model holds the economic law of supply and demand, and price and quantity.

There is a maximum value of Γ where the model revenues are not going to be enough to overcome the investment and the model will cancel links, routes and networks. This situation happens in the fifth study case. In this case, passengers are willing to pay high money for travelling the route by having more frequencies. In this study case, the cost of providing the number of frequencies that passengers are demanding is more expensive than the revenues they can generate from fares determined by the CFEM model (competitive low fare). Then, revenues cannot be higher than the investment, and the model canceled the possibility of all aircraft to operate any possible network that can be designed for the long-haul links under study without carrying cargo. Contrary, study case number six is the same case as number five, but this time carrying cargo in long-haul. It is possible to conclude that cargo is what makes airlines earn money in long-haul business. It can be proved by comparing study case 3 with 4, and 5 with 6.

Study case 3 and 4 indicate that in routes with very few demand when passenger are not willing to pay big money for buying tickets, a possibility appears to exist, especially when cargo is transported. The difference between carrying and not carrying cargo is enormous, reason why it appears to be a possibility, but this is a strategy already performed by FSC's.

The optimization model determines that in order to earn the NPV's, the LF_r must be equal 1. It is forcing the airlines to buy all seats per flight. When airlines sell cargo, revenues increase and the LF_r goes down because the Q_r* to serve does not need to be high since cost are cover by revenues from cargo. Transporting cargo increases revenues over the investment without the pressure of selling all tickets. The fact that $freq_r$ increased and Q_r* decreased confirms that cargo is a better business than transporting passengers. In this case, the LF is very low because flying aircraft full of cargo is a better business. This is a result that confirms that the model optimize, since the model is determining that cargo is a better business something that the air transportation industry knows very well.

7.2.2 Long-haul low-cost passenger's connections through hubs

In this section, the long-haul low-cost hypothetical case is optimized for connecting flights through hubs (Figure 7.7). The long-haul connects four airports/cities in Europe (Amsterdam, Berlin, Rome, and Sicilia) with four airports/cities in North America (Mexico City, Guadalajara, Tijuana, and San Francisco) and four airport/cities in South America (Brasilia, Sao Paolo, Buenos Aires, and Santiago) through hubs (Amsterdam, Mexico City, and Sao Paolo). The network is formed by 12 links. Nine links are short-haul (Figure 7.7, red, blue, and green), and 3 links are long-haul (Figure 7.7, black). In this example, open skies are assumed as it is explained by the Freedom of the Air number 9^{th} (Appendix A). In this example, it is assumed that a long-haul airline company can operate routes from different countries and regions that are not its national country, but they cannot operate short-haul networks in other regions. In Appendix N, Equation Appendix N.1 determines the total pax flow demand for air transportation service per route link, and Equation Appendix N.2 determines the passenger fare per route link.

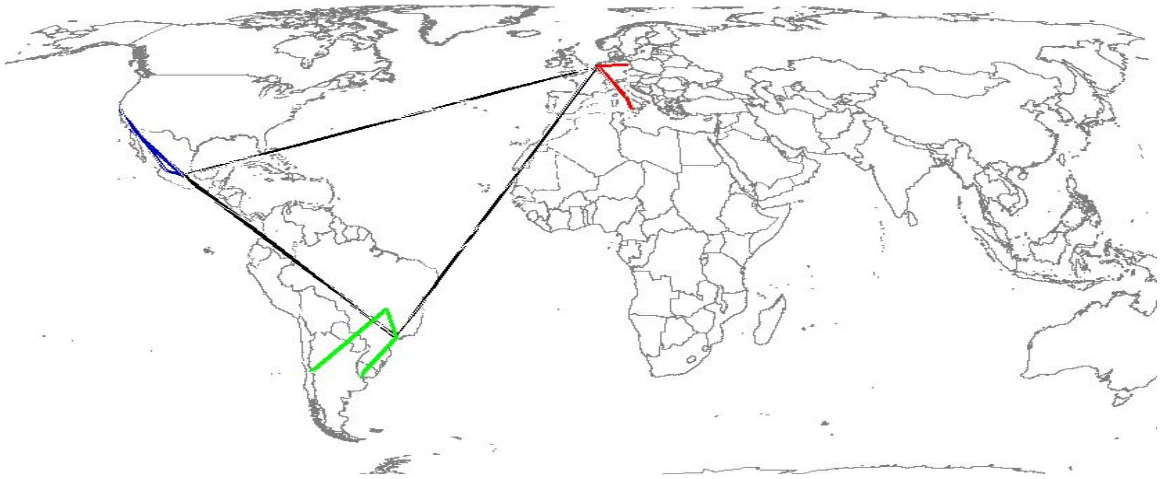


Figure 7.7 Long-haul low-cost connections through hubs

In these cases, the optimization is performed for 4 different Γ values (1, 50, 100, and 200). Γ values are constant for all links. In reality, it may be different per link. Aircraft can carry cargo for the LH network, and passengers are connected through hubs. It allows passengers to travel between all airports in the network. Links pax flows and fares may change. The purpose is to use the optimization model to maximize the net present value (NPV) between three short-haul low-cost networks connecting by three hubs. For simplicity, the links with the highest pax flow demand between SH networks are used to connect the SH networks. In these study cases, these airports are Amsterdam, Mexico City and Sao Paulo.

LH network is formed by 3 links connecting 3 airports. Short-haul networks are formed by 3 links connecting 4 airports in three different regions. Long-haul flights can carry cargo, and short-haul flights cannot carry cargo. Table 7.7 contains the results of the optimization for the best aircraft to operate the long-haul (LH) network and each of the short-haul networks (North America, NA; South America, SA; Europe, EU) through hubs connections.

Fifth long-haul study case: the pax perception of travelling in cost unit (Γ) is equal 1 for all routes in all networks. LH network carry cargo. Short-haul flights never carry cargo, passenger are connected through hubs.

In this case, the airline network designed is shown by Figure 7.7. The network did not change because all routes are operated. The optimization model selected the airbus A350-1000 for the designed LH network (Figure 7.7, black). The optimization model selected the B737-900 for the designed EU SH network (Figure 7.7, red, blue, and green). The optimization model selected the A321 for the designed NA and SA SH networks (Figure 7.7, blue and green). According to the optimization results (Table 7.7) using an A350-1000, in T = 20 years, the NPV for LH is equal to 0.45 billion usd earning 1.26 billion in profits. This aircraft operates 3 links with 2 aircraft attending 14,280 pax per week. The LH network $ROI_{NTW,A350\text{-}1000}$ is equal to 85% with an $IRR_{NTW,A350\text{-}1000}$ = 18%. The EU network $ROI_{NTW,B737\text{-}900}$ = 397% with an

$IRR_{NTW,B737-900}$ = 51%. The NA network $ROI_{NTW,A321}$ = 433% with an $IRR_{NTW,A321}$ = 54%. The SA network $ROI_{NTW,A321}$ = 381% with an $IRR_{NTW,A321}$ = 49%. All networks are shown by Figure 7.7.

Table 7.7 Long-haul low-cost passenger's connections through hubs results

Aircraft	*NPV (mill)*	*Num of routes*	*Num of links*	*NAIR*	*Q per week*	*Freq per week*	*Total Profits (mill)*	*ROI*	*IRR*	*Haul*	*S*	*LF*
Hubs; Γ = 1												
B737-900	680.98	1	3	2	18,900	90	1,736.74	397	51	EU	210	1.00
A321	400.56	1	3	2	14,080	64	1,222.14	433	54	NA	220	1.00
A321	414.04	1	3	2	14,520	66	1,249.61	381	49	SA	220	1.00
A350-1000	446.31	1	3	2	14,280	68	1,258.72	85	18	LH	260	0.81
Hubs; Γ = 50												
A321	4,923.14	1	3	9	131,560	598	11,856.50	549	66	EU	220	1.00
A321	3,452.51	1	3	8	99,880	454	8,657.66	433	54	NA	220	1.00
A321	3,418.95	1	3	9	102,080	464	8,792.39	381	49	SA	220	1.00
A380	1,044.61	1	3	7	50,876	92	7,479.44	42	6	LH	553	1.00
Hubs; Γ = 100												
B737-900	6,739.38	1	3	12	176,400	882	15,825.76	655	77	EU	200	1.00
B737-900	4,685.03	1	3	11	133,600	668	11,466.18	496	61	NA	200	1.00
A321	4,922.37	1	3	12	144,760	658	12,464.21	411	52	SA	220	1.00
B747-8	1,372.71	1	3	11	67,248	144	9,950.99	9	4	LH	467	1.00
Hubs; Γ = 200												
A321	9,619.66	1	3	16	249,600	1,248	22,392.12	701	82	EU	220	0.91
B737-900	6,583.03	1	3	16	188,800	944	16,206.38	480	59	NA	200	1.00
A321	6,378.50	1	3	17	197,534	928	16,445.88	376	48	SA	220	0.97
B747-8	1,475.14	1	3	16	95,268	204	13,411.78	29	12	LH	467	1.00

Sixth long-haul study case: the pax perception of travelling in cost unit (Γ) is equal 50 for all routes in all networks. LH network carry cargo. Short-haul flights never carry cargo, passenger are connected through hubs.

In this case, the airline network designed is shown by Figure 7.7. The network did not change because all routes are operated. The optimization model selected the airbus A380 for the designed LH network (Figure 7.7, black). The optimization model selected the A321 for the designed SH networks (Figure 7.7, red, blue, and green). According to the optimization results (Table 7.7) using an A380, in T = 20 years, the NPV for the designed LH network is equal to 1.04 billion usd earning 7.48 billion in profits. This aircraft operates 3 links with 7 aircraft attending 50,876 pax per week. The LH network $ROI_{NTW,A380}$ is equal to 42% with an $IRR_{NTW,A380}$ = 6%. The EU network $ROI_{NTW,A321}$ = 549% with an $IRR_{NTW,A321}$ = 66%. The NA network $ROI_{NTW,A321}$ = 433% with an $IRR_{NTW,A321}$ = 54%. The SA network $ROI_{NTW,A321}$ = 381% with an $IRR_{NTW,A321}$ = 49%. All networks are shown by Figure 7.7.

Seventh long-haul study case: the pax perception of travelling in cost unit (Γ) is equal 100 for all routes in all networks. LH network carry cargo. Short-haul flights never carry cargo, passenger are connected through hubs.

In this case, the airline network designed is shown by Figure 7.7. The network did not change because all routes are operated. The optimization model selected the airbus B747-8 for the designed LH network (Figure 7.7, black). The optimization model selected the B737-900 for the designed EU and NA SH networks (Figure 7.7, red and blue). The optimization model selected the B737-900 for the designed SA SH network (Figure 7.7, green). According to the optimization results (Table 7.7) using a B747-8, in T = 20 years, the NPV for the designed LH network is equal to 1.37 billion usd earning 9.95 billion in profits. This aircraft operates 3 links with 11 aircraft attending 67,248 pax per week. The LH network $ROI_{NTW, B747\text{-}8}$ is equal to 9% with an $IRR_{NTW,B747\text{-}8}$ = 4%. The EU network $ROI_{NTW, B737\text{-}900}$ = 655% with an $IRR_{NTW, B737\text{-}900}$ = 77%. The NA network $ROI_{NTW, B737\text{-}900}$ = 433% with an $IRR_{NTW, B737\text{-}900}$ = 54%. The SA network $ROI_{NTW, A321}$ = 381% with an $IRR_{NTW,A321}$ = 49%. All networks are shown by Figure 7.7.

Eight long-haul study case: the pax perception of travelling in cost unit (Γ) is equal 200 for all routes in all networks. LH network carry cargo. Short-haul flights never carry cargo, passenger are connected through hubs.

In this case, the airline network designed is shown by Figure 7.7. The network did not change because all routes are operated. The optimization model selected the airbus B747-8 for the designed LH network (Figure 7.7, black). The optimization model selected the A321 for the designed EU and SA SH networks (Figure 7.7, red, and green). The optimization model selected the B737-900 for the designed NA SH network (Figure 7.7, blue). According to the optimization results (Table 7.7) using a B747-8, in T = 20 years, the NPV for the designed LH network is equal to 1.48 billion usd earning 13.41 billion in profits. This aircraft operates 3 links with 16 aircraft attending 95,268 pax per week. The LH network $ROI_{NTW,B747\text{-}8}$ is equal to 29% with an $IRR_{NTW,B747\text{-}8}$ = 12%. The EU network $ROI_{NTW,A321}$ = 701% with an $IRR_{NTW,A321}$ = 82%. The NA network $ROI_{NTW,B737\text{-}900}$ = 480% with an $IRR_{NTW,B737\text{-}900}$ = 59%. The SA network $ROI_{NTW,A321}$ = 376% with an $IRR_{NTW,A321}$ = 48%. All networks are shown by Figure 7.7.

Study cases long-haul low-cost passenger's connections through hubs.
These study cases are analyzing the long-haul low-cost model proposed in this chapter. The frequencies in the LH networks are more than 1 frequency per day. It is important because the LH network needs to connect passengers flying to other destinations than hubs per day. Otherwise, passengers would need to pay a hotel night making the journey expensive. The total passenger flow increased in SH networks in comparison with the pax flow observed in the long-haul direct flights study cases. It is important because this is a good reason for LCC's at different networks to develop this business. The networks NPV's increase for short-haul networks and decrease for LH networks because more cargo can be transported in direct flights. In direct flights Q_r*'s are smaller than in connection flights, allowing more cargo space in aircraft. However, the business model designed is for pax transportation rather than cargo, cargo is extra revenue.

The main disadvantage is the differences between the proposed business model and a common FSC's long-haul operation. FSC's carry passengers and feed aircraft with cargo. The number of Q_r* transported for the study case Γ = 1 is between 10% and 20% the Q_r* transported the study cases with values over Γ = 50. Then, any FSC airline can operate the network offering 20% seats under discount, as they do today, to attract does passengers that have very low perception of travelling. These are passengers that do not care about frequencies or quality service. They just want to pay a little money for travelling.

Other disadvantage is that the long-haul business model with direct flights carrying cargo is a better business than connecting for the long-haul airline. In short-haul, connecting passengers is a better business because pax flow increase in the short-haul networks. However, the increase in NPV is not as it is for airlines operating long-haul flights carrying cargo.

The conclusion is not that the model does not work. The results indicate that there are no so much differences with the long-haul FSC model. Today, FSC's transport passenger with low perception of travelling through hubs increasing revenues and increasing LF's on their routes. The short-haul study cases determine that LF's are lower than 0.90 and with higher fares FSC's must have lower LF's than 0.90 because the results in this chapter indicate that when the perception of travelling is high, LF's are low. It gives FSC's the possibility to offer low fares to provide services to the 10% or 20% of this long-haul markets.

7.2.3 Long-haul low-cost whole network

Today, the hypothetical long-haul cases are impossible to be operated because flying from countries to other countries has regulations that forbid airlines to open flights connecting airports at any locations in the world. For example, Mexico does not allow any airline from other country to operate routes inside Mexico, and it is similar in many countries. However, this case scenario analyzes if a long-haul low-cost airline could be a business if complete open skies agreements would exist between countries. Figure 7.8 illustrates this network.

Finally, the ninth long-haul study case: All networks can be operated by one airline. Aircraft can fly the LH network and SH networks carrying cargo.

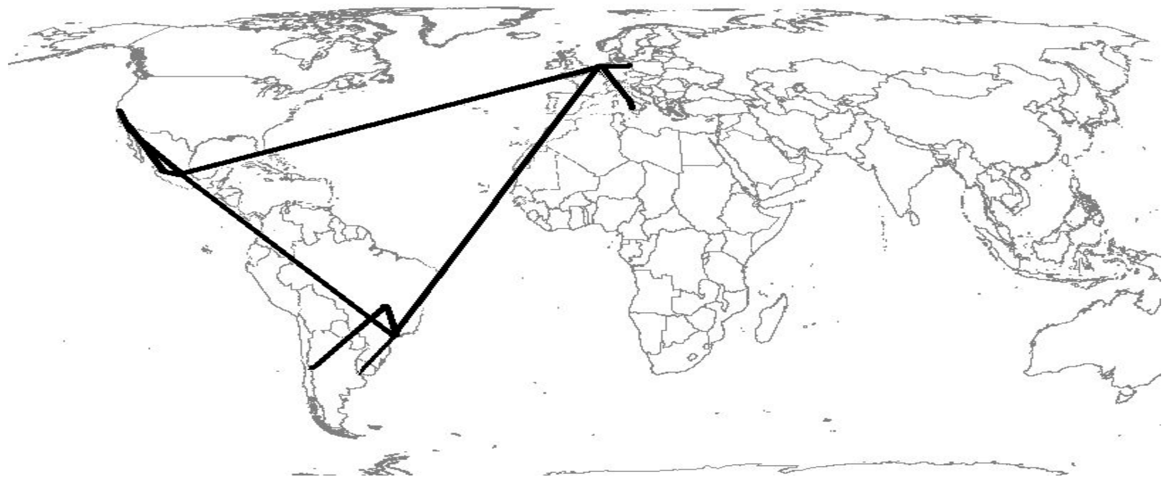


Figure 7.8 Long-haul low-cost model operate by one airline

Table 7.8 contains the results of the optimization for the best aircraft to operate the long-haul (LH) network and each of the short-haul networks (North America, NA; South America, SA; Europe, EU) through hubs connections.

In this case, the airline network designed is shown by Figure 7.8. The network did not change in the four study cases because all routes are operated. The optimization model selected the A350-1000 for the designed complete network (Figure 7.8) when the desire of the people of flying is very low, Γ = 1. The optimization model selected the A340-500 for the designed complete network (Figure 7.8) when the desire of the people of flying is medium, Γ = 50, high, Γ = 100, and Γ = 200 very high.

Table 7.8 Long-haul low-cost model operate by one airline

Aircraft	*NPV (mill)*	*Num of routes*	*Num of links*	*NAIR*	*Q per week*	*Freq per week*	*Total Profits (mill)*	*ROI*	*IRR*	*Haul*	*S*	*LF*
Hubs; Γ = 1												
A350-1000	1,577.76	1	12	4	44,720	172	5,655.97	132	23	ALL	260	1.00
Hubs; Γ = 50												
A340-500	5,527.65	1	12	23	375,000	1,000	23,525.93	92	19	ALL	375	1.00
Hubs; Γ = 100												
A340-500	7,354.81	1	12	33	531,000	1,416	32,580.91	85	18	EU	375	1.00
Hubs; Γ = 200												
A340-500	11,104.77	1	12	41	718,321	1,916	44,486.14	-	-	ALL	375	1.00

This study case represents a better business scenario. Aircraft increase utilization time because they are less time on the ground. It reduces the investment needed because airlines need to buy and operate few aircraft. The Q_r* to be transported increased. It shows attractive pax flows for any airline. It is a good business because FSC airlines transporting pax with cargo in direct flights also compete with cargo companies for cargo revenues. In this study case, the main advantage is the increment of pax flow produce by the increase of frequencies cause by the minimization of operating costs (Equation 6.5). However, this scenario is beneficial for all airlines, not only LCC's.

7.3 Discussion

In this chapter, the first objective was the validation of the optimization model. The validation was done by optimizing one short-haul low-cost network. The short-haul network is based on the analysis of the DOT US Consumer report [2005]. The routes forming the network before optimization were selected by the CFEM and FEM models in previous chapters, 81 routes. It is a study case base on real data.

The validation of the optimization model cannot be demonstrated numerically because data is not available to compare. Airlines do not share specific data per each link they operate. They also do not share aircraft flying paths. If data would be available the effect of the optimization can only compare the NPV value of the network, designed by the optimization model using a certain aircraft type, with the NPV value from airline data, for the same network configuration, finding the optimization results to be higher than the airline NPV. It is compulsory that the optimization conditions are the same. Otherwise, the NPV is not calculated in equal conditions. Then, the validation of the optimization model can be done with the help of real airlines, using detail data. However, the validation of the optimization model can be assumed by the analyses of the results presented in the short-haul study cases.

The results show the capacity of the optimization model for designing different airline networks depending on the aircraft type with the objective of maximize the designed network NPV. The optimization model selects the routes links that represent a possibility to open airline pax transportation services. It designs the network that achieves the maximum net present value and determines the optimum number of passengers to serve. The optimization model is successful in selecting the optimum aircraft type for a particular airline network according to number of seats, aircraft flying ranges, maximum weights and prices. The optimization model resolves the Q_r*, load factor per link (LF_r), and the network average LF.

The results validate that the optimization model parameters take into account physical parameters (distance, weights, aircraft specifications and maximum number of frequencies per route link) according to reality. The results demonstrated the importance of the financial constraints, and why the objective function must be the maximization of the NPV of the networks rather than the profit of the network.

Based on the optimization model characteristics, parameters, and constraints it is possible to validate that the optimization model is successful optimizing, and identifying routes that are opportunities to open services, based on airline operating costs, passenger demand, aircraft and airport capacities and constraints. It is also useful to design networks per aircraft type.

The second objective was a feasibility analysis of the long-haul business model proposed in this chapter. During recent years, the air passenger transportation industry has been thinking different strategies to develop the low-cost business model concept in long-haul operations. The short-haul low-cost business model has been so beneficial for the air passenger transportation industry in short-haul flight. In this chapter, a long-haul low-cost business model has been developed based on literature review. It is a hypothetical case scenario. Nine studies were performed. In four study cases, all airports in the network are connected by direct flights. In other four study cases, airports are connected through hubs. In the last study, aircraft can operate short-haul and long-haul routes in a complete deregulated market. The mathematical optimization model was used, as a tool, to analyze the feasibility of the long-haul business model proposed in this chapter. The model optimized the connection between short-haul low-cost airlines in different regions by a long-haul low-cost carrier.

The results confirm that direct flights carrying cargo are a better business than connecting passengers through hubs. It is very difficult to create an airline company that operates long-haul low-cost networks. These kinds of services need high pax flow demands. The business appears to be beneficial only for short-haul airlines. However, connecting passengers through hubs is an attractive business for short-haul networks. The connections of passenger increase pax flow on short-haul links. However, if the markets are totally deregulated the pax flow increase up to good levels. It increases the possibilities to develop the proposed model.

The study case that simulates the complete deregulation of the markets represents a better business scenario. It reduces the investment needed and the Q_r* to be transported increased. It shows attractive pax flows for any airline. It is a good business because FSC airlines transporting pax with cargo in direct flights also compete with cargo companies for cargo revenues. However, this scenario is beneficial for all airlines, not only LCC's.

In general, the study cases in this chapter showed that carrying cargo is what allows long-haul airlines to earn more money, but this business is already operated by FSC's and cargo companies.

The conclusion is not that the business model does not work. The results indicate that there are no so much differences with the long-haul FSC model. Today, FSC's transport passenger with low perception of travelling through hubs increasing revenues and increasing LF's on routes. It gives FSC's the possibility to offer low fares and provide services to the long-haul markets. The results indicate that the development of a long-haul low-cost is very unlikely.

8 Conclusions and future work

Government and customer request for opening economical services and new markets represent an opportunity for airlines to open new flights and new routes. Airlines invest a lot of money before opening new pax transportation services, for this reason, airlines have to analyze if their profits will be higher than the investment needed to open new services.

In this thesis, the main objective was to find routes and design networks that represent opportunities to open new air passenger transportation services. In other words, the main objective was to answer the question:

What passenger airline networks represent a business opportunity and are attractive for an airline to open new air services?

The dissertation has investigated the development of a tool to design profitable large scale airline networks base on mathematical modelling and optimization techniques. With the developed of different models, it was possible to answer the main thesis question and the questions posed at the beginning of this study, and develop a calculation tool with which airlines, governments, and airports are able to identify routes to deliver new services whilst assuring enough profitability to establish and ensure a successful business.

The developed models are tools that enable the identification of routes that represent an opportunity to open new air passenger transportation services. The models presented in this thesis also enable the identification of cities and airports to operate by assigning the most suitable type of aircraft according to the optimum number of passengers to serve, the optimum number of frequencies to operate, the desire of passengers to travel routes, aircraft characteristics, and airports airside and terminal side capacities and infrastructures.

In summary, the resulted developed optimization model contains mathematical models that forecast the induced demand or non served demand, calculates the most competitive ticket prices, and calculates aircraft and airline operating costs to find viable routes to open new services. The developed optimization model considers airport capacities and aircraft features as constraints to simulate the air passenger transportation system as close as it is possible to reality. The main variable of the optimization model is the routes frequencies. The developed optimization model objective function is the maximization of the designed network net present value by serving the optimum number of passengers from the forecasted induced or non served demand.

This study found that generally 10 questions must be solved to answer the main question. In particular, the models developed in this thesis respond to these questions:

- What are the main consequences of the competition between different airline business models FSC vs. LCC?

The study of the consequences of the competition between different airline business models was necessary to understand what routes were the possible routes to open services, and to find the parameters that determine the passenger demand, airline route fares, and airline operating costs. The analysis of the competition between airlines enabled to understand the airline passenger transport industry. Then, the result of the competition analyses is the CFEM model. This model is based on the fare competition analysis between airlines business models.

- What are the main parameters that determine airline route fares, airline operational costs and airport charges between two airports/cities?

The development of the airline operating cost model (AOC) and the fare estimation model (FEM) confirms the parameters that determine the ticket prices of an airline on a route. These models include most of the variables that have been found to determine airline route fares according to the statistic analyses. However, as it has been explained in question one, the results of this study indicate that distance is the only parameter really needed to calculate a route fare. Therefore, the parameters found to be routes fares determinants were not needed.

Mathematical models based on engineering approaches where found to be better solutions to solve this thesis questions.

- What are the main parameters that determine the passenger demand per route between two airports/cities?

The results confirm that the parameters that determine the demand for air passenger transport are considered in the so-called demand function. However, a main problem occurs when using a parameter that represents the supply in relation with the demand, in this case the total number of seats. It needs to be known. For the purpose of this study, it was not useful to know the parameters that determine the air passenger demand because the objective was to estimate the possible induced demand. The simulation of the air passenger transportation demand using a log-normal distribution and then the optimization of the net present value enabled calculating the optimum number of passengers to serve without using the parameters that are known to determine air passenger route demands.

- How much is the airline going to charge per route? What is the average fare per pax?

This study has found that routes fares can be calculated by using the route distance as the only parameter. The competitive fare estimation model calculates the most competitive fare and the expected range between airlines route fares by simulating the behaviour of the market using distance as the only parameter. The development of this model contributes evidence that the competition between airlines operating same routes or links can be studied with simple functions rather than using models that require searching for data that most of the times are not available. Besides, since the model calculates fares only using distance as a parameter, it is highly probable that the model can be used in other studies, and in other markets. Then, it is a model that can be used for other purposes and not only for the outcome of this research.

In the case of forecasting the increase of fares through the future, the results of the application of the Grey model predicting algorithm is satisfactory. This successful application of the GM model to forecast the consumer price index (CPI), and then the inflation (INF) in countries or cities or regions, confirms and provides additional evidence with respect to the power of the GM predicting algorithm to be used to forecast economic indicators.

- What is the demand of passengers between origin and destination?

The passenger estimation model (PEM) is a method developed in this thesis. It estimates routes market sizes and determines the possible induced demand answering this question. One significant contribution to emerge from the development of the PEM model is that this model is based in the simulation of the behaviour of the air passenger transportation demand by a log-normal distribution. The PEM model is an option to calculate routes pax flow as a first step. It could save airlines, airports and governments money because it is able to find routes that represent an opportunity before paying for marketing studies for all routes in a market. The PEM model can be used by governments, and airports, to analyze their catchment areas. With the results, they can make decisions of infrastructure grow and investment. Then, it is a model that can be used for other purposes and not only for the outcome of this research.

The present study provides additional evidence that the calculation of the number of passengers to transport per route cannot be base only on a forecast. In this thesis, the estimation of the frequency that maximizes the net present value of an airline network has been related to the parameter that determines the optimal number of passengers to serve. Then, the determination of the total passengers to serve is calculated during the optimization. The PEM model determines the induced or non serve demand, but this number of passengers may be or may not be the total number of passenger that an airline will attract. Normally, in literature forecasts are used assuming that airlines will attract all passengers determined by the forecast, which is wrong.

In the case of forecasting the demand of passenger through the future, the results of the application of the Grey model predicting algorithm indicate that this forecasting method, used in similar studies, does not determine reasonable pax flow using few measures historic data. In this thesis, a modification of the Grey predicting algorithm is proposed with successful results. With the modification, the Grey predicting algorithm estimates realistic routes pax flow when the historic data is few.

- What is the operating cost per route?

The aircraft operating cost (POC) model and the aircraft fuel consumption (AGE) model are models developed in this thesis. The models are a significant contribution because together they calculate aircrafts jet fuel consumption volumes based on load and range. The AGE model does not need to be calibrated per aircraft type. It represents a general equation that can be used to calculate aircraft fuel consumption. It just needed to be calibrated once per aircraft manufacturer. However, if a specific aircraft needs to compare performance between engines, the Breguet multi-regression (BMR) model considers engine specifications. The BMR model leads to a better jet fuel consumption volume calculation, but it requires more specific data.

- What is the optimal number of frequencies?

The number of flights between two cities or between two airports is the most important variable in the optimization model. The optimization model uses the frequency variable as main parameter to maximize the net present value of an airline network. The frequency is calculated per route during the optimization process. In the literature, frequency is normally the variable that is used to perform a maximization of the profits of an airline.

The optimization model determines the number of frequencies to operate and the number of passengers to serve, during the optimization. The optimization model includes an equation that expresses the relation between optimum number of passengers to serve with the optimum number of frequencies to operate, desire of passengers for travel routes, and the aircraft operating costs. The results indicate that the optimization model determines the optimum frequency that maximizes the profitability of an airline network by minimizing aircraft operating costs whilst considering the number of passengers to serve, and the desire of passengers for travel routes. It can be concluded because the second derivate of the equation that expresses this relation is always positive.

- What aircraft type is the most convenient for the network? How many aircraft does the airline need to operate?

It is the main reason to maximize the net present value rather than profits. It is not the same maximizing the profits of an airline network than making sure that the maximization of the profits must be higher than the investment required for operating the network. The optimization model responded to this question by designing a network per aircraft type and then calculating the number of aircraft that are needed to maximize the designed network net present value. It is a contribution to the literature and to the airline business studies because it is probably the first study that maximizes the net present value to find routes that are opportunities to open services and design with these routes an airline network assigning the optimal aircraft type.

- Which airports to operate?

The analysis of the airlines business models suggested that airlines do not choose or excludes airports using an airport classification. Today, airlines operate at different airports using different aircraft types because the airports connecting their routes represent a business, and not necessarily because the airport is a hub, or secondary or regional. The analysis of the airlines business showed that what are important for an airline are the airports capacities and infrastructures as well as the location, and catchment area. The question was solved by including all the parameters that allow an airline operating in an airport. It means including all the parameters that allow aircraft to use the airport such as runway size, apron areas size, and the number of passengers that can use the terminal, under different level of services (LOS), during time t.

The airport location and catchment area are taking into account in the PEM model. It means that the forecasting of the induced demand solves the problem not really analyzing the location of the airport. It estimates the possible market size that airports in similar conditions have. One similarity is the economical and social characteristics of the cities where airports are located because these are parameters that determine the demand, and the size of airports are related to the number of pax transported through airports, what determines the classification of airports proposed in this thesis. It means that routes before the optimization process have been indirectly selected according with the location and possible catchment area.

- How long and how to perform the turnaround processes?

The study did not evaluate different ways to perform the turnaround (Tr) process. However, the optimization model Tr parameters allow doing simulations of different Tr processes. This thesis does not propose a Tr process to minimize times, but it gives the possibility for an airline to simulate a new Tr process sequence. If an airline is interested in assessing the advantages and disadvantages of a new Tr, the airlines just need to adjust the parameters that determine the Tr critical path and the processes time will have an impact on the Tr process time as a whole. Then, airlines can analyze if a new Tr process is beneficial to the maximization of their NPV's and the maximization of the total number of pax to transport.

- How many cabin crew and pilots are required to operate the aircraft? And, how many staff members (engineers, ground staff and sales team) are required?

It is important to estimate the number of employees it will need to operate the network designed during the optimization process. A feasible network cannot be feasible if the total number of high skilled employers such as pilots does not exist. The relation between employees and the number of passengers has been described in other studies. In this thesis, the results confirm that the high relation between number of passengers served and number of employees per employee type is described by a linear regression with high accuracy.

- Where to fly? What routes represent a new market opportunity for an airline with better possibilities to succeed or subsist?

This question is answered with the answers of the questions before this. The results of this investigation showed that the models developed in this thesis are able to determine what routes represent an opportunity to open new services. The selection of routes that represent an opportunity to open services can be summarized in four steps. First, the CFEM model determines routes where low fares are competitive enough to allow entering the market. Second, the PEM model determines if the number of passengers served in relation to the complete market size enable an airline entering the market. Third, after selecting routes that represent opportunities to open services under fare competition and passenger demand criteria's, the optimization model determines what are the routes that represent an opportunity to open services by considering the desire of pax to travel these routes, aircraft features and airports capacities and infrastructures, and economic conditions to evaluate a business. Fourth, after optimization the calculation of the number of employees will indicate if the designed model is feasible with the number of available workers.

The study set out 3 sub questions to develop the mathematical models presented in this thesis. These questions came from the analysis of the main research question and the above considerations. In particular, this study responds to the next sub questions:

All mathematical models were validated with real data based on the U.S. domestic air passenger transportation industry. However, the most important limitation lies in the fact that no data are available to compare the results of the study cases, so a discussion was carried out to prove that the results are logical by following the common sense of the expected results in general. Thus, based on the optimization model characteristics, parameters, and constraints it was possible to validate that the optimization model is successful optimizing, and identifying routes that are opportunities to open services, based on airline operating costs, passenger demand, aircraft and airport capacities and constraints. It is also useful model to design networks per aircraft type.

One of the main results of this study indicates that the analysis of the feasibility of airlines networks can be done by using the models developed in this thesis. Based on this result, the feasibility analysis of the long-haul business model was studied by proposing a conceptual design of a long-haul low-cost airline, and optimizing a hypothetical long-haul network. The purpose was to answer the second question of this study:

Can the low-cost model be implemented to long-haul markets?

The conclusion is not that the business model did not work. The results indicate that there are no so much differences with the long-haul FSC model, and this indicates that the development of a long-haul low-cost is very unlikely. In general, the study cases in Chapter 7 showed that carrying cargo is what allows long-haul airlines to earn more money, but this business is already operated by FSC’s and cargo companies.

The contribution of this thesis can be summarized as follows:

The mathematical models developed in this thesis do not require many data to be able to design a large scale airline network. This is a contribution to the literature of airline network design and to the airline business because it is an industry where detail data is not available. It makes difficult to design and analyze the feasibility of airline networks and the air passenger transportation industry in general.

Contrary to models that include many parameters that work for specific geographical locations, the models developed in this thesis are based in parameters that are common for any location. Then, the models developed in this thesis are general and they are expected to be useful at different geographical locations.

The models are reliable tools to support the development of an airline network. The feasibility of airlines networks can be assessed by using the models developed in this thesis.

The models work for the analysis of the expansion of existing airline networks because in reality airline networks grow from few routes to a high number. Then, the models and methodology presented in this thesis can help airlines to visualize and plan future expansion depending on available resources such as aircrafts.

The models and the methodology presented in this thesis can be used by aircraft manufacturer companies to study and design aircrafts that are suitable with the future conditions of the air transportation system.

Airport companies, investors, and governments can use the models and methodology to make investment analysis, and maximization of airports capacities and infrastructures. The models and methodology can be also used for the evaluation of economic and social conditions.

In the case of those models taken from literature, the results of their successful application confirms and provides additional evidence with respect to the capacity of these models to be applied in other studies.

Finally, this research can serve as a base for future studies in airline network design because it includes most of the parameters that are involved in the design of an airline network. The presented optimization model uses models for airline modeling some developed in this thesis, others took from literature. The study contributes by joining all of them into one model.

8.1 Future Work

The optimization model developed in this thesis could be solved by using optimization algorithms that will help to find optimum solutions taking into account all the parameters and constraints included in the model.

The AGE model developed (Chapter 3) needs to be calibrated using detail information about jet fuel consumptions, especially for Airbus aircraft. This information data needs to be regarded or found because their manuals do not include enough data.

The optimization model takes into account different airports parameters. These parameters are constraints for airlines that want to operate a maximum number of frequencies and a certain type of aircraft. These data needs to be gathered to perform more realistic simulations.

The arrival and take-off waiting times distribution function proposed in this thesis (Chapter 6) has to be calibrated for each airport in any network under analysis.

As a future activity remains the collections of data to make more accurate calibration of the optimization model presented in this thesis, and make of the model a calculation tool to ensure that the routes set for the growth of an airline are real businesses.

The model developed in this thesis is based on the United States air transportation databases. It is interesting to create similar databases for other countries or regions such as Europe, Asia and Latin America. It will allow the generalization of this thesis models looking for new airline business opportunities all around the world.

Finally, models application to designing existing airlines networks, and investigate how far or close airlines networks have been designed in respecting to the proposed methodology.

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Appendix A: The Freedoms of the Air

1st Freedom of the Air: the right or privilege to fly over the territory of a foreign Nation without landing [www.icao.com].
2nd Freedom of the Air: the right or privilege to land in a foreign Nation for non-traffic purposes such as re-fuelling, maintenance and technical reasons [www.icao.com].
3rd Freedom of the Air: the right or privilege to disembark traffic in a foreign Nation that was enplaned in the home country of the airline [www.icao.com].
4th Freedom of the Air: the right or privilege to embark traffic in a foreign Nation that is bound for the home country of the airline [www.icao.com].
5th Freedom of the Air: the right or privilege give by one Nation to another Nation to embark and disembark, in the territory of the first Nation, traffic coming from or destined to a third Nation [www.icao.com].
6th Freedom of the Air: the right or privilege to embark traffic from a foreign Nation to another foreign Nation via the home Nation of the airline [www.icao.com].
7th Freedom of the Air: the right or privilege to operate turn around services and embark and disembark traffic between two foreign Nations without serving the home Nation of the airline [www.icao.com].
8th Freedom of the Air al known as "consecutive cabotage": the right or privilege to embark traffic in a foreign nation and disembark it at another point in the same foreign Nations as part of the service from the home Nation of the airline [www.icao.com].
9th Freedom of The Air "stand alone cabotage": A carrier for one Nation operates flights, embark and disembark traffic solely between two points in a foreign nation [www.icao.com].

Appendix B: Airlines IATA codes

Table Appendix B.1 shows the airlines code according with the International Air Transport Association (IATA).

Table Appendix B. 1Airlines IATA codes

Airline	*IATA Code*
AA	American Airlines Inc.
AQ	Aloha Airlines Inc.
AS	Alaska Airlines Inc.
B6	JetBlue Airways
CO	Continental Air Lines Inc.
DL	Delta Air Lines Inc.
F9	Frontier Airlines Inc.
FL	AirTran Airways Corporation
G4	Allegiant Air
NK	Spirit Air Lines
NW	Northwest Airlines Inc.
SY	Sun Country Airlines d/b/a Mn Airlines
U5	USA 3000 Airlines
UA	United Air Lines Inc.
US	US Airways Inc.
WN	Southwest Airlines Co.
YV	Mesa Airlines Inc.
YX	Midwest Airlines Inc.

Appendix C: Airlines aircraft number of seats configurations

Table Appendix C. 1shows aircraft number of seats configuration per airline aircraft type according with the website Seatguru.com.

Table Appendix C. 1 Airlines aircraft number of seats configuration for short-haul and medium-haul flights [Seatguru.com]

Airline	*Short-haul routes*					*Short and medium-haul routes*																				*SH*
	EMBRAER	*CAN AIR*	*Saab 340*	*MD*	*Havilland*	*MD*	*A318*	*A319*	*A320*	*A321*	*A330-200*	*717-200*	*737-300*	*737-400*	*737-500*	*737-700*	*737-800*	*737-900*	*747-400*	*757-200*	*757-300*	*767-200*	*767-300*	*767-400*	*777-200*	*AVERAGE*
AA	44	63				140											154			185		159				124
AQ		70									294	123											262			187
AS		70		74										144		124	160	167								123
B6	100								150																	125

Table Appendix C. 2 Airlines aircraft number of seats configuration for short-haul and medium-haul flights [Seatguru.com]

	Short-haul routes					*Short and medium-haul routes*																			*SH*
Airline	*EMBRAER*	*CAN AIR*	*Saab 340*	*MD*	*Havilland*	*MD*	*A318*	*A319*	*A320*	*A321*	*A330-200*	*717-200*	*737-300*	*737-400*	*737-500*	*737-700*	*737-800*	*737-900*	*747-400*	*757-200*	*757-300*	*767-200*	*767-300*	*767-400*	*777-200*	*AVERAGE*
CO	50		34	74											114	124	156	173			216			256		133
DL		69	34	57		142										124	160	182			192		216			131
F9							120	136	162																	139
FL												107				127										117
G4						135																				135
NK								145	178	218																180
NW			34			125		124	148											171						120
SY																	162									162
U5									168																	168
UA	50	61	34					120	140										347	182			244		348	170
US	78	69	34		46			124	150	173			130	144						183						113
WN													137		122	137										132
YV				50																						50
YX	79	50										99														76

Table Appendix C. 3 Airlines aircraft number of seats configuration for long-haul flights [Seatguru.com]

Airline	*Long-haul*															*LH*
	A319	*A320*	*CAN AIR*	*EMBRAER*	*A330-200*	*A330-300*	*717-200*	*737-800*	*747-400*	*757-200*	*757-300*	*767-200*	*767-300*	*767-400*	*777-200*	*AVERAGE*
AA													224		252	238
AQ																
AS																
B6																
CO								156		176		256		235	281	221
DL									403	184			263	244	272	273
F9																
FL																
G4																
NK																
NW					243	298				171						237
SY																
U5																
UA	120	140	66	70					374	182			244		307	277
US																
WN					258	254				176		204				223
YV																
YX							99									99

Table Appendix C. 4 Airlines aircraft average number of seats configuration [Seatguru.com] [RITA]

Airline	*SH*	*MH*	*LH*	*LH*
	Average	*Average*	*Average*	*Average RITA database*
AA	53	160	238	170
AQ	70	226	226	120
AS	72	149	149	148
B6	100	150	150	138
CO	53	173	221	160
DL	53	169	273	175
F9	139	139	139	134
FL	117	117	117	124
G4	135	135	135	147
NK	180	180	180	148
NW	34	142	237	174
SY	162	162	162	163
U5	168	168	168	168
UA	48	230	277	181
US	60	151	151	149
WN	132	132	132	136
YV	50	50	50	63
YX	65	99	99	102

Appendix D: AOC model coefficient values

Table Appendix D. 1 AOC model coefficient values, 2005

2005	*17,303 routes*				*2005*	*17,303 routes*			
A_2				34.05	α_2				0.22
AOC	*f'a [AviationDB]*	β_2	*f'a*	β_2	*AOC*	*f'a [AviationDB]*	β_2	*f'a*	β_2
AA	18.76	0.01	0.96	- 0.69	OO	6.80	0.24	0.21	- 0.30
AQ	30.61	- 0.01	0.66	0.07	PN				
AS	34.21	0.00	0.83	- 0.14	QX	10.09	- 0.13	0.21	0.19
B6	10.83	- 0.10	0.58	0.45	SY	12.17	- 0.12	0.03	0.08
CO	24.11	0.04	0.85	- 0.77	TZ	29.90	- 0.07	0.00	0.04
DL	24.57	0.01	0.74	- 0.13	U5	13.35	- 0.17	0.38	0.47
F9	13.30	- 0.03	0.43	0.10	UA	21.63	0.03	0.79	- 0.44
FL	11.30	- 0.07	0.27	0.13	US	22.36	- 0.01	0.67	0.07
G4	11.50	- 0.17	0.40	0.47	WN	10.81	- 0.12	0.60	0.55
HP	16.62	0.02	0.41	- 0.05	XP	21.78	- 0.02	0.76	0.23
NK	14.89	- 0.13	0.30	0.30	YV				
NW	41.50	0.01	0.32	- 0.08	YX	23.40	- 0.01	0.41	0.02

Table Appendix D. 2 shows the competition between FSC's without LCC's operating these routes. These routes are only operated by FSC's and they are AA, AQ, AS and CO.

Table Appendix D. 2 AOC model coefficient values competition market FSC-FSC, 2005

Factors				*2005*	*Factors*				*2005*
A_2				28.99	α_2				0.24
AOC	*f'a [AviationDB]*	β_2	*f'a*	β_2	*AOC*	*f'a [AviationDB]*	β_2	*f'a*	β_2
AA	18.76	0.01	0.96	-0.57	AS	34.21	0	0.73	-0.04
AQ	30.61	-0.01	0.68	0.11	CO	24.11	0.07	0.75	-0.79

Table Appendix D. 3 AOC model coefficient values competition market FSC-LCC, 2005

Factors	*2005*				*Factors*	*2005*			
A_2	38.38				α_2	0.19			
AOC	*f'a [AviationDB]*	β_2	*f'a*	β_2	*AOC*	*f'a [AviationDB]*	β_2	*f'a*	β_2
AA	18.76	- 0.02	1.07	- 0.65	NW	41.50	0.03	0.92	- 1.37
AQ	30.61	- 0.01	0.67	0.13	OO	6.80	0.09	0.52	0.10
AS	34.21	- 0.01	0.70	- 0.12	QX	10.09	- 0.17	0.54	0.15
B6	10.83	- 0.06	0.64	0.26	SY	12.17	- 0.09	0.48	0.33
CO	24.11	0.05	0.82	- 0.76	TZ	29.90	- 0.07	0.62	0.55
DL	24.57	0.03	0.61	- 0.17	U5	13.35	- 0.16	0.40	0.52
F9	13.30	- 0.00	1.00	0.54	UA	21.63	0.05	0.75	- 0.50
FL	11.30	- 0.08	0.61	0.39	US	22.36	- 0.02	0.78	0.19
G4	11.50	- 0.19	0.44	0.55	WN	10.81	- 0.13	0.55	0.52
HP	16.62	0.03	0.69	- 0.22	XP	21.78	- 0.05	0.85	0.25
NK	14.89	- 0.15	0.45	0.49	YX	23.40	- 0.01	0.96	- 0.10

Table Appendix D. 4 shows the competition between LCC's without FSC's airlines operating these routes. These routes are only operated by LCC'. In these routes, the only airline operating the market is B6.

Table Appendix D. 4 AOC model coefficient values competition market LCC-LCC, 2005

2005	17,583 routes			
A_2	8.83			
α_2	0.37			
AOC	*f'a [AviationDB]*	β_2	*f'a*	β_2
B6	10.83	- 0.00	0.50	0.00

Table Appendix D. 5 AOC model coefficient values, 2006

2006	*17,511 routes*				*2006*	*17,511 routes*			
A_2	32.43				α_2	0.24			
AOC	*f'a [AviationDB]*	β_2	*f'a*	β_2	*AOC*	*f'a [AviationDB]*	β_2	*f'a*	β_2
AA	20.00	0.00	0.99	- 0.78	OO	7.45	- 0.27	0.26	0.40
AQ	21.85	- 0.06	0.60	0.35	PN				
AS	30.83	0.00	0.82	- 0.15	QX	11.29	- 0.13	0.21	0.19
B6	12.00	- 0.10	0.58	0.45	SY	13.44	- 0.11	0.02	0.07
CO	25.34	0.04	0.85	- 0.77	TZ	21.00	- 0.13	0.26	0.36
DL	28.12	0.01	0.74	- 0.13	U5	29.75	- 0.04	0.42	0.44
E9	29.78	- 0.06	0.39	0.58	UA	23.04	0.03	0.79	- 0.42
F9	13.64	- 0.05	0.39	0.15	US	24.55	0.03	0.45	- 0.11
FL	11.97	- 0.12	0.14	0.15	WN	11.99	- 0.11	0.61	0.54
G4	8.59	- 0.25	0.36	0.53	XP	27.72	- 0.02	0.76	0.23
HP	18.57	0.03	0.23	- 0.05	YV				
NK	16.04	- 0.12	0.31	0.29	YX	22.23	- 0.01	0.41	0.03
NW	22.86	0.02	0.65	- 0.13					

Table Appendix D. 6 AOC model coefficient values, 2007

2007	*17,309 routes*				*2007*	*17,309 routes*			
A_2	26.19				α_2	0.28			
AOC	*f'a [AviationDB]*	β_2	*f'a*	β_2	*AOC*	*f'a [AviationDB]*	β_2	*f'a*	β_2
AA	20.86	- 0.02	0.65	0.17	OO	6.82	- 0.31	3.12	- 0.53
AQ	23.34	- 0.07	0.85	1.38	PN				
AS	36.29	- 0.03	0.72	0.28	QX	12.21	- 0.12	1.42	- 0.82
B6	12.08	- 0.13	0.53	0.50	SY	13.31	- 0.18	0.21	0.30
CO	25.42	- 0.00	0.84	0.09	TZ			0.25	0.37
DL	28.26	- 0.02	0.63	0.16	U5	16.59	- 0.18	0.51	0.76
E9	13.17	0.03	0.79	- 0.42	UA	23.77	- 0.00	0.70	0.04
F9	14.02	- 0.09	0.73	0.79	US	25.14	0.00	1.01	0.37
FL	11.96	- 0.18	0.06	0.16	WN	12.41	- 0.14	0.68	0.90
G4	12.31	- 0.29	0.34	0.67	XP	16.09	0.03	0.45	- 0.11
HP			0.73	0.11	YV	9.44	- 0.29	0.32	0.58
NK	12.68	- 0.23	0.75	2.03	YX	27.25	- 0.04	1.52	- 0.34
NW	22.97	- 0.02	0.67	0.15					

Table Appendix D. 7 AOC model coefficient values, 2008

2008	*16,739 routes*				*2008*	*16,739 routes*			
A_2	37.09				α_2	0.25			
AOC	*f'a [AviationDB]*	β_2	*f'a*	β_2	*AOC*	*f'a [AviationDB]*	β_2	*f'a*	β_2
AA	24.67	- 0.04	0.62	0.22	OO	7.24	- 0.38	3.13	- 0.66
AQ	23.34	- 0.12	0.76	1.36	PN			0.84	0.09
AS	33.50	- 0.01	0.66	0.37	QX			1.42	- 0.82
B6	14.24	- 0.14	0.51	0.51	SY	19.21	- 0.15	0.23	0.29
CO	29.23	- 0.03	0.78	0.33	TZ			0.84	0.09
DL	32.25	- 0.03	0.61	0.20	U5			0.51	0.76
E9			0.79	- 0.42	UA	28.74	- 0.02	0.75	0.25
F9	16.14	- 0.11	0.69	0.83	US	28.92	- 0.02	0.83	0.29
FL	13.87	- 0.15	0.07	0.15	WN	13.95	- 0.13	0.69	0.95
G4	15.32	- 0.31	0.30	0.69	XP			0.45	- 0.11
HP			0.84	0.09	YV			0.32	0.58
NK			0.75	2.03	YX			1.53	- 0.41
NW	31.61	- 0.04	0.61	0.25					

Table Appendix D. 8 AOC coefficient A, α and β values for f'a equal to the airline operation costs per day per mile [AviationDB]

AOC model	*2005*			*2006*			*2007*			*2008*		
A_2	36.89			36.88			35.93			36.79		
α_2	0.20			0.19			0.28			0.19		
β_2 *[AviationDB]*	*Operating Expense*	*IOC*	*DOC*	*Operating Expense*	*IOC*	*DOC*	*Operating Expense*	*IOC*	*DOC*	*Operating Expense*	*IOC*	*DOC*
AA	0.63	0.61	0.43	0.08	-0.62	0.00	-0.11	-0.39	-0.49	0.10	-0.25	-0.08
AQ	0.62	0.05	0.69	0.01	-0.25	-0.33	-0.16	-0.52	-0.47	0.02	0.02	-2.18
AS	0.58	0.54	0.40	0.08	-0.02	-0.44	-0.11	-0.40	-0.43	0.07	-0.30	-0.07
B6	0.64	0.84	0.09	-0.02	-0.26	-0.65	-0.24	-0.81	-0.73	0.00	-0.21	-0.57
CO	0.61	0.41	0.59	0.11	-0.27	-0.03	-0.08	-0.40	-0.36	0.10	-0.41	0.03
DH	0.68	0.26	0.66	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
DL	0.59	0.50	0.44	0.08	-0.07	-0.29	-0.10	-0.31	-0.49	0.09	0.01	-0.37
F9	0.66	0.09	0.72	0.05	-0.02	-0.86	-0.20	-0.64	-0.63	0.06	0.07	-1.37
FL	0.68	0.93	0.27	-0.02	-0.85	-0.23	-0.29	-0.77	-0.97	0.02	-1.10	-0.08
G4	0.74	1.34	-2.80	-0.12	-0.43	-1.89	-0.37	-1.05	-1.03	-0.10	-0.51	-0.58
HP	0.67	0.64	0.47	0.12	-0.21	-0.10	-0.12	-0.69	-0.56	0.00	-0.41	-0.46
NK	0.67	1.07	-0.58	-0.02	-0.06	-1.55	-0.33	-1.23	-0.94	-0.15	-0.73	-0.75
NW	0.57	0.27	0.57	0.09	-0.11	-0.24	-0.10	-0.45	-0.38	0.09	0.05	-0.57
OO	-1.43	-3.35	-2.79	-2.25	-5.33	-3.36	-0.46	-1.40	-1.59	-2.23	-5.56	-3.69
QX	0.95	1.04	0.84	0.00	0.00	0.00	0.02	-0.32	-0.38	-1.28	-0.87	0.02
SY	-0.11	-0.34	-0.47	-0.03	0.02	-6.17	-0.24	-1.06	-0.68	0.01	-1.03	-0.09
TZ	0.35	-0.38	0.35	0.03	-0.02	-1.34	-0.17	-0.59	-0.44	-3.64	-0.01	-1.09
U5	0.00	-1.16	-0.11	-0.02	-0.37	-0.21	-0.16	-0.48	-0.46	-1.98	0.00	-4.25
UA	0.62	0.22	0.72	0.10	-0.09	-0.23	-0.08	-0.42	-0.36	0.10	-0.16	-0.10
US	0.57	0.41	0.49	0.09	-0.17	-0.14	-0.08	-0.35	-0.40	0.11	-0.05	-0.21
WN	0.62	0.68	0.17	-0.02	-0.44	-0.40	-0.24	-0.74	-0.71	0.03	-0.80	-0.10
XP	-0.91	-1.94	-1.20	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
YX	0.77	0.99	0.53	0.10	0.17	-1.52	-0.20	-0.72	-0.92	0.10	0.18	-2.25

Table Appendix D. 9. 0 AOC f'a values for each airline operation costs per day per mile, 2005 [AviationDB]

2005	Salaries + Benefits	Materials	Services	Landing Fees	Rentals	Depreciation	Amortization	Other	Transport Expense
AA	-12.51	- 11.96	- 7.24	5.61	4.72	- 1.63	11.84	11.06	- 4.15
AQ	-12.86	- 12.35	- 7.97	2.80	1.75	- 5.66	9.82	9.09	- 5.74
AS	-25.63	- 24.71	- 16.73	- 3.53	- 7.86	- 6.85	15.68	14.35	- 12.90
B6	-15.91	- 17.66	- 8.25	15.81	- 14.35	0.60	32.04	14.55	38.09
CO	-4.15	- 3.67	- 2.21	- 1.03	0.39	- 2.21	3.88	3.51	- 4.83
DH	-3.73	- 4.10	5.03	4.90	- 1.70	3.57	18.28	3.82	25.61
DL	-19.38	- 19.00	- 13.23	12.14	5.29	4.28	15.57	73.16	- 18.64
F9	-7.27	- 8.34	- 2.40	5.49	- 2.32	6.09	44.02	6.27	4.08
FL	-19.79	- 26.22	- 5.12	24.64	- 11.98	35.17	132.10	- 5.05	132.10
G4	-9.07	- 19.20	5.31	8.70	2.01	8.17	75.86	6.51	75.86
HP	-3.02	- 3.58	- 0.19	3.49	0.75	3.94	9.62	- 2.76	- 3.06
NK	-2.27	- 2.84	- 0.56	0.55	2.14	0.69	12.85	6.92	12.85
NW	-25.58	- 24.68	- 16.87	- 4.07	- 8.20	- 4.52	14.87	13.57	- 13.11
OO	-75.08	- 110.56	108.45	187.89	- 36.00	101.94	603.85	157.73	819.20
QX	-13.84	- 8.14	7.51	12.24	- 6.04	14.78	33.18	2.79	75.43
SY	-97.45	- 182.15	- 105.56	164.18	- 99.83	310.09	439.56	231.59	819.14
TZ	-12.81	- 21.12	- 8.53	3.08	- 3.62	- 0.73	38.09	51.19	51.19
U5	-0.92	- 4.23	- 4.79	4.52	- 0.80	3.88	7.68	6.01	12.76
UA	-13.68	- 13.81	- 9.29	8.11	1.69	- 8.61	17.89	17.30	- 14.99
US	-4.40	- 4.58	- 3.22	2.65	- 0.41	3.04	6.55	- 2.28	- 5.63
WN	-18.59	- 11.70	- 6.77	13.56	5.78	- 4.69	51.29	22.29	47.17
XP	-352.11	- 550.48	- 69.48	-189.97	119.84	- 34.64	1,670.77	48.03	- 101.55
YV									
YX	-2.24	- 2.93	0.88	0.02	3.61	2.25	9.52	6.90	12.80

Table Appendix D. 9. 1 AOC f'a values for each airline operation costs per day per mile, 2005 [AviationDB]

β_2 [AviationDB]	*Salaries*						*Benefits*				*Salaries + Benefits*
Airline Code	*Management*	*Flight*	*Maintenance*	*Traffic*	*Other*	*Total*	*Personnel*	*Pensions*	*Payroll*	*Total*	*Salaries Benefits Total*
AA	0.12	1.75	0.83	0.92	0.28	3.90	0.23	1.33	0.32	1.88	5.78
AQ	0.15	2.10	0.99	1.11	0.33	4.68	0.27	1.59	0.39	2.25	6.93
AS	0.18	2.52	1.19	1.33	0.40	5.62	0.33	1.91	0.47	2.70	8.32
B6	0.04	1.00	0.17	0.59	0.49	2.29	0.30	0.30	0.18	0.78	3.07
CO	0.08	1.64	0.56	1.14	0.42	3.83	0.29	1.13	0.20	1.61	5.45
DH	0.01	1.00	0.20	0.56	0.40	2.16	0.27	0.34	0.17	0.79	2.95
DL	0.05	1.97	0.48	1.00	0.66	4.17	0.24	1.49	0.33	2.07	6.23
F9	0.09	1.12	0.29	0.63	0.26	2.40	0.20	0.35	0.18	0.73	3.13
FL	0.13	1.14	0.16	0.44	0.28	2.15	0.23	0.28	0.16	0.66	2.82
G4	0.18	0.79	0.30	0.28	0.05	1.59	0.41	0.17	0.13	0.70	2.29
HP	0.04	1.20	0.21	0.46	0.58	2.49	0.20	0.62	0.18	1.00	3.49
NK	0.42	1.30	0.47	0.45	0.35	3.00	0.35	0.54	0.25	1.14	4.14
NW	0.19	2.62	1.24	1.39	0.42	5.85	0.34	1.99	0.48	2.82	8.67
OO	0.17	0.67	0.12	0.35	0.00	1.32	0.18	0.28	0.11	0.57	1.88
QX	0.01	0.90	0.39	0.93	0.30	2.53	0.29	0.50	0.23	1.02	3.55
SY	0.11	0.74	0.13	0.78	0.12	1.89	0.05	0.19	0.14	0.39	2.27
TZ	0.25	1.51	1.12	0.14	0.68	3.70	1.01	0.67	0.26	1.94	5.63
U5	0.00	1.12	0.29	0.23	0.19	1.83	0.19	0.21	0.15	0.55	2.38
UA	0.02	1.35	0.39	0.85	0.65	3.25	0.26	1.14	0.28	1.69	4.94
US	0.06	1.35	0.25	0.97	0.55	3.19	0.24	0.67	0.31	1.23	4.42
WN	0.22	1.59	0.22	0.92	0.18	3.13	0.21	0.97	0.22	1.40	4.54
XP	0.33	0.97	0.71	0.43	0.64	3.08	0.59	0.28	0.33	1.21	4.29
YV	0.00	0.68	0.13	0.01	0.02	0.85	0.01	0.03	0.07	0.11	0.96
YX	0.22	1.16	0.25	0.51	0.22	2.36	0.12	0.58	0.07	0.77	3.13

Table Appendix D. 9. 2 AOC coefficient β values for f'a equal to the airline operation costs per day per mile, 2005 [AviationDB]

β_2 [AviationDB]	*Aircraft Fuel*	*Maintenance Material*	*Food*	*Other Materials*	*Materials Total*	*Advertising*	*Communication*	*Insurance*	*Outside Equipment*	*Commissions Passenger*	*Commissions Cargo*
AA	4.55	0.33	0.38	0.10	5.36	0.13	0.07	0.10	0.40	0.18	0.00
AQ	5.46	0.40	0.45	0.12	6.43	0.15	0.09	0.12	0.48	0.22	0.01
AS	6.55	0.48	0.54	0.14	7.71	0.18	0.10	0.15	0.58	0.26	0.01
B6	3.22	0.08	0.08	0.10	3.47	0.21	0.07	0.14	0.37	0.00	0.00
CO	3.97	0.16	0.37	0.09	4.59	0.18	0.10	0.15	0.71	0.20	0.02
DH	2.79	0.15	0.03	0.19	3.16	0.22	0.06	0.14	0.17	0.26	0.00
DL	4.98	0.38	0.43	0.23	6.01	0.23	0.25	0.13	0.51	0.26	0.02
F9	3.43	0.08	0.08	0.12	3.70	0.19	0.39	0.21	0.53	0.12	0.01
FL	3.63	0.19	0.06	0.06	3.94	0.29	0.06	0.15	0.52	0.08	0.00
G4	4.88	0.66	0.14	0.07	5.74	0.21	0.12	0.31	0.03	0.03	0.00
HP	3.77	0.13	0.05	0.08	4.03	0.05	0.07	0.14	1.10	0.06	0.00
NK	4.35	0.35	0.08	0.17	4.95	0.24	0.26	0.22	0.78	0.14	0.00
NW	6.82	0.50	0.56	0.15	8.03	0.19	0.11	0.16	0.60	0.27	0.01
OO	2.21	0.26	0.04	0.03	2.54	0.02	0.01	0.08	0.16	0.00	0.00
QX	1.76	0.24	0.05	0.07	2.12	0.02	0.04	0.15	0.55	0.05	0.00
SY	3.50	0.86	0.19	0.10	4.65	0.06	0.05	0.27	0.16	0.28	0.00
TZ	16.32	0.88	0.00	0.08	17.28	0.00	0.05	0.21	2.53	0.00	0.00
U5	3.15	0.07	0.53	0.09	3.84	0.76	0.06	0.29	0.83	0.04	0.00
UA	4.30	0.28	0.31	0.13	5.02	0.17	0.11	0.13	0.83	0.22	0.00
US	4.21	0.16	0.21	0.09	4.66	0.08	0.43	0.26	0.85	0.23	0.00
WN	2.35	0.12	0.03	0.08	2.59	0.28	0.03	0.10	0.61	0.02	0.00
XP	8.03	1.39	0.00	0.31	9.74	0.06	0.11	0.66	0.00	0.00	0.00
YV	2.25	0.00	0.01	0.00	2.27	0.00	0.00	0.15	0.00	0.00	0.00
YX	3.60	0.28	0.20	0.09	4.17	0.26	0.10	0.12	0.45	0.28	0.00

Table Appendix D. 10 AOC coefficient β values for f'a equal to the airline operation costs per day per mile, 2005 [AviationDB]

β_2 [AviationDB]	*Other Services*	*Services Total*	*Landing Fees*	*Rentals*	*Depreciation*	*Amortization*	*Other*	*Transport Expense*	*Total Operating Expense*	*Total indirect costs*	*Total direct costs*
AA	1.88	2.77	0.44	1.36	0.64	0.19	0.21	2.02	18.76	7.89	10.88
AQ	2.26	3.32	0.53	1.63	0.77	0.23	0.25	2.42	22.52	9.46	13.05
AS	2.71	3.99	0.63	1.96	0.92	0.27	0.31	2.90	27.02	11.36	15.66
B6	1.07	1.86	0.33	0.91	0.66	0.10	0.36	0.07	10.83	4.15	6.68
CO	1.86	3.22	0.49	2.24	0.58	0.20	0.23	7.12	24.11	13.17	10.94
DH	0.52	1.36	0.26	2.35	0.35	0.01	0.33	0.00	10.77	3.40	7.37
DL	2.08	3.49	0.32	1.26	1.31	0.23	0.00	5.81	24.57	12.87	11.70
F9	0.47	1.91	0.41	1.91	0.38	0.00	0.37	1.48	13.30	5.68	7.61
FL	0.41	1.51	0.28	1.88	0.16	0.00	0.72	0.00	11.30	3.63	7.67
G4	0.70	1.39	0.45	0.62	0.47	0.00	0.53	0.00	11.50	3.23	8.27
HP	0.93	2.36	0.25	2.10	0.22	0.03	0.61	3.52	16.62	8.11	8.51
NK	1.46	3.10	0.32	2.03	0.32	0.00	0.02	0.00	14.89	4.85	10.04
NW	2.83	4.15	0.66	2.04	0.96	0.28	0.32	3.03	28.14	11.83	16.31
OO	0.13	0.40	0.21	1.08	0.42	0.01	0.26	0.00	6.80	2.22	4.59
QX	0.52	1.34	0.33	1.83	0.26	0.05	0.62	0.00	10.09	4.42	5.67
SY	1.61	2.44	0.25	2.32	0.07	0.02	0.14	0.00	12.17	2.41	9.75
TZ	0.38	3.16	1.23	1.89	0.69	0.01	0.00	0.00	29.90	7.68	22.22
U5	2.53	4.52	0.32	2.12	0.12	0.02	0.04	0.00	13.35	3.47	9.88
UA	1.49	2.96	0.39	1.48	0.83	0.12	0.13	5.76	21.63	11.81	9.82
US	1.54	3.39	0.37	2.03	0.38	0.11	0.49	6.51	22.36	12.27	10.09
WN	0.74	1.77	0.33	0.65	0.73	0.02	0.16	0.02	10.81	4.97	5.84
XP	0.80	1.33	2.19	0.61	1.16	0.00	0.94	1.52	21.78	7.78	14.00
YV	0.17	0.32	0.00	1.29	0.26	0.01	1.66	0.00	6.78	2.36	4.42
YX	0.87	2.08	0.27	1.42	0.25	0.03	0.07	0.01	11.44	3.35	8.09

Appendix E: Aircraft payload - jet fuel consumption volume charts

The graphs in this appendix provide information on aircraft jet fuel consumption and payload. These graphs were generated by analyzing the aircraft payload-range diagrams that provided information on jets fuel consumption at different load at different distance range [Airbus and Boeing aircraft manuals].

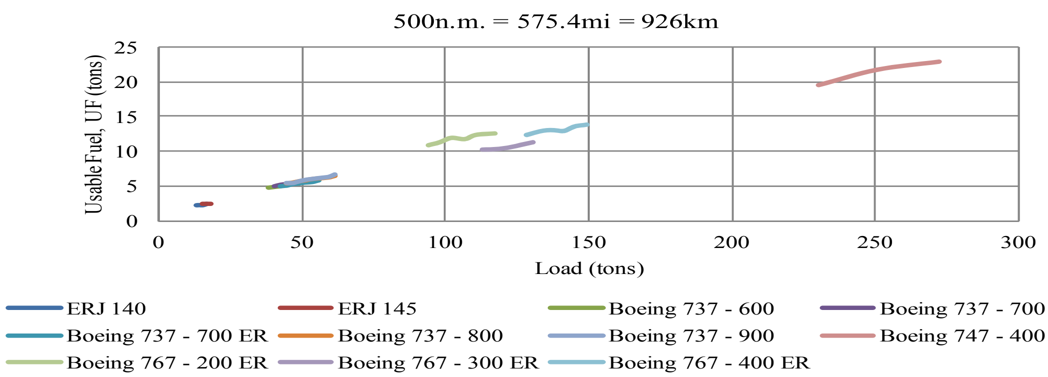


Figure Appendix E. 1 Aircraft payload vs. jet fuel consumption volume at 926km

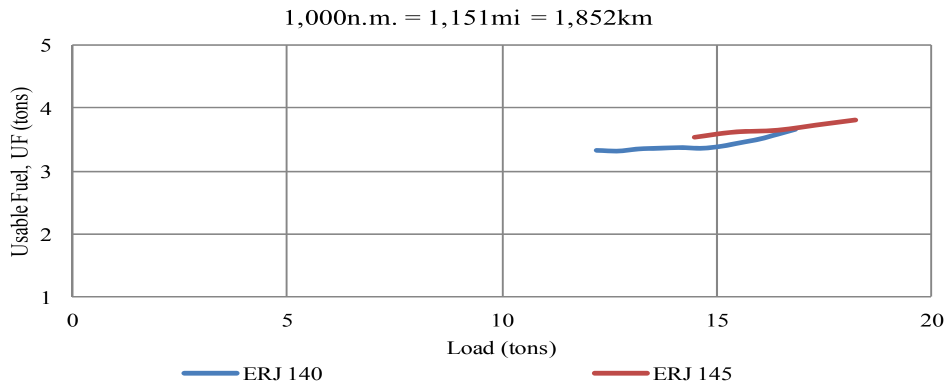


Figure Appendix E. 2 Aircraft payload vs. jet fuel consumption volume at 1,852km

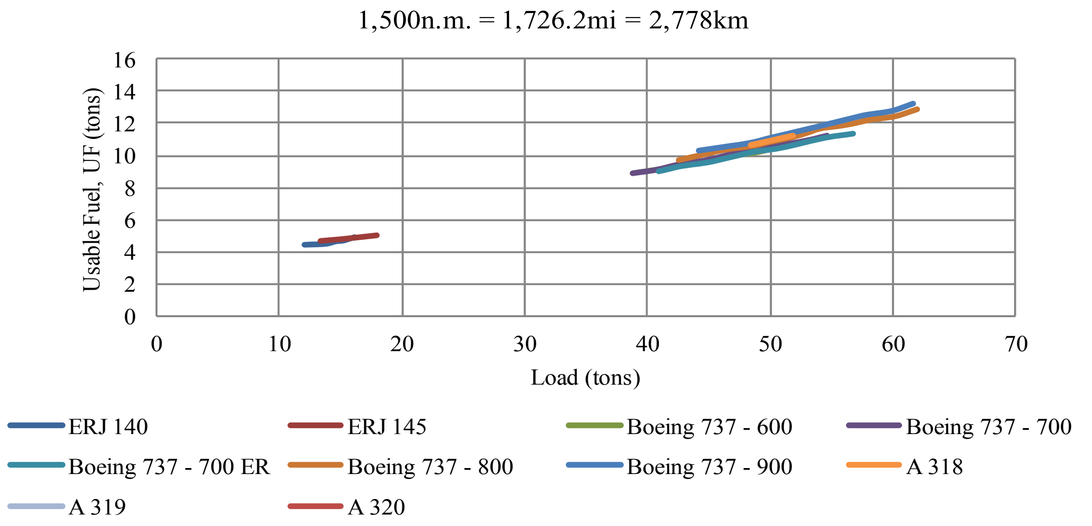


Figure Appendix E. 3 Aircraft payload vs. jet fuel consumption volume at 2,778km

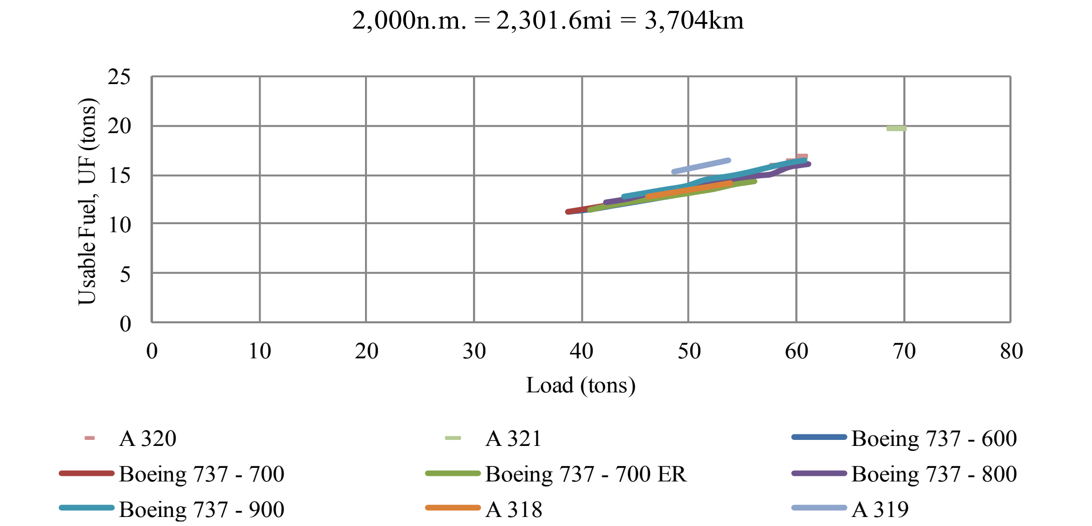


Figure Appendix E. 4 Aircraft payload vs. jet fuel consumption volume at 3,704km

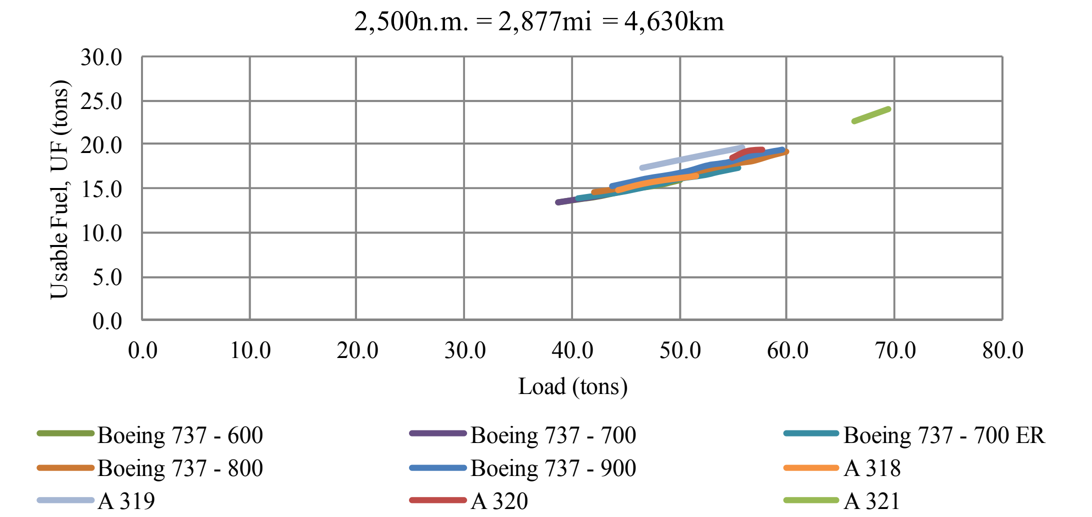


Figure Appendix E. 5 Aircraft payload vs. jet fuel consumption volume at 4,630km

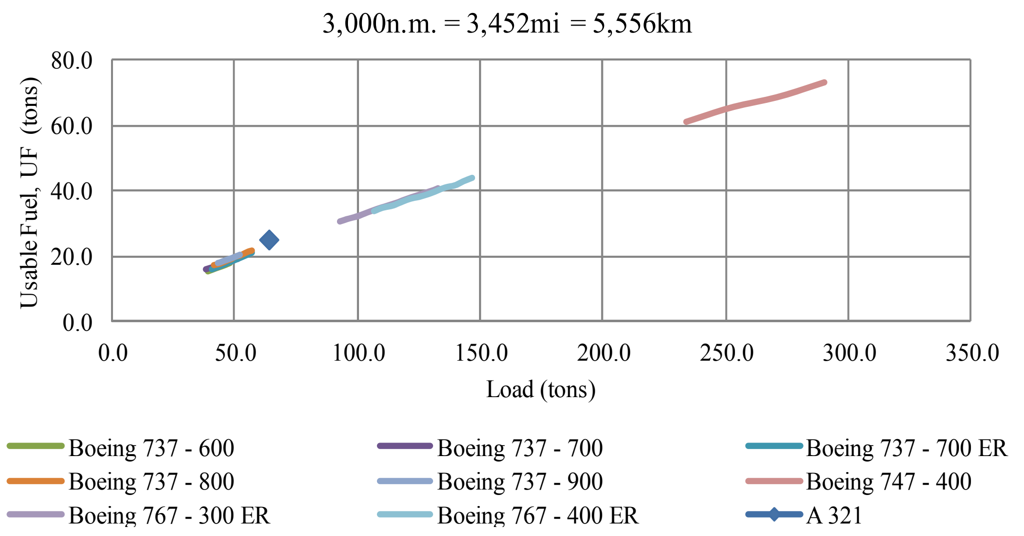


Figure Appendix E. 6 Aircraft payload vs. jet fuel consumption volume at 5,556km

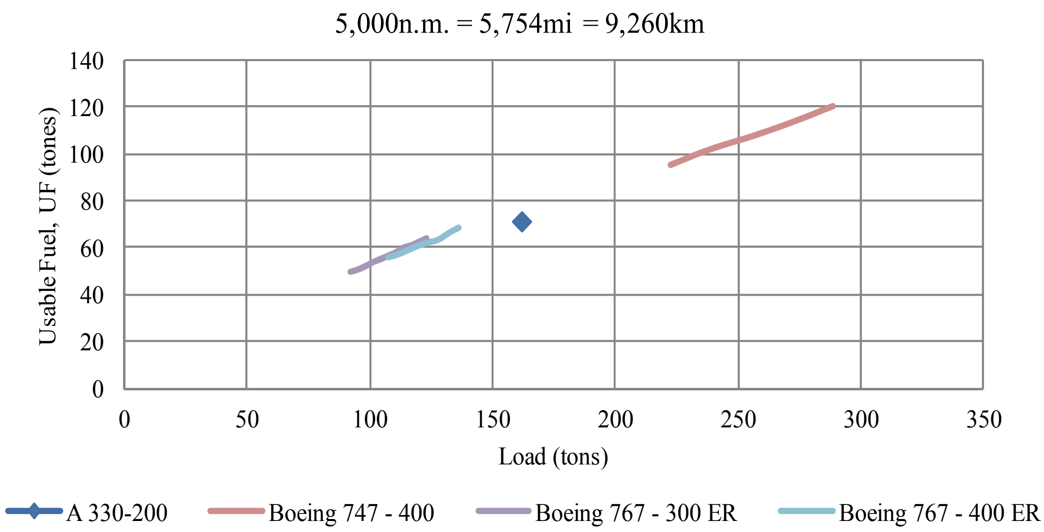


Figure Appendix E. 7 Aircraft payload vs. jet fuel consumption volume at 9,260km

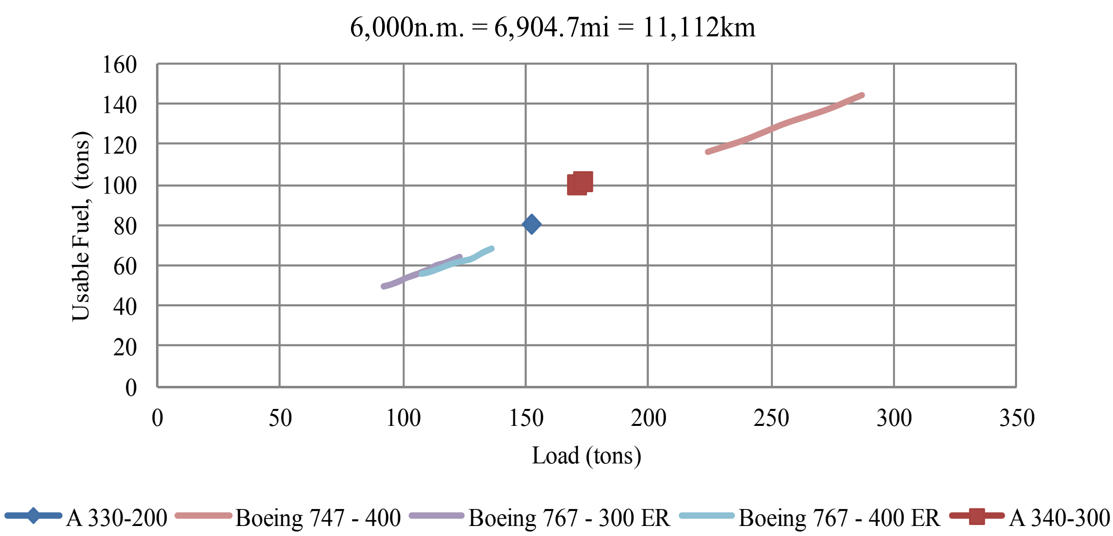


Figure Appendix E. 8 Aircraft payload vs. jet fuel consumption volume at 11,112km

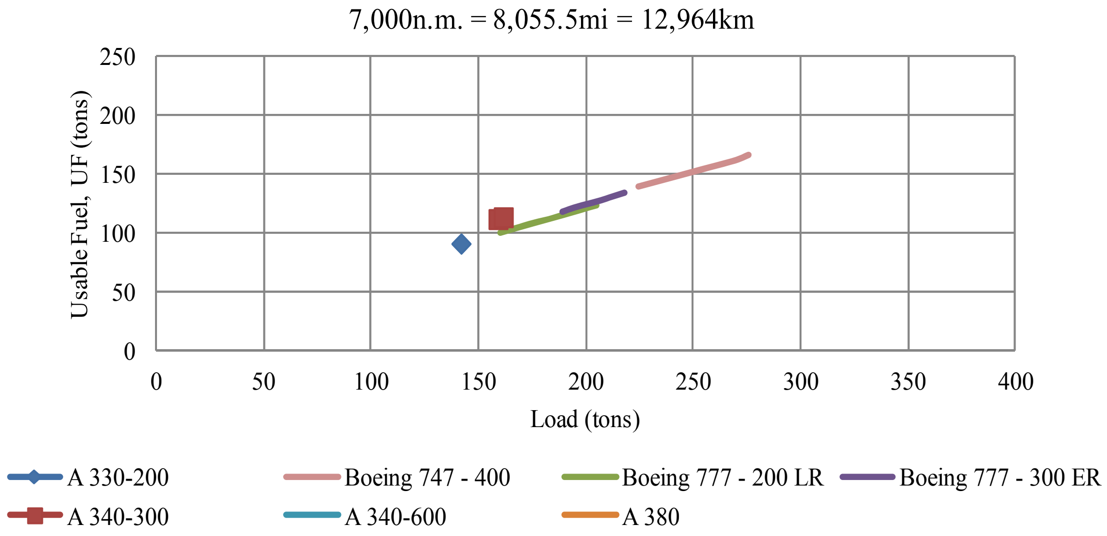


Figure Appendix E. 9 Aircraft payload vs. jet fuel consumption volume at 12,964km

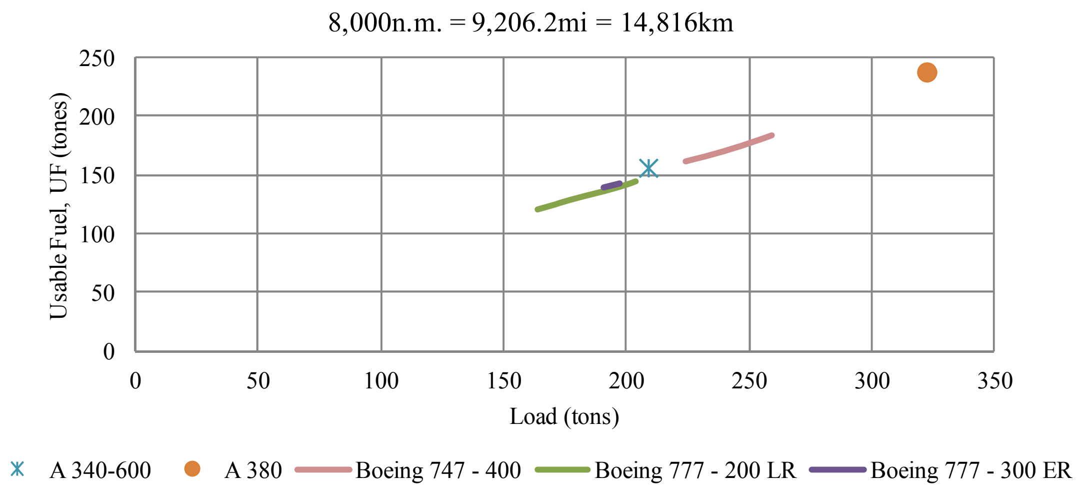


Figure Appendix E. 10 Aircraft payload vs. jet fuel consumption volume at 14,816km

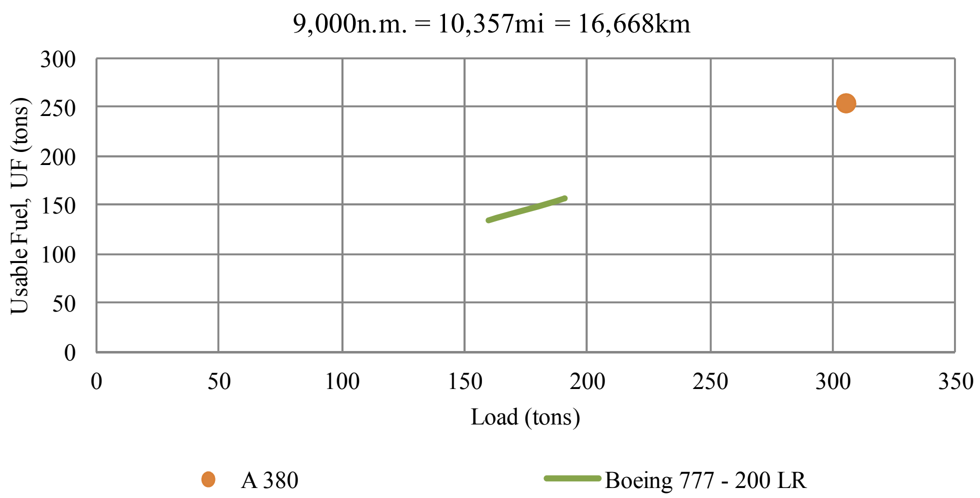


Figure Appendix E. 11 Aircraft payload vs. jet fuel consumption volume at 16,668km

Appendix F: Database airline business models and airport type's definition analysis

The database analysis presented in this appendix refers to year 2005. It is based on the analysis made by Carmona Benitez and Lodewijks [2012]. FSC's transported two times more passengers (pax) than LCC's. The average weighted fare for the FSC business model (162.80 usd) was more expensive than LCC business model (109.28 usd). The average weighted fare for the FSC model was higher because the average weighted distance was longer for FSC's than LCC's. Although, the unit price average weighted fare per km showed that FSC's are more expensive than LCC's. Almost 90% of the US domestic market routes were operated by FSC's. This means, the market was dominated by FSC's in 2005. The number of pax transported by FSC's was approximately 70% from the total US domestic air transport market. On the other hand, the number of pax per km transported by LCC's was more than 4 times the number transported by FSC's. This means, LCC's routes were shorter than FSC's routes (Table Appendix F. 1).

To measure and understand the competition between FSC's and LCC's, all routes have been classified in three groups: FSC-FSC, FSC-LCC and LCC-LCC. The FSC-FSC routes are those where no presence of LCC's exists. The LCC-LCC routes are those without FSC's operations. Finally, LCC-FSC routes are routes with at least one LCC and one FSC competing between each other.

Table Appendix F. 1 FSC and LCC business models characteristics

Market	*Ave. Dist (km)*	*Number of pax per day*	*Ave. Fare (usd)*	*Pax / Dist (pax/km)*	*Ave. Fare / Dist (usd/km)*	*Number of airlines*	*Number of routes*
Total	1,751	1,108,826	$147	10.6	0.13	26	17,636
FSC's	1,899	775,434	$163	8.7	0.13	17	15,574
LCC's	1,405	330,558	$109	31.7	0.10	9	2,062

The FSC-FSC routes were the most expensive and the most common. Table Appendix F. 2 shows that LCC's were competing in just one third of the US domestic market. The LCC-LCC routes transported 105 pax per km. This was almost 8 times more than the FSC-LCC routes and around sixteen times more than the FSC-FSC routes. The LCC-LCC routes were the cheapest routes. Their average travel distance was 1,210km. The distance was shorter than in the other two markets. It was expected since the LCC model primarily operates short-haul routes. The number of LCC-LCC routes was small and showed clearly that LCC's main strategy is to provide service with lower fares and more aircraft passenger load.

Table Appendix F. 2 Competition markets characteristics

Market	*Ave. Dist (km)*	*Number of pax per day*	*Ave. Fare (usd)*	*Pax / Dist (pax/km)*	*Ave. Fare / Dist (usd/mi)*	*Number of routes*
FSC-FSC	1,948.9	509,017	173	6.8	0.22	12,346
FSC-LCC	1,686.6	465,492	132	16.8	0.17	4,973
LCC-LCC	1,210.2	131,093	101	105.0	0.19	317

Airports fees have a direct impact on airline fares. To measure and understand this influence the database has been classified into five different airport types depending on the number of US domestic pax per day using the airport, as Table Appendix F. 3 shows. The average fare per km was similar for most of the airport types but not for type E. Airports type E was the most expensive. Airports type B showed the longest average travel distance and airports type E the shortest. This results might suggest that airports type D and E are feeding airports type A and B. Airports type A had the biggest number of pax per km whilst airports D and E the smallest.

Table Appendix F. 3 Airport type classification characteristics

Airport type	*Pax per day (1000)*	*Airports*	*Ave. Fare ($)*	*Ave. Dist (km)*	*Total Pax per day*	*Fare/Dist ($/km)*	*Pax/Dist (pax/km)*
A	≥ 65	5	143	1,828.2	378,118	0.12	26.7
B	50 – 65	23	150	1,870.1	966,020	0.12	16.8
C	20 – 50	33	139	1,578.8	552,338	0.12	9.9
D	10 – 20	117	154	1,602.9	299,704	0.13	4.3
E	0 – 10	139	187	1,525.7	16,136	0.16	2.5

Table Appendix F. 4 showed that FSC's fares were more expensive than LCC's fares, Table Appendix F. 5. Apparently, airport charges lower fees to LCC's, no matter the airport type, or FSC's utilities were higher than LCC's per route. The LCC's numbers of pax per km were bigger than the FSC's. This means, an LCC flight is expected to transports more passengers to an airport than an FSC flight. These might be a reason for lower airport fees to LCC's because airports can increase revenues and reduce operation costs.

Table Appendix F. 4 Airport type classification characteristics, FSC market

Airport type	Ave. Fare ($)	Ave. Dist (km)	Total Pax per day	Fare/Dist ($/km)	Pax/Dist (pax/mi)
A	155	1,976.3	276,088	0.13	21.7
B	165	1,989.2	689,749	0.12	13.1
C	159	1,800.9	347,980	0.13	7.5
D	170	1,701.1	221,459	0.14	3.7
E	188	1,514.4	15,926	0.16	2.5

Table Appendix F. 6 shows that most of the routes are connecting airports type D with airports type B and C. Routes connecting big airports, such as AA, BB, AB, AC and CC, are expected to have cheap fares. Opposite, type E airports are expected to be very expensive. It is clear that the number of pax per km have a positive relation with fares per km, what means that the bigger the number of pax per km, the cheapest fare per km can be.

Table Appendix F. 5 Airport type classification characteristics, LCC market

Airport type	*Ave. Fare ($)*	*Ave. Dist (km)*	*Total Pax per day*	*Fare/Dist ($/km)*	*Pax/Dist (pax/km)*
A	109	1,425.9	102,031	0.09	66.5
B	112	1,570.7	276,271	0.09	47.8
C	105	1,200.6	204,359	0.10	25.5
D	110	1,329.3	78,246	0.11	14.3
E	135	2,375.4	211	0.11	5.6

Table Appendix F. 6 Airport relationship classification characteristics

Airport relationship	*Ave. Fare ($)*	*Ave. Dist (km)*	*Total Pax per day*	*Fare/Dist ($/km)*	*Pax/Dist (pax/km)*	*Number of routes*
AA	142	1,952.1	21,731	0.10	134.2	27
AB	132	1,631.9	89,064	0.11	101.3	146
AC	135	1,606.1	62,801	0.11	42.3	227
AD	151	1,572.3	33,490	0.14	8.7	647
AE	180	1,493.5	1,901	0.16	2.5	165
BB	156	2,068.0	191,994	0.11	47.2	518
BC	139	1,643.1	149,665	0.10	21.7	849
BD	150	1,501.5	79,932	0.13	5.6	2,389
BE	192	1,578.8	3,820	0.16	2.5	343
CC	134	1,453.2	66,937	0.10	8.1	1,246
CD	145	1,203.8	36,488	0.16	3.7	2,257
CE	186	1,329.3	460	0.19	2.5	49
DD	172	1,562.7	5,546	0.15	1.9	587
DE	196	880.3	750	0.27	23.0	13

In Table Appendix F. 7 and Table Appendix F. 8, the airport relationship classification characteristics for the FSC and LCC models are presented. Again it is clear that LCC routes were cheaper than FSC routes and the aircraft load factor were higher for LCC's. The FSC's provide service to all type of airport connections, whilst the LCC's did not provide services connecting to small airports, type E. The majority of the US domestic passengers flew between airports type A, B and C. Airports type E were the most expensive. Airports type A the cheapest. These analyses prove that airports have a direct impact on the passenger demand and fares.

The airports with more LCC's passenger's traffic are in high populated and tourism cities or nearby, Figure Appendix F. 1. As example, Las Vegas was the airport with more LCC's passenger's traffic during year 2005. It should be because Las Vegas could be considered as Southwest Airlines (WN) hub since most of the departures and arrivals are operated by WN. Some of these airports have been classified as the second city airports such as Chicago Midway (MDW), Oakland/Burbank (OAK) near San Francisco, Baltimore (BWI) near Washington D.C., etc.

The competition between airline business models (FSC against LCC) is also affected by the competition between airports. In Figure Appendix F. 1, the US Airports with more LCC's pax traffic per day are shown. The main characteristic and advantage of these airports was to be located near airline airports hub or in big cities. Figure Appendix F. 2 shows the US airports with more than 60% LCC passenger's traffic. These airports are located either in tourism cities or nearby airline airport hubs in big cities such as Chicago (MDW), Oakland (OAK), Baltimore (BWI), Houston (HOU) near Houston George Bush (IAH), and Dallas (DAL) near Dallas Fort Worth (DFW), etc. Nowadays, these airports are competing and bringing more passengers providing service to LCC's affecting fares on similar routes operated by other airports. From Table Appendix F. 9 to Table Appendix F. 11, the airports classification based on the percentage of low cost passengers and cities average fares are presented.

Table Appendix F. 7 Airport relationship classification characteristics, FSC market

Airport relationship	*Ave. Fare ($)*	*Ave. Dist (km)*	*Total Pax per day*	*Fare/Dist ($/km)*	*Pax/Dist (pax/km)*	*Number of routes*
AA	149	2,129.2	17,896	0.10	138.6	21
AB	145	1,800.9	60,957	0.11	90.1	105
AC	151	1,855.6	40,279	0.11	32.9	174
AD	168	1,667.3	24,056	0.14	7.5	582
AE	180	1,491.9	1,898	0.16	2.5	164
BB	172	2,182.3	134,839	0.12	41.0	396
BC	153	1,781.5	102,859	0.10	17.4	686
BD	162	1,477.4	60,859	0.13	4.3	2,212
BE	194	1,545.0	3,694	0.17	2.5	340
CC	162	1,862.0	35,706	0.11	5.6	966
CD	169	1,376.0	23,319	0.16	3.1	1,999
CE	185	1,329.3	460	0.19	2.5	49
DD	178	1,594.9	4,997	0.15	1.9	544
DE	196	880.3	750	0.27	23.6	13

Table Appendix F. 8 Airport relationship classification characteristics, LCC market

Airport relationship	*Ave. Fare ($)*	*Ave. Dist (km)*	*Total pax per day*	*Fare/Dist ($/km)*	*Pax/Dist (pax/km)*	*Number of routes*
AA	106	1,128.2	3,835	0.11	116.8	6
AB	105	1,266.6	28,107	0.09	139.8	41
AC	105	1,160.3	22,522	0.11	93.2	53
AD	109	1,327.7	9,434	0.11	31.7	65
AE	157	2,208.0	-	0.07	0.6	1
BB	116	1,796.0	57,154	0.08	77.7	122
BC	107	1,339.0	46,807	0.09	50.3	163
BD	115	1,577.2	19,074	0.11	24.9	177
BE	136	2,565.3	127	0.09	8.7	3
CC	102	986.5	31,231	0.09	20.5	280
CD	102	896.4	13,170	0.12	13.0	258
CE	-	-	-	-	-	-
DD	122	196.3	549	0.13	3.1	43
DE	-	-	-	-	-	-

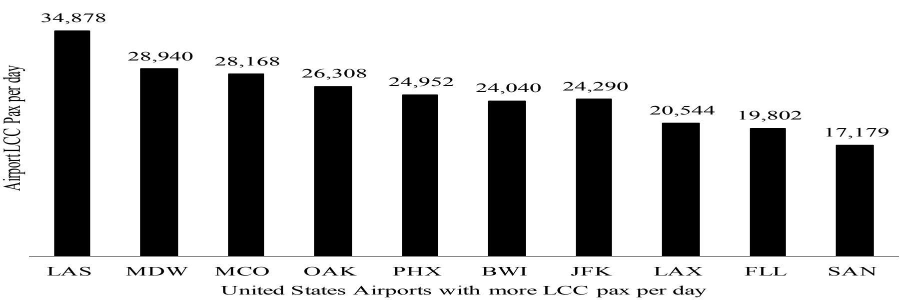


Figure Appendix F. 1 US airports with more LCC domestic pax per day

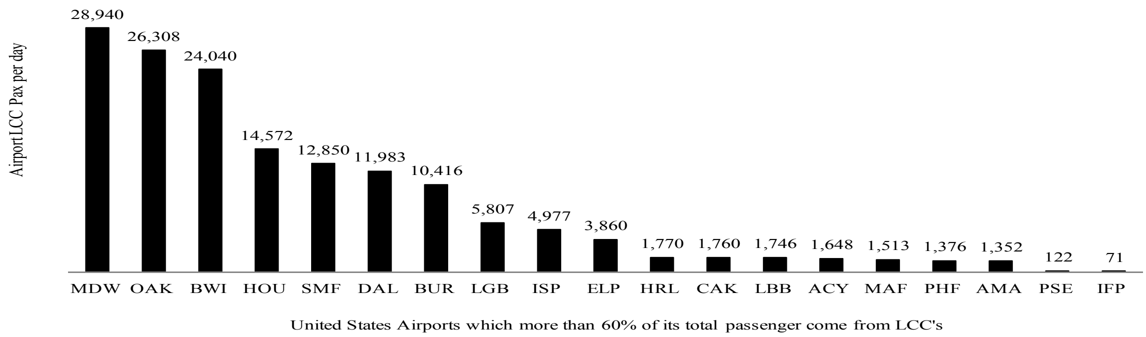


Figure Appendix F. 2 US airports with more than 60% of LCC domestic pax per day

Table Appendix F. 9 Expensive low cost and cheap cities and full service expensive cities

US AIRPORTS	*Airport City (Tourism)*	*State*	*US AIRPORTS*	*Airport City (Business)*	*State*
PHX	Phoenix	AZ	ANC	Anchorage	AK
TUS	Tucson	AZ	FAI	Fairbanks	AK
PSP	Indio/Palm Springs	CA	JNU	Juneau	AK
MCO	Orlando/Kissimmee	FL	KTN	Ketchikan	AK
FLL	Ft. Lauderdale	FL	BET	Bethel	AK
TPA	Tampa/St. Petersburg/Lakeland	FL	OME	Nome	AK
RSW	Ft. Myers	FL	SFO	San Francisco	CA
PBI	West Palm Beach	FL	DEN	Denver	CO
JAX	Jacksonville	FL	DCA	Washington	DC
SRQ	Sarasota/Bradenton	FL	IAD	Washington	DC
DAB	Daytona Beach	FL	MIA	Miami	FL
PIE	Tampa/St. Petersburg/Lakeland	FL	BDL	Hartford/Springfield	FL
OAJ	Jacksonville	FL	ATL	Atlanta	GA
SFB	Orlando/Kissimmee	FL	BOS	Boston	MA
HNL	Honolulu	HI	MSP	Minneapolis/St. Paul	MI
OGG	Maui	HI	DTW	Detroit	MI
LIH	Kauai Island	HI	CLT	Charlotte	NC
KOA	Kona	HI	LGA	New York	NY
ITO	Hilo	HI	JFK	New York	NY
PPG	Pago Pago	PR	EWR	New York	NY
LAS	Las Vegas	NV	CLE	Cleveland	OH
RNO	Reno	NV	CVG	Cincinnati	OH
SJU	San Juan	PR	PDX	Portland	OR
STT	Charlotte Amalie, St. Thomas	PR	PHL	Philadelphia	PA
BQN	Borinquen	PR	PIT	Pittsburgh	PA
STX	Christiansted, St. Croix	PR	DFW	Dallas/Ft. Worth	TX
PSE	Ponce	PR	DAL	Dallas/Ft. Worth	TX
SPN	Obyan	PR	SEA	Seattle	WA
MYR	Myrtle Beach	SC			
HRL	Harlingen	TX			
MFE	Mission/McAllen	TX			

Table Appendix F. 10 Normal airports located in tourism or business cities

US Airports	*Airport City*	*State*	*US Airports*	*Airport City*	*State*	*US Airports*	*Airport City*	*State*
BHM	Birmingham	AL	ORD	Chicago	IL	CAE	Columbia	SC
SAN	San Diego	CA	LAX	Los Angeles	CA	PNS	Pensacola	FL
HSV	Huntsville/Decatur	AL	MDW	Chicago	IL	TLH	Tallahassee	FL
LIT	Little Rock	AR	MLI	Moline/Davenport	IL	EYW	Key West	FL
IFP	Bullhead City/Laughlin	AZ	BMI	Bloomington	IL	SAV	Savannah	GA
LAX	Los Angeles	CA	IND	Indianapolis	IN	DSM	Des Moines	IA
SAN	San Diego	CA	MCI	Kansas City	KS	CID	Iowa City	IA
OAK	Oakland/Berkeley	CA	ICT	Wichita	KS	BOI	Boise	ID
SMF	Sacramento	CA	SDF	Louisville	KY	PIA	Peoria	IL
SJC	San Jose/Palo Alto	CA	MSY	New Orleans	LA	MSN	Madison	WI
SNA	Santa Ana	CA	BTR	Baton Rouge	LA	GRB	Green Bay	WI
ONT	Ontario	CA	BWI	Baltimore	MD	DAY	Dayton	OH
BUR	Glendale/Burbank	CA	MHT	Manchester	ME	CAK	Akron/Canton	OH
LGB	Long Beach	CA	PWM	Portland, ME	ME	TOL	Toledo	OH
FAT	Fresno	CA	GRR	Grand Rapids	MI	OKC	Oklahoma City	OK
SBA	Santa Barbara	CA	FNT	Flint	MI	TUL	Tulsa	OK
SIT	San Jose/Palo Alto	AZ	LAN	Lansing	MI	MDT	Harrisburg	PA
COS	Colorado Springs	CO	STL	St. Louis	MO	CHS	Charleston	SC
EGE	Eagle	CO	JAN	Jackson/Vicksburg	MS	FSD	Sioux Falls	SD
PVD	Providence	RI	GPT	Gulfport/Biloxi	MS	BNA	Nashville	TN
RDU	Raleigh/Durham	NC	ABQ	Albuquerque	NM	MEM	Memphis	TN
GSO	Greensboro/High Point	NC	BUF	Buffalo	NY	GEG	Spokane	WA
OMA	Omaha	NE	ALB	Albany	NY	BLI	Bellingham	WA
ISP	Islip/Long Island	NY	IAH	Houston	TX	LBB	Lubbock	TX
SYR	Syracuse	NY	HOU	Houston	TX	MAF	Midland/Odessa	TX
CMH	Columbus	OH	SAT	San Antonio	TX	CRP	Corpus Christi	TX
MKE	Milwaukee	WI	AUS	Austin	TX	SLC	Salt Lake City	UT
TYS	Knoxville	TN	ELP	El Paso	TX	ORF	Norfolk	VA
RIC	Richmond	VA	PHF	Newport News/Hampton	VA			

Table Appendix F. 11. 0 Airports on remote areas or located in small towns

US Airports	*Airport City*	*State*	*US Airports*	*Airport City*	*State*
ADQ	Kodiak	AK	GJT	Grand Junction	CO
OTZ	Kotzebue	AK	DRO	Durango	CO
BRW	Barrow	AK	FNL	Ft. Collins/Loveland	CO
DUT	Dutch Harbor	AK	MTJ	Montrose	CO
SCC	Prudhoe Bay	AK	GUC	Gunnison	CO
PSG	Petersburg	AK	HPN	Westchester County	CT
CDV	Cordova	AK	HVN	New Haven	CT
AKN	King Salmon	AK	VPS	Valparaiso	FL
YAK	Yakutat	AK	MLB	Melbourne	FL
DLG	Dillingham	AK	PFN	Panama City	FL
WRG	Wrangell	AK	GNV	Gainesville	FL
ENA	Kenai	AK	APF	Naples	FL
MOB	Mobile	AL	BQK	Brunswick	GA
MGM	Montgomery	AL	CSG	Columbus GA	GA
DHN	Dothan	AL	ABY	Southwest	GA
XNA	Fayetteville XNA	AR	VLD	Valdosta	GA
FSM	Ft. Smith	AR	GUM	Guam Island	GUM
YUM	Yuma	AZ	DBQ	Dubuque	IA
FLG	Flagstaff	AZ	SUX	Sioux City Int.	IA
MRY	Monterey/Carmel	CA	IDA	Idaho Falls	ID
SBP	San Luis Obispo	CA	SUN	Sun Valley/Hailey	ID
BFL	Bakersfield	CA	PIH	Pocatello	ID
RDD	Redding	CA	CMI	Champaign	IL
SMX	Santa Maria	CA	SPI	Springfield	IL
CLD	Carlsbad	CA	RFD	Rockford	IL
IYK	Inyokern	CA	SBN	South Bend	IN
OXR	Oxnard/Ventura	CA	FWA	Ft. Wayne	IN
ASE	Aspen	CO	EVV	Evansville	IN
HDN	Hayden	CO	LEX	Lexington	KY
PAH	Barkley Regional	KY	BIL	Billings	MT
SHV	Shreveport	LA	BZN	Bozeman	MT
LFT	Lafayette	LA	MSO	Missoula	MT
MLU	Monroe	LA	FCA	Kalispell	MT
AEX	Alexandria	LA	GTF	Great Falls	MT
BPT	Beaumont	TX	HLN	Helena	MT
LCH	Lake Charles	LA	BTM	Butte	MT
ACK	Nantucket	MA	ILM	Wilmington	NC
MVY	Marthas Vineyard	MA	TRI	Blountville	NC
HYA	Hyannis	MA	FAY	Fayetteville FAY	NC
BGR	Bangor	ME	EWN	New Bern	NC
BHB	Bar Harbor	ME	ISO	Kinston	NC
SJT	San Angelo	TX	ILE	Killeen	TX

Table Appendix F.11. 1 Airports on remote areas or located in small towns

US Airports	*Airport City*	*State*	*US Airports*	*Airport City*	*State*
PQI	Pesque Isle	ME	PGV	Greenville	NC
RKD	Red Oak	ME	BIS	Bismarck	ND
FAR	Fargo	ND	GFK	Grand Forks	ND
AZO	Kalamazoo	MI	MOT	Minot	ND
TVC	Traverse City	MI	LNK	Lincoln	NE
MBS	Midland/Bay City	MI	ACY	Atlantic City	NJ
RST	Rochester RST	MN	FMN	Farmington	NM
MKG	Muskegon	MI	ROW	Roswell	NM
ACT	Waco	TX	EKO	Elko	NV
DLH	Duluth	MN	VGT	North Las Vegas	NV
BJI	Bemidji	MN	ROC	Rochester ROC	NY
INL	International Falls	MN	SWF	Newburgh/Poughkeepsie	NY
SGF	Springfield/Branson	MO	BGM	Binghamton	NY
COU	Columbia Regional	MO	ITH	Ithaca	NY
MEI	Meridian	MS	ELM	Corning	NY
GTR	Columbus MS	MS	BLV	Belleville	NY
TUP	Tupelo	MS	PBG	Plattsburgh	NY
LCK	Rickenbacker	OH	SPS	Wichita Falls	TX
LAW	Lawton	OK	TYR	Tyler	TX
EUG	Eugene	OR	TXK	Texarkana	TX
MFR	Medford	OR	SGU	Saint George	UT
RDM	Bend	OR	ROA	Roanoke	VA
ACV	Arcata	CA	CRW	Charleston CRW	WV
LMT	Klamath Falls	OR	CHO	Charlottesville	VA
OTH	North Bend	OR	LYH	Lynchburg	VA
ABE	Allentown	PA	HTS	Huntington/Ashland	VA
AVP	Wilkes-Barre/Scranton	PA	LEB	Lebanon/Hanover	VT
ERI	Erie	PA	PSC	Pasco	WA
SCE	State Colleague	PA	YKM	Yakima	WA
SBY	Salisbury	MD	EAT	Wenatchee	WA
IPT	Williamsport	PA	LWS	Lewistown	WA
AVL	Fletcher	SC	PUW	Provincetown	WA
AGS	Augusta	GA	ALW	Walla Walla	WA
HHH	Hilton Head	SC	ILG	Newcastle	DE
FLO	Florence	SC	ATW	Appleton	WI
RAP	Rapid City	SD	CWA	Wausau	WI
ABR	Aberdeen	SD	LSE	La Crosse	WI
CHA	Chattanooga	TN	MQT	Marquette	WI
GRK	Killen-Ft. Hood	TX	CMX	Hancock	WI
LRD	Laredo	TX	RHI	Rhinelander City	WI
BRO	Brownsville	TX	JAC	Jackson Hole	WY
ABI	Abilene	TX	RKS	Rock Springs	WY

Appendix G: FEM model coefficient values and ANOVA tests results

Table Appendix G. 1 FEM model ANOVA test results 2005

ANOVA						
Model	FEM	Sum of Squares	df	Mean Square	F	Sig.
2005	Regression	946.16	360	2.63	130.89	0
	Residual	346.94	17,278	0.02		
	Total	1,293.11	17,638			

Table Appendix G. 2 FEM model ANOVA test results 2006

ANOVA						
Model	FEM	Sum of Squares	df	Mean Square	F	Sig.
2006	Regression	1,020.70	344	2.97	135.93	0.000
	Residual	376.270	17,237	0.02		
	Total	1,396.96	17,581			

Table Appendix G. 3 FEM model ANOVA test results 2007

ANOVA						
Model	FEM	Sum of Squares	df	Mean Square	F	Sig.
2007	Regression	1,142.67	341	3.35	147.12	0.000
	Residual	390.89	17,260	0.023		
	Total	1,533.52	17,501			

Table Appendix G. 4 FEM model ANOVA test results 2008

ANOVA						
Model	FEM	Sum of Squares	df	Mean Square	F	Sig.
2008	Regression	1,109.77	338	3.28	140.35	0.000
	Residual	393.56	16,823	0.02		
	Total	1,503.32	17,161			

Table Appendix G. 5. 0 FEM model coefficient values 2005

2005 Coefficient	*Unstand. Coef.*		*Std.. Coef.*	*t*	*Sig.*	*2005 Variables*	*Unstand. Coef.*		*Std.. Coef.*	*t*	*Sig.*
$\alpha, \beta, \gamma, \delta, \varphi_1, \varphi_{10}$	*B*	*Std. E.*	*Beta*			*Variable*	*B*	*Std. E.*	*Beta*		
A_4	-3.7E+01	1.6E+01		-2.3E+00	2.1E-02	DIST	2.0E-01	5.3E-03	4.8E-01	3.7E+01	6.2E-296
VERY SHORT	2.9E-04	6.1E-05	3.5E-02	4.8E+00	1.7E-06	NA	-6.9E-04	3.6E-04	-7.6E-03	-1.9E+00	5.6E-02
SHORT	1.6E-04	3.6E-05	4.0E-02	4.3E+00	1.4E-05	NK	-7.6E-04	1.2E-04	-2.9E-02	-6.4E+00	1.3E-10
MEDIUM	-5.6E-07	2.0E-05	-2.3E-04	-2.9E-02	9.8E-01	NW	4.5E-05	1.8E-05	1.3E-02	2.5E+00	1.2E-02
AA	-1.5E-04	1.3E-04	-4.9E-03	-1.1E+00	2.5E-01	OO	1.6E-03	8.7E-04	1.0E-02	1.9E+00	6.4E-02
AB	-5.1E-05	4.9E-05	-5.4E-03	-1.0E+00	3.0E-01	QX	-1.3E-03	4.6E-04	-1.2E-02	-2.8E+00	5.6E-03
AC	1.7E-05	4.2E-05	2.0E-03	4.0E-01	6.9E-01	SY	-9.0E-04	1.4E-04	-2.7E-02	-6.4E+00	1.8E-10
AE	-6.0E-05	4.6E-05	-7.4E-03	-1.3E+00	1.9E-01	TZ	-2.3E-04	1.0E-04	-9.3E-03	-2.2E+00	2.7E-02
BB	1.3E-04	3.7E-05	1.9E-02	3.5E+00	4.1E-04	U5	-1.1E-03	1.8E-04	-3.0E-02	-6.2E+00	6.8E-10
CC	-2.3E-05	2.8E-05	-4.9E-03	-8.1E-01	4.2E-01	UA	2.1E-04	1.8E-05	6.2E-02	1.2E+01	3.5E-31
CE	3.4E-06	5.7E-05	2.8E-04	5.9E-02	9.5E-01	US	-2.2E-04	2.1E-05	-5.2E-02	-1.0E+01	1.1E-25
DD	3.2E-05	4.0E-05	4.9E-03	8.1E-01	4.2E-01	WN	-7.4E-04	2.6E-05	-1.6E-01	-2.8E+01	3.3E-174
DE	-3.2E-05	2.1E-04	-9.1E-04	-1.5E-01	8.8E-01	XP	-2.4E-03	8.7E-04	-1.5E-02	-2.8E+00	5.4E-03
LCC-LCC	-6.1E-04	6.5E-05	-6.9E-02	-9.3E+00	1.0E-20	YX	-1.9E-04	6.1E-05	-1.3E-02	-3.1E+00	2.0E-03
FSC-LCC	-3.3E-04	4.4E-05	-1.2E-01	-7.4E+00	1.3E-13	ABE	-3.7E-04	4.8E-04	-2.5E-02	-7.6E-01	4.5E-01
T-T	1.4E-04	4.7E-05	1.5E-02	2.9E+00	3.3E-03	ABI	-1.2E-03	5.5E-04	-1.8E-02	-2.2E+00	2.7E-02
T-B	-1.3E-04	2.8E-05	-2.6E-02	-4.6E+00	3.9E-06	ABQ	-3.2E-04	4.9E-05	-3.5E-02	-6.5E+00	1.0E-10
T-R	-8.9E-05	4.8E-04	-1.7E-02	-1.9E-01	8.5E-01	ABR	-9.5E-04	7.8E-04	-6.1E-03	-1.2E+00	2.2E-01
B-B	1.5E-04	3.8E-05	2.2E-02	4.0E+00	7.7E-05	ABY	7.7E-04	7.8E-04	4.9E-03	9.8E-01	3.3E-01
B-R	8.4E-05	4.8E-04	2.3E-02	1.8E-01	8.6E-01	ACK	4.1E-04	6.0E-04	4.6E-03	6.9E-01	4.9E-01
N-R	8.7E-05	4.8E-04	2.3E-02	1.8E-01	8.6E-01	ACT	-9.0E-04	5.4E-04	-1.4E-02	-1.6E+00	1.0E-01
WN	-2.6E-05	4.4E-05	-8.5E-03	-5.9E-01	5.6E-01	ACV	-1.0E-03	5.1E-04	-2.5E-02	-2.0E+00	4.6E-02
LCC	5.8E-05	4.1E-05	1.7E-02	1.4E+00	1.6E-01	ACY	-6.8E-04	5.2E-04	-1.4E-02	-1.3E+00	1.9E-01
NO LCC	-2.0E-04	8.1E-05	-1.2E-02	-2.5E+00	1.4E-02	ADQ	-1.8E-04	4.5E-04	-1.7E-03	-4.0E-01	6.9E-01
MS	2.3E-02	2.2E-03	5.6E-02	1.0E+01	2.5E-24	AEX	-5.0E-04	5.0E-04	-1.7E-02	-1.0E+00	3.1E-01
LOWCMS	-1.1E-02	3.4E-03	-2.5E-02	-3.2E+00	1.6E-03	AGS	1.1E-04	4.9E-04	5.2E-03	2.3E-01	8.2E-01
LCMS	4.0E-02	4.6E-03	5.5E-02	8.7E+00	5.0E-18	AKN	3.3E-04	4.5E-04	3.0E-03	7.2E-01	4.7E-01
ALONE	1.6E-04	3.2E-05	3.9E-02	5.1E+00	3.6E-07	ALB	-4.2E-04	6.0E-05	-3.5E-02	-6.9E+00	5.9E-12
7H	3.0E-04	8.7E-04	1.9E-03	3.5E-01	7.3E-01	ALW	-1.6E-03	7.8E-04	-1.0E-02	-2.0E+00	4.3E-02
AA	-1.1E-04	1.7E-05	-3.3E-02	-6.2E+00	5.8E-10	AMA	-4.5E-04	9.3E-05	-2.3E-02	-4.9E+00	1.2E-06
AQ	-7.3E-04	1.2E-04	-2.6E-02	-5.9E+00	4.7E-09	ANC	1.4E-04	5.5E-05	1.5E-02	2.6E+00	1.0E-02
AS	-2.0E-04	4.6E-05	-2.3E-02	-4.4E+00	9.0E-06	APF	-9.6E-04	7.8E-04	-6.1E-03	-1.2E+00	2.2E-01
B6	-1.3E-05	7.1E-05	-7.9E-04	-1.8E-01	8.6E-01	ASE	-2.0E-04	4.9E-04	-7.6E-03	-4.0E-01	6.9E-01
BFL	-1.2E-03	5.0E-04	-4.1E-02	-2.4E+00	1.5E-02	COS	-4.7E-04	6.3E-05	-3.8E-02	-7.5E+00	9.5E-14
BGM	-8.4E-04	4.9E-04	-4.0E-02	-1.7E+00	8.7E-02	COU	-2.1E-03	7.8E-04	-1.4E-02	-2.7E+00	6.3E-03
BGR	-7.8E-04	4.8E-04	-4.8E-02	-1.6E+00	1.1E-01	CPR	-4.7E-04	5.1E-04	-1.0E-02	-9.1E-01	3.6E-01
BHB	-1.9E-04	7.8E-04	-1.2E-03	-2.4E-01	8.1E-01	CRP	-4.7E-04	7.6E-05	-3.1E-02	-6.2E+00	5.0E-10
BHM	-2.1E-04	6.3E-05	-1.8E-02	-3.4E+00	7.4E-04	CRW	-6.9E-04	4.8E-04	-4.4E-02	-1.4E+00	1.6E-01
BIL	-7.4E-04	4.8E-04	-5.2E-02	-1.5E+00	1.3E-01	CSG	9.5E-04	6.5E-04	8.6E-03	1.5E+00	1.4E-01
BIS	-4.6E-04	4.9E-04	-1.6E-02	-9.3E-01	3.5E-01	CVG	-1.4E-04	5.8E-05	-1.2E-02	-2.4E+00	1.7E-02
BJI	-1.7E-03	7.8E-04	-1.1E-02	-2.2E+00	2.6E-02	CWA	-1.0E-03	4.9E-04	-5.1E-02	-2.1E+00	3.6E-02
BLI	-1.3E-03	1.9E-04	-2.8E-02	-6.6E+00	3.7E-11	DAB	-1.7E-03	1.1E-04	-6.5E-02	-1.5E+01	2.5E-48
BLV	-1.4E-03	7.9E-04	-8.7E-03	-1.7E+00	8.7E-02	DAL	-7.0E-04	1.0E-04	-3.1E-02	-7.0E+00	3.1E-12
BMI	-1.1E-03	9.0E-05	-5.9E-02	-1.2E+01	1.3E-33	DAY	-5.1E-04	6.5E-05	-3.9E-02	-7.8E+00	5.5E-15

Table Appendix G. 5. 1 FEM model coefficient values 2005

2005 Coefficient	*Unstand. Coef.*		*Std.. Coef.*	*t*	*Sig.*	*2005 Variables*	*Unstand. Coef.*		*Std.. Coef.*	*t*	*Sig.*
γ	*B*	*Std. E.*	*Beta*			*Variable*	*B*	*Std. E.*	*Beta*		
BNA	-1.4E-04	4.7E-05	-1.7E-02	-3.0E+00	2.9E-03	DBQ	-1.4E-03	6.5E-04	-1.2E-02	-2.1E+00	3.6E-02
BOI	-6.4E-04	6.1E-05	-5.4E-02	-1.0E+01	1.9E-25	DCA	3.2E-06	4.3E-05	4.1E-04	7.6E-02	9.4E-01
BOS	-1.5E-05	4.1E-05	-1.9E-03	-3.6E-01	7.2E-01	DEN	-4.7E-05	4.1E-05	-6.5E-03	-1.1E+00	2.5E-01
BPT	-2.5E-03	6.5E-04	-2.2E-02	-3.8E+00	1.4E-04	DFW	3.8E-04	4.2E-05	4.9E-02	8.9E+00	5.7E-19
BQK	-1.4E-03	7.8E-04	-9.1E-03	-1.8E+00	6.9E-02	DHN	-3.5E-04	5.7E-04	-4.5E-03	-6.2E-01	5.4E-01
BQN	-1.3E-03	4.4E-04	-1.2E-02	-3.0E+00	2.6E-03	DLG	-9.8E-04	6.5E-04	-6.3E-03	-1.5E+00	1.3E-01
BRO	-1.5E-03	5.6E-04	-2.2E-02	-2.7E+00	6.3E-03	DLH	-1.0E-03	5.0E-04	-3.2E-02	-2.1E+00	3.7E-02
BRW	6.4E-04	6.5E-04	4.1E-03	9.8E-01	3.2E-01	DRO	-8.0E-04	5.0E-04	-2.3E-02	-1.6E+00	1.1E-01
BTM	-1.4E-03	6.5E-04	-1.3E-02	-2.2E+00	2.8E-02	DSM	-2.6E-04	6.2E-05	-2.3E-02	-4.3E+00	2.0E-05
BTR	-1.4E-04	6.7E-05	-1.1E-02	-2.1E+00	3.8E-02	DTW	1.7E-04	4.5E-05	2.0E-02	3.8E+00	1.4E-04
BTV	-7.1E-04	6.6E-05	-5.7E-02	-1.1E+01	2.1E-27	DUT	4.3E-03	6.2E-04	2.7E-02	6.9E+00	7.2E-12
BUF	-6.4E-04	5.2E-05	-6.7E-02	-1.2E+01	1.3E-34	EAT	-1.6E-03	6.0E-04	-1.7E-02	-2.6E+00	9.4E-03
BUR	-6.3E-04	5.8E-05	-5.7E-02	-1.1E+01	1.5E-27	EGE	-8.2E-04	9.3E-05	-4.0E-02	-8.8E+00	1.3E-18
BWI	-2.1E-04	4.5E-05	-2.6E-02	-4.7E+00	2.8E-06	EKO	6.7E-04	7.8E-04	6.0E-03	8.5E-01	3.9E-01
BZN	-8.2E-04	4.8E-04	-5.4E-02	-1.7E+00	9.0E-02	ELM	-1.2E-03	5.1E-04	-3.0E-02	-2.3E+00	2.2E-02
CAE	-2.0E-04	6.9E-05	-1.5E-02	-2.9E+00	3.7E-03	ELP	-2.4E-04	6.4E-05	-1.9E-02	-3.8E+00	1.6E-04
CAK	-9.5E-04	8.1E-05	-5.7E-02	-1.2E+01	7.3E-32	ENA	9.1E-05	6.2E-04	5.8E-04	1.5E-01	8.8E-01
CDV	-1.7E-03	6.5E-04	-1.6E-02	-2.7E+00	7.5E-03	ERI	-1.7E-03	4.9E-04	-9.8E-02	-3.4E+00	6.3E-04
CHA	-3.8E-04	4.9E-04	-2.2E-02	-7.8E-01	4.4E-01	EUG	-9.2E-04	4.8E-04	-5.5E-02	-1.9E+00	5.8E-02
CHO	-3.9E-04	4.9E-04	-2.1E-02	-8.1E-01	4.2E-01	EVV	-6.9E-04	4.9E-04	-4.2E-02	-1.4E+00	1.5E-01
CHS	-3.2E-04	6.9E-05	-2.3E-02	-4.7E+00	3.3E-06	EWN	-1.3E-03	5.1E-04	-3.1E-02	-2.5E+00	1.2E-02
CID	-4.7E-04	6.8E-05	-3.6E-02	-7.0E+00	2.4E-12	EWR	3.5E-04	4.4E-05	4.3E-02	8.0E+00	1.1E-15
FLL	-5.5E-04	4.4E-05	-7.0E-02	-1.2E+01	1.4E-35	IPT	-1.5E-03	7.8E-04	-9.5E-03	-1.9E+00	5.8E-02
FLO	-1.2E-03	5.4E-04	-1.9E-02	-2.2E+00	2.7E-02	ISO	-2.5E-03	7.8E-04	-1.6E-02	-3.2E+00	1.4E-03
FMN	-5.5E-04	7.8E-04	-3.5E-03	-7.1E-01	4.8E-01	ISP	-1.1E-03	8.4E-05	-6.3E-02	-1.3E+01	1.0E-39
FNL	-4.6E-04	7.9E-04	-3.0E-03	-5.8E-01	5.6E-01	ITH	-3.3E-04	5.1E-04	-7.9E-03	-6.5E-01	5.2E-01
FNT	-9.9E-04	8.5E-05	-5.4E-02	-1.2E+01	5.7E-31	ITO	-9.8E-06	1.7E-04	-2.6E-04	-5.7E-02	9.5E-01
FSD	-4.2E-04	7.4E-05	-2.9E-02	-5.7E+00	1.2E-08	IYK	3.1E-04	7.8E-04	2.0E-03	4.0E-01	6.9E-01
FSM	-7.3E-04	5.0E-04	-2.1E-02	-1.4E+00	1.5E-01	JAC	-6.3E-04	4.8E-04	-4.1E-02	-1.3E+00	1.9E-01
FWA	-3.4E-04	4.8E-04	-2.5E-02	-7.0E-01	4.9E-01	JAN	-6.5E-05	6.6E-05	-5.3E-03	-9.9E-01	3.2E-01
GEG	-5.1E-04	6.0E-05	-4.4E-02	-8.6E+00	1.1E-17	JAX	-4.1E-04	4.8E-05	-4.7E-02	-8.5E+00	1.5E-17
GFK	-7.5E-04	5.3E-04	-1.3E-02	-1.4E+00	1.6E-01	JFK	-1.9E-04	5.6E-05	-1.7E-02	-3.5E+00	5.2E-04
GJT	-5.3E-04	4.9E-04	-2.3E-02	-1.1E+00	2.8E-01	JNU	-4.7E-04	1.8E-04	-1.1E-02	-2.6E+00	9.5E-03
GNV	-1.1E-03	4.9E-04	-4.8E-02	-2.2E+00	2.9E-02	KOA	6.1E-04	8.8E-05	3.2E-02	6.9E+00	4.9E-12
GPT	-5.7E-04	8.0E-05	-3.5E-02	-7.1E+00	1.2E-12	KTN	6.2E-05	3.7E-04	6.9E-04	1.7E-01	8.7E-01
GRB	-7.8E-04	6.7E-05	-6.2E-02	-1.2E+01	1.3E-31	LAN	-1.1E-03	8.4E-05	-6.1E-02	-1.3E+01	7.2E-37
GRK	-6.8E-04	4.9E-04	-3.0E-02	-1.4E+00	1.6E-01	LAS	-2.6E-04	4.4E-05	-3.7E-02	-5.9E+00	3.1E-09
GRR	-4.6E-04	6.5E-05	-3.6E-02	-7.1E+00	9.4E-13	LAW	-2.0E-03	7.8E-04	-1.3E-02	-2.6E+00	1.0E-02
GSO	-4.7E-04	6.4E-05	-3.8E-02	-7.4E+00	1.8E-13	LAX	1.3E-04	4.2E-05	1.9E-02	3.1E+00	1.9E-03
GSP	-2.6E-04	6.6E-05	-2.0E-02	-4.0E+00	6.8E-05	LBB	-5.9E-04	8.6E-05	-3.3E-02	-6.9E+00	6.1E-12
GTF	-9.4E-04	4.9E-04	-3.7E-02	-1.9E+00	5.5E-02	LCH	-2.2E-03	7.8E-04	-1.4E-02	-2.8E+00	5.3E-03
GTR	-7.1E-04	7.9E-04	-4.6E-03	-9.1E-01	3.6E-01	LEB	1.3E-03	7.8E-04	8.0E-03	1.6E+00	1.1E-01
GUC	-1.8E-03	5.2E-04	-3.5E-02	-3.5E+00	5.2E-04	LEX	-6.0E-04	4.8E-04	-4.1E-02	-1.2E+00	2.2E-01
GUM	3.3E-03	5.3E-04	5.7E-02	6.3E+00	3.9E-10	LFT	-5.5E-04	4.9E-04	-2.6E-02	-1.1E+00	2.6E-01
HDN	-1.6E-03	4.9E-04	-7.6E-02	-3.4E+00	8.0E-04	LGA	1.6E-05	4.2E-05	2.1E-03	3.8E-01	7.0E-01
HHH	-1.6E-03	5.2E-04	-3.1E-02	-3.1E+00	1.9E-03	LGB	-1.5E-03	9.1E-05	-7.7E-02	-1.7E+01	3.4E-62
HLN	-5.9E-04	5.1E-04	-1.4E-02	-1.2E+00	2.4E-01	LIH	5.2E-04	9.3E-05	2.6E-02	5.6E+00	2.0E-08
HNL	8.0E-04	4.8E-05	9.4E-02	1.7E+01	6.3E-63	LIT	-2.2E-04	6.3E-05	-1.9E-02	-3.5E+00	4.2E-04
HOU	-1.2E-04	6.8E-05	-9.3E-03	-1.8E+00	6.7E-02	LMT	-8.5E-04	6.5E-04	-7.7E-03	-1.3E+00	1.9E-01
HPN	-6.5E-04	4.8E-04	-4.3E-02	-1.3E+00	1.8E-01	LNK	-1.1E-03	4.9E-04	-5.1E-02	-2.3E+00	1.9E-02
HRL	-6.3E-04	1.1E-04	-2.6E-02	-5.8E+00	5.4E-09	LRD	-3.0E-04	5.1E-04	-7.1E-03	-5.8E-01	5.6E-01
HSV	-1.2E-04	7.1E-05	-8.3E-03	-1.7E+00	9.9E-02	LSE	-9.0E-04	4.9E-04	-3.8E-02	-1.8E+00	6.7E-02
HTS	-1.1E-03	5.4E-04	-1.7E-02	-1.9E+00	5.3E-02	LWS	-6.8E-04	5.7E-04	-8.7E-03	-1.2E+00	2.4E-01

Table Appendix G. 5. 2 FEM model coefficient values 2005

2005 Coefficient	*Unstand. Coef.*		*Std.. Coef.*	*t*	*Sig.*	*2005 Variables*	*Unstand. Coef.*		*Std.. Coef.*	*t*	*Sig.*
γ	*B*	*Std. E.*	*Beta*			*Variable*	*B*	*Std. E.*	*Beta*		
HVN	-1.5E-03	5.3E-04	-2.8E-02	-2.9E+00	3.8E-03	LYH	-9.5E-04	5.7E-04	-1.2E-02	-1.7E+00	9.9E-02
HYA	2.0E-03	7.8E-04	1.3E-02	2.5E+00	1.2E-02	MAF	-4.1E-04	9.1E-05	-2.1E-02	-4.5E+00	7.7E-06
MFE	-5.4E-04	8.8E-05	-2.9E-02	-6.1E+00	8.2E-10	PIA	-9.4E-04	8.7E-05	-5.1E-02	-1.1E+01	2.9E-27
MFR	-8.1E-04	4.9E-04	-4.3E-02	-1.7E+00	9.5E-02	PIE	-2.0E-03	2.5E-04	-3.9E-02	-8.0E+00	1.9E-15
MGM	-2.8E-04	4.9E-04	-1.4E-02	-5.7E-01	5.7E-01	PIH	-5.1E-04	5.7E-04	-6.5E-03	-8.8E-01	3.8E-01
MHT	-5.7E-04	6.3E-05	-4.5E-02	-9.1E+00	8.0E-20	PIT	1.1E-04	4.8E-05	1.3E-02	2.4E+00	1.8E-02
MIA	-4.7E-04	4.6E-05	-5.4E-02	-1.0E+01	4.2E-24	PLN	-1.6E-03	7.8E-04	-1.1E-02	-2.1E+00	3.5E-02
MKE	-1.9E-04	4.9E-05	-2.2E-02	-3.9E+00	8.8E-05	PNS	-3.5E-04	6.5E-05	-2.8E-02	-5.3E+00	8.9E-08
MKG	-1.3E-03	6.5E-04	-1.2E-02	-2.0E+00	5.0E-02	PPG	2.2E-03	4.5E-04	2.0E-02	4.9E+00	1.0E-06
MLB	-1.7E-03	4.9E-04	-5.7E-02	-3.4E+00	6.5E-04	PQI	2.7E-04	7.8E-04	1.7E-03	3.5E-01	7.3E-01
MLI	-9.0E-04	7.0E-05	-6.7E-02	-1.3E+01	2.0E-37	PSC	-5.2E-04	4.9E-04	-2.7E-02	-1.1E+00	2.8E-01
MLU	-1.1E-03	5.0E-04	-3.5E-02	-2.1E+00	3.2E-02	PSE	-2.4E-03	4.4E-04	-2.2E-02	-5.5E+00	3.0E-08
MOB	-1.6E-04	4.8E-04	-9.7E-03	-3.2E-01	7.5E-01	PSG	-8.6E-04	4.5E-04	-7.8E-03	-1.9E+00	5.7E-02
MOT	-7.0E-04	5.4E-04	-1.2E-02	-1.3E+00	1.9E-01	PSP	-6.9E-04	7.1E-05	-4.7E-02	-9.7E+00	3.8E-22
MQT	-1.1E-03	5.2E-04	-2.2E-02	-2.1E+00	3.8E-02	PUW	-1.4E-03	7.8E-04	-8.7E-03	-1.7E+00	8.2E-02
MRY	-6.3E-04	4.9E-04	-2.8E-02	-1.3E+00	2.0E-01	PVD	-5.0E-04	5.1E-05	-5.2E-02	-9.9E+00	5.4E-23
MSN	-4.9E-04	6.5E-05	-4.0E-02	-7.6E+00	3.7E-14	PWM	-5.7E-04	6.6E-05	-4.3E-02	-8.6E+00	7.8E-18
MSO	-7.7E-04	4.9E-04	-4.4E-02	-1.6E+00	1.1E-01	RAP	-6.0E-04	4.9E-04	-3.2E-02	-1.2E+00	2.2E-01
MSP	3.0E-04	4.4E-05	3.7E-02	6.7E+00	2.6E-11	RDD	-9.3E-04	5.3E-04	-1.7E-02	-1.8E+00	8.0E-02
MSY	-3.3E-04	4.6E-05	-3.9E-02	-7.0E+00	2.5E-12	RDM	-8.1E-04	4.9E-04	-3.1E-02	-1.6E+00	1.0E-01
MTJ	-1.2E-03	5.1E-04	-2.9E-02	-2.3E+00	2.2E-02	RDU	-3.2E-04	4.5E-05	-4.1E-02	-7.1E+00	1.5E-12
MVY	8.0E-04	6.5E-04	7.2E-03	1.2E+00	2.2E-01	RFD	-1.4E-03	7.9E-04	-8.9E-03	-1.7E+00	8.1E-02
MYR	-7.5E-04	7.4E-05	-5.0E-02	-1.0E+01	1.1E-23	RIC	1.5E-05	6.3E-05	1.2E-03	2.4E-01	8.1E-01
OAJ	-1.2E-03	1.9E-04	-2.6E-02	-6.2E+00	7.0E-10	RKS	1.5E-03	6.5E-04	1.4E-02	2.3E+00	2.1E-02
OAK	-3.3E-04	5.1E-05	-3.4E-02	-6.6E+00	4.5E-11	RNO	-6.7E-04	5.2E-05	-6.8E-02	-1.3E+01	1.2E-37
OGG	4.9E-04	5.8E-05	4.4E-02	8.4E+00	4.7E-17	ROA	-2.8E-04	4.8E-04	-1.8E-02	-5.8E-01	5.6E-01
OKC	-1.8E-04	6.0E-05	-1.6E-02	-3.0E+00	2.8E-03	ROC	-7.0E-04	4.8E-04	-5.9E-02	-1.5E+00	1.4E-01
OMA	-4.4E-04	5.3E-05	-4.9E-02	-8.2E+00	3.7E-16	RST	-6.4E-04	4.9E-04	-2.3E-02	-1.3E+00	1.9E-01
OME	2.1E-04	6.5E-04	1.4E-03	3.2E-01	7.5E-01	RSW	-7.1E-04	4.9E-05	-7.9E-02	-1.4E+01	3.9E-47
ONT	-2.8E-04	4.8E-05	-3.2E-02	-5.9E+00	3.3E-09	SAN	-8.3E-05	4.1E-05	-1.1E-02	-2.0E+00	4.4E-02
ORD	7.3E-05	4.6E-05	9.7E-03	1.6E+00	1.1E-01	SAT	3.9E-05	4.5E-05	4.9E-03	8.5E-01	3.9E-01
ORF	-3.5E-04	6.1E-05	-2.9E-02	-5.8E+00	8.1E-09	SAV	-6.7E-04	6.9E-05	-4.9E-02	-9.8E+00	1.5E-22
OTH	-1.7E-03	6.5E-04	-1.5E-02	-2.6E+00	1.1E-02	SBA	-7.3E-04	7.7E-05	-4.6E-02	-9.6E+00	1.3E-21
OTZ	3.9E-04	6.5E-04	2.5E-03	6.0E-01	5.5E-01	SBN	-7.3E-04	4.8E-04	-5.1E-02	-1.5E+00	1.3E-01
OXR	4.1E-04	7.8E-04	2.6E-03	5.3E-01	6.0E-01	SBP	-9.7E-04	4.9E-04	-4.3E-02	-2.0E+00	4.6E-02
SGU	-1.7E-03	7.8E-04	-1.6E-02	-2.2E+00	2.8E-02	CO	3.5E-04	2.2E-05	7.8E-02	1.6E+01	6.6E-57
SHV	-3.2E-04	4.8E-04	-2.1E-02	-6.6E-01	5.1E-01	DH	-7.0E-04	5.8E-05	-5.3E-02	-1.2E+01	2.1E-33
SIT	-5.7E-04	3.7E-04	-6.3E-03	-1.5E+00	1.2E-01	F9	-6.8E-05	5.5E-05	-5.5E-03	-1.2E+00	2.1E-01
SJC	-3.3E-04	4.8E-05	-3.6E-02	-6.9E+00	5.6E-12	FL	-4.3E-04	3.8E-05	-5.2E-02	-1.1E+01	1.6E-28
SJT	-2.1E-03	6.5E-04	-1.9E-02	-3.3E+00	1.1E-03	G4	-1.6E-03	1.3E-04	-5.4E-02	-1.2E+01	1.3E-34
SJU	3.9E-04	5.7E-05	3.4E-02	6.9E+00	6.7E-12	HA	-2.7E-04	1.0E-04	-1.2E-02	-2.6E+00	9.3E-03
SLC	-3.1E-04	4.7E-05	-3.5E-02	-6.6E+00	4.1E-11	HP	3.7E-04	2.9E-05	6.0E-02	1.2E+01	1.3E-35
SMF	-2.5E-04	4.7E-05	-2.8E-02	-5.3E+00	1.3E-07	YKM	-1.5E-03	6.0E-04	-1.7E-02	-2.5E+00	1.2E-02
SMX	-2.8E-04	6.0E-04	-3.1E-03	-4.7E-01	6.4E-01	YUM	-9.3E-04	5.6E-04	-1.3E-02	-1.7E+00	9.4E-02
SNA	-1.6E-04	4.7E-05	-1.8E-02	-3.4E+00	7.0E-04	5.0E+01	-7.1E-02	3.3E-03	-1.2E-01	-2.1E+01	2.3E-100
SPI	-8.8E-04	5.0E-04	-2.3E-02	-1.7E+00	8.2E-02	1.0E+02	-1.5E-01	4.8E-03	-2.1E-01	-3.2E+01	1.3E-221
SPN	2.3E-03	4.4E-04	2.1E-02	5.2E+00	2.4E-07	2.0E+02	-2.2E-01	6.0E-03	-2.5E-01	-3.6E+01	1.1E-278
SRQ	-1.1E-03	8.3E-05	-6.3E-02	-1.3E+01	5.1E-41	5.0E+02	-2.9E-01	7.4E-03	-2.9E-01	-3.9E+01	0.0E+00
STL	2.0E-04	4.7E-05	2.4E-02	4.3E+00	1.4E-05	5.0E+02	-4.3E-01	9.5E-03	-3.9E-01	-4.5E+01	0.0E+00
STT	-2.8E-05	8.2E-05	-1.6E-03	-3.4E-01	7.3E-01	SBY	-2.1E-03	5.4E-04	-3.2E-02	-3.8E+00	1.5E-04
STX	7.3E-05	1.5E-04	2.1E-03	4.9E-01	6.2E-01	SCC	1.7E-03	6.5E-04	1.1E-02	2.7E+00	8.0E-03
SUN	-3.6E-04	5.2E-04	-6.8E-03	-6.8E-01	5.0E-01	SCE	-6.2E-04	4.9E-04	-2.9E-02	-1.3E+00	2.1E-01
SUX	-1.0E-04	7.8E-04	-6.5E-04	-1.3E-01	9.0E-01	SDF	-4.1E-04	5.6E-05	-4.4E-02	-7.4E+00	1.3E-13

Table Appendix G. 5. 3 FEM model coefficient values 2005

2005 Coefficient	*Unstand. Coef.*		*Std.. Coef.*	*t*	*Sig.*	*2005 Variables*	*Unstand. Coef.*		*Std.. Coef.*	*t*	*Sig.*
γ	*B*	*Std. E.*	*Beta*			*Variable*	*B*	*Std. E.*	*Beta*		
SWF	-1.0E-03	4.9E-04	-5.5E-02	-2.1E+00	3.4E-02	SFB	-4.2E-03	6.2E-04	-2.7E-02	-6.7E+00	1.6E-11
SYR	-4.8E-04	6.7E-05	-3.6E-02	-7.3E+00	3.8E-13	SFO	-1.4E-04	4.1E-05	-1.8E-02	-3.3E+00	8.4E-04
TLH	-7.7E-04	8.3E-05	-4.4E-02	-9.3E+00	1.5E-20	SGF	-5.0E-04	4.8E-04	-3.6E-02	-1.0E+00	3.1E-01
TOL	-9.8E-04	8.4E-05	-5.6E-02	-1.2E+01	4.4E-31	PBI	-7.8E-04	5.0E-05	-8.4E-02	-1.6E+01	5.5E-55
TPA	-5.0E-04	4.4E-05	-6.4E-02	-1.1E+01	9.1E-30	PDX	-1.5E-04	4.1E-05	-1.9E-02	-3.6E+00	2.8E-04
TRI	-4.0E-04	4.9E-04	-2.1E-02	-8.2E-01	4.1E-01	PFN	-5.6E-04	4.9E-04	-2.3E-02	-1.1E+00	2.5E-01
TUL	-2.5E-04	6.5E-05	-2.0E-02	-3.9E+00	1.0E-04	PGV	-1.8E-03	6.0E-04	-2.0E-02	-3.1E+00	2.2E-03
TUS	-4.2E-04	5.6E-05	-4.1E-02	-7.5E+00	8.0E-14	PHF	-1.0E-03	8.4E-05	-5.8E-02	-1.2E+01	4.0E-33
TVC	-9.8E-04	4.9E-04	-5.1E-02	-2.0E+00	4.5E-02	PHL	1.3E-04	4.2E-05	1.7E-02	3.1E+00	2.2E-03
TYR	-9.6E-04	4.4E-04	-2.1E-02	-2.2E+00	2.9E-02	PHX	-1.5E-04	4.2E-05	-2.1E-02	-3.6E+00	3.1E-04
TYS	-2.1E-04	6.9E-05	-1.5E-02	-3.0E+00	2.3E-03	MBS	-1.1E-03	4.9E-04	-5.3E-02	-2.4E+00	1.9E-02
VPS	-5.7E-04	4.8E-04	-3.4E-02	-1.2E+00	2.4E-01	MCI	-2.1E-04	4.5E-05	-2.7E-02	-4.7E+00	3.2E-06
WRG	-1.4E-03	6.2E-04	-8.9E-03	-2.2E+00	2.6E-02	MCO	-3.2E-04	4.4E-05	-4.5E-02	-7.2E+00	5.4E-13
XNA	-2.6E-04	4.8E-04	-1.8E-02	-5.3E-01	5.9E-01	MDT	-1.4E-04	6.7E-05	-1.1E-02	-2.2E+00	3.1E-02
YAK	-1.9E-03	4.5E-04	-1.7E-02	-4.2E+00	2.7E-05	MDW	-6.9E-04	6.7E-05	-5.2E-02	-1.0E+01	6.8E-25
MEI	-4.7E-04	7.8E-04	-3.0E-03	-6.0E-01	5.5E-01	FAI	6.1E-04	1.1E-04	2.6E-02	5.8E+00	8.0E-09
MEM	2.9E-04	5.5E-05	3.2E-02	5.4E+00	8.2E-08	FAR	-5.1E-04	4.9E-04	-2.8E-02	-1.1E+00	2.9E-01
IAD	-2.9E-04	4.6E-05	-3.4E-02	-6.3E+00	2.9E-10	FAT	-5.0E-04	6.9E-05	-3.6E-02	-7.3E+00	2.6E-13
IAH	-1.5E-05	4.5E-05	-1.9E-03	-3.3E-01	7.4E-01	FAY	-5.3E-04	4.9E-04	-2.0E-02	-1.1E+00	2.8E-01
ICT	-3.2E-04	6.4E-05	-2.7E-02	-5.1E+00	4.0E-07	FCA	-7.7E-04	4.9E-04	-3.5E-02	-1.6E+00	1.1E-01
IDA	-4.6E-04	5.0E-04	-1.3E-02	-9.2E-01	3.6E-01	FLG	-2.2E-03	7.8E-04	-1.4E-02	-2.8E+00	5.4E-03
IFP	-1.7E-03	6.3E-04	-1.1E-02	-2.6E+00	8.9E-03	CLD	-2.5E-03	7.8E-04	-1.6E-02	-3.2E+00	1.2E-03
ILM	-1.1E-03	4.9E-04	-6.1E-02	-2.2E+00	2.5E-02	CLE	-8.4E-06	4.7E-05	-9.7E-04	-1.8E-01	8.6E-01
IND	-3.1E-04	4.7E-05	-3.8E-02	-6.7E+00	2.6E-11	CLL	-1.1E-03	5.1E-04	-2.6E-02	-2.2E+00	3.1E-02
EYW	-1.1E-03	8.5E-05	-6.2E-02	-1.3E+01	5.3E-41	CLT	2.4E-04	4.8E-05	2.8E-02	5.1E+00	3.3E-07
AVL	-5.6E-04	4.8E-04	-3.5E-02	-1.2E+00	2.5E-01	CMH	-2.1E-04	4.7E-05	-2.5E-02	-4.3E+00	1.5E-05
AVP	-7.3E-04	4.9E-04	-3.9E-02	-1.5E+00	1.3E-01	CMI	-1.1E-03	4.9E-04	-4.3E-02	-2.3E+00	2.1E-02
AZO	-6.7E-04	4.8E-04	-4.3E-02	-1.4E+00	1.7E-01	CMX	-1.2E-03	7.8E-04	-7.8E-03	-1.6E+00	1.2E-01
BDL	-2.9E-04	4.6E-05	-3.3E-02	-6.2E+00	6.5E-10	ATW	-9.4E-04	4.8E-04	-6.3E-02	-1.9E+00	5.2E-02
BET	-1.0E-04	6.5E-04	-6.7E-04	-1.6E-01	8.7E-01	AUS	-6.6E-05	4.7E-05	-7.9E-03	-1.4E+00	1.6E-01
ATL	2.9E-04	4.6E-05	3.6E-02	6.3E+00	3.8E-10						

Table Appendix G. 6. 0 FEM model coefficient values 2006

2006 Coefficient	*Unstand. Coef.*		*Std.. Coef.*	*t*	*Sig.*	*2005 Variables*	*Unstand. Coef.*		*Std.. Coef.*	*t*	*Sig.*
α, β, γ, δ, φ_1, φ_{10}	*B*	*Std. E.*	*Beta*			*Variable*	*B*	*Std. E.*	*Beta*		
A_4	1.4E+02	9.5E+00		1.5E+01	1.3E-51	DIST	2.2E-01	5.5E-03	5.1E-01	4.0E+01	0.0E+00
VERY SHORT	4.3E-04	6.5E-05	4.8E-02	6.6E+00	4.2E-11	F9	-1.9E-04	5.4E-05	-1.6E-02	-3.5E+00	3.9E-04
SHORT	2.4E-04	3.8E-05	5.8E-02	6.4E+00	1.7E-10	FL	-7.4E-04	3.9E-05	-9.3E-02	-1.9E+01	8.5E-79
MEDIUM	4.5E-05	2.0E-05	1.8E-02	2.2E+00	2.7E-02	G4	-1.8E-03	1.2E-04	-6.4E-02	-1.5E+01	1.8E-48
AA	-2.0E-04	1.4E-04	-6.4E-03	-1.5E+00	1.3E-01	HA	9.4E-05	1.1E-04	4.1E-03	8.7E-01	3.8E-01
AB	-9.5E-05	5.2E-05	-9.5E-03	-1.8E+00	6.7E-02	HP	5.7E-04	3.2E-05	8.5E-02	1.8E+01	2.1E-72
AC	-1.8E-05	4.4E-05	-2.1E-03	-4.1E-01	6.8E-01	NK	-3.0E-04	1.2E-04	-1.1E-02	-2.5E+00	1.4E-02
AE	-9.6E-05	4.7E-05	-1.2E-02	-2.0E+00	4.2E-02	NW	8.8E-05	2.1E-05	2.3E-02	4.2E+00	2.7E-05
BB	8.6E-05	3.9E-05	1.2E-02	2.2E+00	2.7E-02	OO	-1.4E-04	2.8E-04	-2.1E-03	-5.0E-01	6.2E-01
CC	-3.0E-05	2.9E-05	-6.5E-03	-1.1E+00	2.9E-01	SY	-7.7E-04	1.5E-04	-2.2E-02	-5.1E+00	3.9E-07
CE	-1.0E-04	5.6E-05	-9.0E-03	-1.9E+00	6.4E-02	TZ	-5.5E-05	1.5E-04	-1.6E-03	-3.8E-01	7.0E-01
DD	5.6E-06	4.2E-05	8.2E-04	1.4E-01	8.9E-01	U5	-4.3E-04	2.3E-04	-9.8E-03	-1.8E+00	6.8E-02
DE	-2.4E-04	2.0E-04	-6.7E-03	-1.2E+00	2.3E-01	UA	3.6E-04	1.9E-05	1.1E-01	1.9E+01	3.7E-77
LCC-LCC	-6.1E-04	5.2E-05	-7.2E-02	-1.2E+01	3.3E-31	US	3.9E-04	2.4E-05	9.3E-02	1.7E+01	8.2E-61
FSC-LCC	-3.4E-04	2.4E-05	-1.3E-01	-1.4E+01	3.7E-46	WN	-5.1E-04	2.7E-05	-1.1E-01	-1.9E+01	2.2E-81
T-T	2.0E-04	4.7E-05	2.1E-02	4.3E+00	2.0E-05	YX	1.9E-04	6.6E-05	1.2E-02	2.8E+00	4.6E-03
T-B	-9.9E-05	2.9E-05	-1.9E-02	-3.4E+00	6.5E-04	ABE	2.0E-03	1.6E-04	1.3E-01	1.3E+01	1.3E-38
T-R	-2.1E-04	3.3E-05	-3.9E-02	-6.5E+00	9.0E-11	ABI	1.5E-03	3.0E-04	2.2E-02	5.0E+00	6.2E-07
B-B	1.3E-04	3.9E-05	1.8E-02	3.3E+00	1.0E-03	ABQ	2.5E-03	1.5E-04	2.7E-01	1.6E+01	1.7E-59
N-R	-3.7E-05	2.7E-05	-9.3E-03	-1.3E+00	1.8E-01	ABR	1.9E-03	6.6E-04	1.2E-02	3.0E+00	3.1E-03
LCC	4.3E-05	3.0E-05	1.2E-02	1.4E+00	1.5E-01	ABY	2.9E-03	6.6E-04	1.8E-02	4.5E+00	7.8E-06
MORE THAN 1	-1.2E-04	3.8E-05	-1.6E-02	-3.2E+00	1.3E-03	ACK	3.1E-03	4.0E-04	3.3E-02	7.8E+00	7.7E-15
MS	1.9E-02	2.4E-03	4.3E-02	7.9E+00	4.1E-15	ACT	1.8E-03	2.6E-04	3.3E-02	6.9E+00	5.1E-12
LOWCMS	-2.1E-03	3.6E-03	-4.6E-03	-5.9E-01	5.6E-01	ACV	1.6E-03	2.3E-04	3.5E-02	6.9E+00	6.5E-12
LCMS	2.6E-02	4.8E-03	3.4E-02	5.3E+00	1.0E-07	ACY	1.6E-03	2.8E-04	2.8E-02	5.7E+00	1.0E-08
NOT ALONE	-1.3E-04	3.3E-05	-3.0E-02	-3.9E+00	8.8E-05	ADQ	2.5E-03	4.9E-04	2.2E-02	5.1E+00	4.1E-07
7H	-3.9E-04	9.1E-04	-2.4E-03	-4.3E-01	6.6E-01	AEX	2.1E-03	1.8E-04	7.2E-02	1.1E+01	3.1E-30
AQ	-2.8E-04	1.4E-04	-8.5E-03	-2.0E+00	4.7E-02	AGS	3.0E-03	1.8E-04	1.0E-01	1.6E+01	3.2E-60
AS	-8.8E-05	4.7E-05	-1.0E-02	-1.9E+00	5.9E-02	AKN	3.1E-03	4.9E-04	2.7E-02	6.3E+00	2.9E-10
B6	-1.3E-04	5.8E-05	-1.0E-02	-2.2E+00	2.7E-02	ALB	2.3E-03	1.5E-04	1.7E-01	1.5E+01	1.5E-48
CO	4.8E-04	2.3E-05	1.1E-01	2.1E+01	2.9E-98	ALW	1.1E-03	6.6E-04	6.5E-03	1.6E+00	1.1E-01
DL	8.7E-05	1.8E-05	2.8E-02	4.8E+00	1.9E-06	AMA	2.2E-03	1.6E-04	1.2E-01	1.4E+01	6.6E-43
E9	-2.6E-03	6.6E-04	-2.8E-02	-4.0E+00	6.6E-05	ANC	3.0E-03	1.5E-04	2.7E-01	1.9E+01	2.5E-82
APF	1.5E-03	6.6E-04	9.1E-03	2.2E+00	2.5E-02	BZN	2.4E-03	1.6E-04	1.5E-01	1.5E+01	4.0E-52
ASE	2.4E-03	1.8E-04	9.1E-02	1.4E+01	8.9E-43	CAE	2.6E-03	1.5E-04	1.9E-01	1.7E+01	8.9E-66
ATL	3.2E-03	1.5E-04	3.9E-01	2.1E+01	2.4E-92	CAK	1.6E-03	1.6E-04	9.7E-02	1.0E+01	2.5E-24
ATW	1.7E-03	1.6E-04	1.1E-01	1.1E+01	7.5E-28	CDV	1.3E-03	6.9E-04	1.1E-02	1.9E+00	5.7E-02
AUS	2.6E-03	1.5E-04	3.0E-01	1.7E+01	2.2E-67	CHA	2.5E-03	1.6E-04	1.4E-01	1.6E+01	3.1E-54
AVL	2.4E-03	1.6E-04	1.3E-01	1.5E+01	2.2E-49	CHO	2.3E-03	1.6E-04	1.1E-01	1.4E+01	6.8E-46
AVP	1.8E-03	1.6E-04	9.4E-02	1.1E+01	9.4E-30	CHS	2.8E-03	1.5E-04	2.0E-01	1.8E+01	4.0E-71
AZO	2.2E-03	1.6E-04	1.3E-01	1.4E+01	2.2E-45	CID	2.1E-03	1.5E-04	1.6E-01	1.4E+01	5.2E-42
BDL	2.4E-03	1.5E-04	2.6E-01	1.6E+01	1.4E-55	CLD	5.7E-05	2.3E-04	1.2E-03	2.5E-01	8.1E-01
BET	2.8E-03	6.9E-04	1.7E-02	4.1E+00	4.0E-05	CLE	2.5E-03	1.5E-04	2.7E-01	1.7E+01	5.1E-61
BFL	1.5E-03	1.7E-04	6.6E-02	8.8E+00	1.3E-18	CLL	1.4E-03	2.4E-04	2.8E-02	5.8E+00	7.4E-09
BGM	2.0E-03	1.7E-04	8.0E-02	1.2E+01	4.1E-31	CLT	2.6E-03	1.5E-04	2.9E-01	1.7E+01	6.6E-63
BGR	2.2E-03	1.6E-04	1.3E-01	1.4E+01	1.5E-44	CMH	2.4E-03	1.5E-04	2.8E-01	1.6E+01	2.8E-58
BHM	2.6E-03	1.5E-04	2.0E-01	1.7E+01	1.1E-62	CMI	1.6E-03	1.8E-04	5.5E-02	8.9E+00	9.2E-19
BIL	2.3E-03	1.6E-04	1.5E-01	1.5E+01	3.3E-49	COS	1.9E-03	1.5E-04	1.5E-01	1.2E+01	1.4E-34
BIS	2.4E-03	1.8E-04	8.0E-02	1.3E+01	8.7E-38	CPR	2.9E-03	2.5E-04	5.6E-02	1.2E+01	6.1E-31
BLI	1.7E-03	2.2E-04	4.0E-02	7.6E+00	2.5E-14	CRP	2.1E-03	1.6E-04	1.3E-01	1.3E+01	4.9E-40
BLV	1.6E-03	6.7E-04	1.0E-02	2.5E+00	1.3E-02	CRW	2.2E-03	1.6E-04	1.3E-01	1.4E+01	8.5E-43

Table Appendix G. 6. 1 FEM model coefficient values 2006

2006 Coefficient	*Unstand. Coef.*		*Stand. Coef.*	*t*	*Sig.*	*2006 Variables*	*Unstand. Coef.*		*Stand. Coef.*	*T*	*Sig.*
γ	*B*	*Std. E.*	*Beta*			*Variable*	*B*	*Std. E.*	*Beta*		
BMI	1.6E-03	1.6E-04	8.9E-02	1.0E+01	2.0E-23	CSG	4.7E-03	6.6E-04	2.9E-02	7.2E+00	6.0E-13
BNA	2.5E-03	1.5E-04	2.9E-01	1.7E+01	2.2E-63	CVG	3.2E-03	1.5E-04	2.6E-01	2.1E+01	1.1E-94
BOI	2.2E-03	1.5E-04	1.8E-01	1.4E+01	3.6E-45	CWA	1.7E-03	1.6E-04	8.1E-02	1.1E+01	7.4E-26
BOS	2.7E-03	1.5E-04	3.4E-01	1.7E+01	7.6E-67	DAB	1.1E-03	1.7E-04	4.7E-02	6.6E+00	4.5E-11
BPT	4.4E-04	6.6E-04	2.7E-03	6.7E-01	5.0E-01	DAL	1.3E-03	1.7E-04	6.6E-02	7.8E+00	5.1E-15
BQK	1.4E-03	6.6E-04	8.4E-03	2.1E+00	3.8E-02	DAY	2.3E-03	1.5E-04	1.7E-01	1.5E+01	1.6E-51
BQN	1.1E-03	3.2E-04	1.5E-02	3.4E+00	6.2E-04	DBQ	1.2E-03	3.5E-04	1.5E-02	3.5E+00	5.1E-04
BRO	1.0E-03	2.7E-04	1.8E-02	3.8E+00	1.6E-04	DCA	2.7E-03	1.5E-04	3.2E-01	1.8E+01	2.3E-70
BRW	3.8E-03	6.9E-04	2.3E-02	5.5E+00	4.2E-08	DEN	2.6E-03	1.5E-04	3.4E-01	1.7E+01	1.2E-62
BTM	1.6E-03	6.6E-04	9.6E-03	2.4E+00	1.8E-02	DFW	2.9E-03	1.5E-04	3.6E-01	1.9E+01	2.0E-80
BTR	2.1E-03	1.5E-04	1.5E-01	1.4E+01	5.1E-42	DHN	3.1E-03	4.0E-04	3.3E-02	7.9E+00	3.6E-15
BTV	1.9E-03	1.5E-04	1.4E-01	1.3E+01	9.8E-36	DLG	2.6E-03	4.9E-04	2.3E-02	5.3E+00	1.0E-07
BUF	2.0E-03	1.5E-04	2.0E-01	1.3E+01	4.0E-38	DLH	1.7E-03	2.0E-04	4.7E-02	8.5E+00	1.7E-17
BUR	2.2E-03	1.5E-04	1.8E-01	1.4E+01	2.4E-45	DRO	1.9E-03	1.9E-04	6.0E-02	1.0E+01	6.8E-24
BWI	2.4E-03	1.5E-04	2.9E-01	1.6E+01	4.4E-58	DSM	2.4E-03	1.5E-04	1.9E-01	1.5E+01	1.8E-53
DTW	2.8E-03	1.5E-04	3.3E-01	1.8E+01	5.4E-73	GRK	2.2E-03	1.7E-04	1.0E-01	1.3E+01	1.3E-38
DUT	6.7E-03	6.6E-04	4.1E-02	1.0E+01	4.1E-24	GRR	2.3E-03	1.5E-04	1.8E-01	1.5E+01	2.9E-51
EAT	1.4E-03	3.5E-04	1.7E-02	3.8E+00	1.2E-04	GSO	2.3E-03	1.5E-04	1.7E-01	1.5E+01	3.6E-49
EGE	1.8E-03	1.7E-04	8.5E-02	1.1E+01	1.5E-27	GSP	2.8E-03	1.5E-04	2.0E-01	1.8E+01	4.0E-72
EKO	1.7E-03	4.8E-04	1.5E-02	3.5E+00	4.5E-04	GTF	2.3E-03	1.7E-04	9.3E-02	1.3E+01	1.7E-39
ELM	1.2E-03	2.0E-04	3.3E-02	5.9E+00	2.9E-09	GUC	1.5E-03	3.2E-04	2.1E-02	4.7E+00	2.9E-06
ELP	2.3E-03	1.5E-04	1.7E-01	1.5E+01	1.1E-51	GUM	5.8E-03	2.7E-04	1.0E-01	2.2E+01	3.4E-102
ENA	2.6E-03	6.6E-04	1.6E-02	3.9E+00	9.8E-05	HDN	1.2E-03	1.7E-04	5.2E-02	7.1E+00	9.3E-13
ERI	1.1E-03	1.6E-04	6.0E-02	7.0E+00	2.3E-12	HHH	1.5E-03	2.7E-04	2.7E-02	5.7E+00	9.2E-09
EUG	1.8E-03	1.6E-04	1.1E-01	1.2E+01	3.9E-31	HLN	2.4E-03	2.2E-04	5.6E-02	1.1E+01	5.1E-28
EVV	2.3E-03	1.6E-04	1.3E-01	1.4E+01	1.2E-45	HNL	3.2E-03	1.5E-04	3.6E-01	2.1E+01	4.6E-95
EWN	1.5E-03	2.1E-04	3.7E-02	7.0E+00	2.9E-12	HOU	2.3E-03	1.6E-04	1.7E-01	1.5E+01	1.0E-47
EWR	2.8E-03	1.5E-04	3.3E-01	1.8E+01	1.8E-75	HPN	2.1E-03	1.6E-04	1.2E-01	1.3E+01	3.7E-38
EYW	1.6E-03	1.6E-04	7.8E-02	9.5E+00	1.8E-21	HRL	2.0E-03	1.7E-04	8.1E-02	1.1E+01	7.9E-30
FAI	3.3E-03	1.8E-04	1.3E-01	1.8E+01	2.1E-75	HSV	2.8E-03	1.5E-04	2.0E-01	1.8E+01	9.9E-72
FAR	2.3E-03	1.6E-04	1.2E-01	1.4E+01	5.9E-45	HTS	1.7E-03	3.5E-04	2.1E-02	4.8E+00	1.5E-06
FAT	2.2E-03	1.5E-04	1.6E-01	1.4E+01	2.4E-47	HVN	1.3E-05	6.6E-04	8.0E-05	2.0E-02	9.8E-01
FAY	2.3E-03	1.8E-04	9.0E-02	1.3E+01	2.9E-40	IAD	2.5E-03	1.5E-04	2.6E-01	1.6E+01	1.1E-58
FCA	2.4E-03	1.7E-04	1.0E-01	1.4E+01	1.6E-43	IAH	2.5E-03	1.5E-04	2.9E-01	1.7E+01	1.9E-61
FLG	1.1E-03	3.5E-04	1.4E-02	3.2E+00	1.5E-03	ICT	2.6E-03	1.5E-04	2.0E-01	1.7E+01	8.4E-66
FLL	2.1E-03	1.5E-04	2.6E-01	1.4E+01	3.7E-44	IDA	2.4E-03	1.8E-04	9.3E-02	1.4E+01	8.9E-44
FLO	1.3E-03	4.8E-04	1.1E-02	2.7E+00	7.1E-03	IFP	1.2E-03	5.0E-04	1.1E-02	2.4E+00	1.5E-02
FNL	1.4E-03	6.7E-04	8.9E-03	2.2E+00	3.1E-02	ILM	1.9E-03	1.6E-04	1.0E-01	1.2E+01	1.7E-31
FNT	1.6E-03	1.6E-04	9.0E-02	1.0E+01	2.1E-23	IND	2.4E-03	1.5E-04	2.9E-01	1.6E+01	6.8E-59
FSD	2.4E-03	1.6E-04	1.5E-01	1.5E+01	8.0E-52	IPT	7.7E-04	6.6E-04	4.7E-03	1.2E+00	2.4E-01
FSM	1.8E-03	2.1E-04	4.5E-02	8.5E+00	2.7E-17	ISO	3.2E-04	6.6E-04	2.0E-03	4.9E-01	6.3E-01
FWA	2.6E-03	1.5E-04	1.7E-01	1.7E+01	5.3E-63	ISP	1.4E-03	1.7E-04	6.0E-02	7.9E+00	2.5E-15
GEG	2.3E-03	1.5E-04	1.9E-01	1.5E+01	6.4E-51	ITH	2.0E-03	2.2E-04	4.7E-02	9.2E+00	3.8E-20
GFK	2.1E-03	2.6E-04	3.8E-02	8.0E+00	1.1E-15	ITO	1.9E-03	2.3E-04	4.7E-02	8.3E+00	1.4E-16
GJT	2.2E-03	1.7E-04	9.1E-02	1.3E+01	1.9E-37	IYK	3.3E-03	6.6E-04	2.0E-02	4.9E+00	7.9E-07
GNV	2.0E-03	1.8E-04	7.8E-02	1.2E+01	4.5E-31	JAC	1.9E-03	1.6E-04	1.2E-01	1.2E+01	1.8E-35
GPT	2.1E-03	1.6E-04	1.4E-01	1.3E+01	2.2E-40	JAN	2.6E-03	1.5E-04	2.0E-01	1.7E+01	2.2E-63
GRB	1.8E-03	1.5E-04	1.3E-01	1.2E+01	2.4E-32	JAX	2.3E-03	1.5E-04	2.5E-01	1.5E+01	2.8E-50
JFK	2.3E-03	1.6E-04	1.9E-01	1.5E+01	1.5E-49	MHT	2.2E-03	1.5E-04	1.6E-01	1.4E+01	1.9E-45
JNU	2.3E-03	2.2E-04	5.9E-02	1.1E+01	4.2E-27	MIA	2.2E-03	1.5E-04	2.3E-01	1.4E+01	2.5E-45
KOA	2.7E-03	1.6E-04	1.6E-01	1.7E+01	4.3E-62	MKE	2.5E-03	1.5E-04	2.6E-01	1.6E+01	1.3E-59
KTN	2.6E-03	3.6E-04	3.2E-02	7.3E+00	2.4E-13	MKG	1.0E-03	4.8E-04	8.7E-03	2.1E+00	3.6E-02
LAN	1.6E-03	1.6E-04	8.2E-02	9.7E+00	3.0E-22	MLB	1.4E-03	2.0E-04	3.9E-02	7.0E+00	2.7E-12

Table Appendix G. 6. 2 FEM model coefficient values 2006

2006 Coefficient	*Unstand. Coef.*		*Stand. Coef.*	*t*	*Sig.*	*2006 Variables*	*Unstand. Coef.*		*Stand. Coef.*	*T*	*Sig.*
γ	*B*	*Std. E.*	*Beta*			*Variable*	*B*	*Std. E.*	*Beta*		
LAS	2.5E-03	1.5E-04	3.3E-01	1.6E+01	1.4E-56	MLI	1.5E-03	1.5E-04	1.1E-01	9.5E+00	2.7E-21
LAW	1.3E-03	4.8E-04	1.2E-02	2.8E+00	5.3E-03	MLU	1.9E-03	1.8E-04	6.4E-02	1.0E+01	7.0E-25
LAX	2.8E-03	1.5E-04	3.9E-01	1.8E+01	2.2E-74	MOB	2.8E-03	1.6E-04	1.6E-01	1.8E+01	3.2E-69
LBB	2.1E-03	1.6E-04	1.1E-01	1.3E+01	3.4E-37	MOT	1.8E-03	3.0E-04	2.8E-02	6.1E+00	8.3E-10
LCH	1.1E-03	4.0E-04	1.2E-02	2.8E+00	5.5E-03	MQT	1.3E-03	2.2E-04	3.0E-02	5.9E+00	3.5E-09
LEB	3.5E-03	6.6E-04	2.1E-02	5.3E+00	1.3E-07	MRY	2.0E-03	1.6E-04	9.8E-02	1.2E+01	4.7E-34
LEX	2.4E-03	1.5E-04	1.6E-01	1.5E+01	3.3E-53	MSN	2.1E-03	1.5E-04	1.6E-01	1.4E+01	1.1E-43
LFT	2.1E-03	1.6E-04	1.1E-01	1.3E+01	9.0E-39	MSO	2.3E-03	1.6E-04	1.3E-01	1.5E+01	6.4E-49
LGA	2.6E-03	1.5E-04	3.1E-01	1.7E+01	1.9E-62	MSP	3.0E-03	1.5E-04	3.7E-01	2.0E+01	3.5E-87
LGB	1.3E-03	1.8E-04	4.8E-02	7.1E+00	1.1E-12	MSY	2.3E-03	1.5E-04	2.6E-01	1.6E+01	6.4E-54
LIH	2.8E-03	1.6E-04	1.6E-01	1.7E+01	6.4E-65	MTJ	1.4E-03	2.0E-04	4.0E-02	7.0E+00	3.7E-12
LIT	2.6E-03	1.5E-04	2.1E-01	1.7E+01	3.3E-66	MYR	2.0E-03	1.6E-04	1.3E-01	1.3E+01	3.8E-37
LMT	1.9E-03	4.8E-04	1.6E-02	3.9E+00	9.2E-05	OAJ	1.8E-03	2.5E-04	3.4E-02	7.1E+00	1.7E-12
LNK	1.8E-03	1.7E-04	7.2E-02	1.0E+01	1.6E-25	OAK	2.3E-03	1.5E-04	2.2E-01	1.5E+01	2.3E-51
LRD	2.3E-03	2.4E-04	4.8E-02	9.7E+00	2.6E-22	OGG	2.8E-03	1.6E-04	2.5E-01	1.8E+01	3.6E-74
LSE	1.9E-03	1.9E-04	6.0E-02	1.0E+01	3.0E-24	OKC	2.6E-03	1.5E-04	2.2E-01	1.7E+01	7.1E-63
LWS	1.8E-03	2.8E-04	3.0E-02	6.5E+00	7.3E-11	OMA	2.2E-03	1.5E-04	2.4E-01	1.5E+01	6.0E-50
LYH	2.1E-03	2.8E-04	3.4E-02	7.4E+00	1.2E-13	OME	2.8E-03	6.9E-04	1.7E-02	4.1E+00	4.3E-05
MAF	2.1E-03	1.6E-04	1.0E-01	1.3E+01	6.3E-36	ONT	2.4E-03	1.5E-04	2.5E-01	1.6E+01	6.5E-54
MBS	1.6E-03	1.7E-04	6.5E-02	9.3E+00	1.1E-20	ORD	2.7E-03	1.5E-04	3.4E-01	1.8E+01	3.4E-68
MCI	2.5E-03	1.5E-04	3.1E-01	1.6E+01	2.0E-60	ORF	2.4E-03	1.5E-04	1.9E-01	1.6E+01	3.9E-55
MCO	2.4E-03	1.5E-04	3.2E-01	1.5E+01	1.0E-53	OTH	1.3E-03	4.8E-04	1.1E-02	2.6E+00	8.8E-03
MDT	2.6E-03	1.5E-04	1.8E-01	1.7E+01	2.2E-62	OTZ	3.1E-03	6.9E-04	1.9E-02	4.5E+00	7.9E-06
MDW	2.0E-03	1.6E-04	1.4E-01	1.3E+01	7.6E-37	OXR	2.9E-03	6.6E-04	1.8E-02	4.4E+00	1.4E-05
MEM	3.1E-03	1.5E-04	3.2E-01	2.0E+01	8.0E-91	PBI	1.9E-03	1.5E-04	2.0E-01	1.3E+01	1.7E-37
MFE	2.0E-03	1.6E-04	1.1E-01	1.3E+01	8.4E-36	PDX	2.5E-03	1.5E-04	3.1E-01	1.6E+01	1.7E-58
MFR	2.1E-03	1.6E-04	1.1E-01	1.3E+01	5.0E-37	PFN	2.3E-03	1.8E-04	8.6E-02	1.3E+01	1.7E-38
MGM	2.5E-03	1.7E-04	1.2E-01	1.5E+01	9.3E-51	PGV	2.0E-04	6.6E-04	1.2E-03	3.0E-01	7.7E-01
PHF	1.7E-03	1.6E-04	9.5E-02	1.1E+01	5.4E-27	SBY	7.4E-04	2.8E-04	1.2E-02	2.6E+00	8.6E-03
PHL	2.6E-03	1.5E-04	3.3E-01	1.7E+01	1.6E-66	SCC	4.9E-03	6.9E-04	3.0E-02	7.1E+00	1.1E-12
PHX	2.4E-03	1.5E-04	3.3E-01	1.6E+01	4.2E-57	SCE	2.1E-03	1.7E-04	9.7E-02	1.3E+01	1.1E-37
PIA	1.7E-03	1.6E-04	9.0E-02	1.1E+01	2.3E-26	SDF	2.4E-03	1.5E-04	2.5E-01	1.6E+01	3.7E-58
PIE	5.4E-04	3.4E-04	9.4E-03	1.6E+00	1.1E-01	SEA	2.7E-03	1.5E-04	3.7E-01	1.7E+01	1.0E-66
PIT	2.5E-03	1.5E-04	2.8E-01	1.7E+01	2.3E-62	SFB	1.6E-03	7.9E-04	1.4E-02	2.1E+00	3.9E-02
PNS	2.5E-03	1.5E-04	1.9E-01	1.6E+01	9.9E-59	SFO	2.5E-03	1.5E-04	3.2E-01	1.6E+01	5.0E-58
PPG	4.4E-03	4.9E-04	3.8E-02	9.0E+00	1.6E-19	SGF	2.6E-03	1.5E-04	1.8E-01	1.7E+01	1.0E-62
PSC	2.4E-03	1.7E-04	1.2E-01	1.5E+01	5.9E-49	SGU	4.2E-04	4.0E-04	4.5E-03	1.1E+00	2.9E-01
PSE	4.8E-04	3.5E-04	6.0E-03	1.4E+00	1.7E-01	SHV	2.6E-03	1.6E-04	1.7E-01	1.7E+01	8.9E-63
PSG	2.0E-03	6.6E-04	1.3E-02	3.1E+00	1.9E-03	SIT	2.2E-03	4.0E-04	2.3E-02	5.4E+00	6.2E-08
PSP	2.0E-03	1.6E-04	1.4E-01	1.3E+01	4.1E-36	SJC	2.3E-03	1.5E-04	2.5E-01	1.5E+01	7.6E-51
PUW	1.4E-03	6.6E-04	8.7E-03	2.1E+00	3.3E-02	SJT	5.3E-04	4.8E-04	4.6E-03	1.1E+00	2.6E-01
PVD	2.2E-03	1.5E-04	2.1E-01	1.5E+01	5.7E-48	SJU	2.7E-03	1.5E-04	2.6E-01	1.8E+01	3.5E-70
PWM	2.2E-03	1.5E-04	1.6E-01	1.4E+01	2.5E-45	SLC	2.7E-03	1.5E-04	3.1E-01	1.8E+01	6.7E-69
RAP	2.6E-03	1.6E-04	1.3E-01	1.6E+01	8.1E-56	SMF	2.4E-03	1.5E-04	2.7E-01	1.6E+01	2.0E-55
RDD	1.7E-03	2.7E-04	2.9E-02	6.2E+00	4.9E-10	SMX	1.2E-03	3.2E-04	1.6E-02	3.7E+00	2.5E-04
RDM	1.7E-03	1.7E-04	7.6E-02	1.0E+01	1.1E-23	SNA	2.5E-03	1.5E-04	2.8E-01	1.6E+01	2.1E-58
RDU	2.5E-03	1.5E-04	3.0E-01	1.7E+01	1.3E-61	SPI	1.6E-03	3.2E-04	2.2E-02	5.0E+00	6.7E-07
RFD	7.2E-04	4.0E-04	7.7E-03	1.8E+00	6.9E-02	SPN	5.1E-03	4.8E-04	4.4E-02	1.1E+01	4.8E-26
RIC	2.6E-03	1.5E-04	2.0E-01	1.7E+01	7.7E-63	SRQ	1.5E-03	1.6E-04	8.4E-02	9.3E+00	1.4E-20
RKS	3.4E-03	6.6E-04	2.1E-02	5.2E+00	1.9E-07	STL	2.8E-03	1.5E-04	3.3E-01	1.9E+01	2.0E-76
RNO	2.1E-03	1.5E-04	2.1E-01	1.4E+01	1.1E-44	STT	2.5E-03	1.6E-04	1.4E-01	1.5E+01	2.0E-51
ROA	2.6E-03	1.6E-04	1.6E-01	1.6E+01	2.0E-59	STX	2.4E-03	2.1E-04	6.4E-02	1.2E+01	3.3E-31
ROC	2.1E-03	1.5E-04	1.6E-01	1.4E+01	1.4E-42	SUN	2.6E-03	2.5E-04	5.0E-02	1.0E+01	6.7E-25

Table Appendix G. 6. 3 FEM model coefficient values 2006

2006 Coefficient	*Unstand. Coef.*		*Stand. Coef.*	*t*	*Sig.*	*2006 Variables*	*Unstand. Coef.*		*Stand. Coef.*	*T*	*Sig.*
γ	*B*	*Std. E.*	*Beta*			*Variable*	*B*	*Std. E.*	*Beta*		
RST	1.9E-03	1.7E-04	7.5E-02	1.1E+01	9.1E-28	SUX	2.7E-03	6.6E-04	1.6E-02	4.0E+00	5.3E-05
RSW	2.0E-03	1.5E-04	2.2E-01	1.3E+01	9.0E-41	SWF	1.5E-03	1.7E-04	6.4E-02	8.8E+00	1.4E-18
SAN	2.5E-03	1.5E-04	3.3E-01	1.6E+01	6.6E-60	SYR	2.2E-03	1.5E-04	1.8E-01	1.5E+01	3.5E-48
SAT	2.6E-03	1.5E-04	3.1E-01	1.7E+01	4.8E-65	TLH	2.1E-03	1.6E-04	1.1E-01	1.3E+01	8.5E-38
SAV	2.4E-03	1.5E-04	1.7E-01	1.6E+01	2.8E-54	TOL	1.9E-03	1.7E-04	7.8E-02	1.1E+01	2.8E-28
SBA	1.8E-03	1.6E-04	1.2E-01	1.1E+01	6.4E-30	TPA	2.2E-03	1.5E-04	2.7E-01	1.5E+01	2.7E-48
SBN	1.8E-03	1.6E-04	1.2E-01	1.2E+01	1.4E-30	TRI	2.7E-03	1.7E-04	1.3E-01	1.6E+01	3.6E-58
SBP	1.6E-03	1.7E-04	7.3E-02	9.8E+00	9.7E-23	TUL	2.4E-03	1.5E-04	2.0E-01	1.6E+01	8.6E-57
YAK	9.7E-04	4.9E-04	8.4E-03	2.0E+00	4.7E-02	TUS	2.3E-03	1.5E-04	2.3E-01	1.5E+01	1.7E-50
YKM	1.4E-03	4.0E-04	1.5E-02	3.6E+00	3.3E-04	TVC	1.9E-03	1.6E-04	9.5E-02	1.2E+01	1.1E-31
YUM	3.9E-04	2.7E-04	6.7E-03	1.5E+00	1.5E-01	TYR	2.0E-03	2.5E-04	4.0E-02	8.2E+00	2.1E-16
TYS	2.5E-03	1.5E-04	1.9E-01	1.6E+01	4.3E-60	WRG	1.7E-03	6.6E-04	1.1E-02	2.6E+00	8.1E-03
VPS	2.5E-03	1.6E-04	1.4E-01	1.6E+01	1.4E-56	XNA	2.7E-03	1.5E-04	2.0E-01	1.7E+01	5.3E-67

Table Appendix G. 7. 0 FEM model coefficient values 2007

2007 Coefficient	*Unstand. Coef.*		*Std.. Coef.*	*t*	*Sig.*	*2005 Variables*	*Unstand. Coef.*		*Std.. Coef.*	*t*	*Sig.*
α, β, γ, δ, φ_1*,* φ_{10}	*B*	*Std. E.*	*Beta*			*Variable*	*B*	*Std. E.*	*Beta*		
A_4	1.2E+02	2.5E+01		4.7E+00	2.6E-06	DIST	2.5E-01	5.6E-03	5.5E-01	4.4E+01	0.0E+00
VERY SHORT	5.0E-04	6.7E-05	5.2E-02	7.5E+00	7.2E-14	CO	2.8E-03	2.1E-04	5.6E-01	1.3E+01	1.4E-38
SHORT	2.9E-04	3.9E-05	6.8E-02	7.6E+00	3.1E-14	DL	2.6E-03	2.1E-04	8.0E-01	1.2E+01	7.2E-33
MEDIUM	6.5E-05	2.1E-05	2.5E-02	3.1E+00	2.0E-03	F9	2.2E-03	2.2E-04	1.8E-01	1.0E+01	1.8E-23
AA	-2.8E-04	1.4E-04	-8.5E-03	-2.0E+00	4.1E-02	FL	1.5E-03	2.2E-04	1.9E-01	6.9E+00	7.3E-12
AB	-9.6E-05	5.3E-05	-9.3E-03	-1.8E+00	6.9E-02	G4	1.4E-04	2.3E-04	6.3E-03	6.2E-01	5.4E-01
AC	-7.6E-05	4.5E-05	-8.3E-03	-1.7E+00	9.2E-02	HA	2.2E-03	2.4E-04	9.1E-02	9.0E+00	1.8E-19
AE	-1.4E-04	4.7E-05	-1.7E-02	-3.1E+00	2.1E-03	HP	2.6E-03	2.3E-04	1.5E-01	1.2E+01	2.1E-31
BB	7.7E-05	3.9E-05	1.0E-02	2.0E+00	5.1E-02	NK	1.6E-03	2.4E-04	6.4E-02	6.7E+00	2.8E-11
CC	-2.2E-05	3.0E-05	-4.3E-03	-7.2E-01	4.7E-01	NW	2.5E-03	2.1E-04	6.2E-01	1.2E+01	4.6E-31
CE	-1.1E-04	5.4E-05	-9.7E-03	-2.0E+00	4.1E-02	OO	1.1E-03	3.3E-04	1.9E-02	3.5E+00	4.8E-04
DD	5.4E-07	4.3E-05	7.4E-05	1.3E-02	9.9E-01	QX	2.6E-03	7.0E-04	1.5E-02	3.7E+00	2.0E-04
DE	-5.4E-04	1.9E-04	-1.5E-02	-2.8E+00	5.0E-03	SY	1.6E-03	2.7E-04	4.1E-02	5.8E+00	8.3E-09
LCC-LCC	-3.8E-04	5.1E-05	-4.9E-02	-7.5E+00	8.7E-14	TZ	2.2E-03	2.5E-04	7.0E-02	9.0E+00	3.4E-19
FSC-LCC	-2.4E-04	2.4E-05	-8.5E-02	-9.7E+00	3.3E-22	U5	1.8E-03	3.0E-04	4.3E-02	6.0E+00	1.7E-09
T-T	1.2E-04	4.8E-05	1.3E-02	2.6E+00	1.0E-02	UA	2.8E-03	2.1E-04	7.8E-01	1.3E+01	8.0E-39
T-B	-4.5E-05	2.9E-05	-8.5E-03	-1.5E+00	1.3E-01	US	3.0E-03	2.1E-04	7.8E-01	1.4E+01	7.3E-45
T-R	-1.3E-03	7.0E-04	-2.3E-01	-1.8E+00	6.4E-02	YV	7.7E-05	7.2E-04	4.5E-04	1.1E-01	9.1E-01
B-B	2.0E-04	4.0E-05	2.6E-02	4.9E+00	1.1E-06	YX	2.6E-03	2.2E-04	1.7E-01	1.2E+01	1.6E-30
B-R	-1.1E-03	7.0E-04	-2.7E-01	-1.6E+00	1.2E-01	ABE	1.9E-03	1.4E-04	1.1E-01	1.3E+01	1.5E-39
N-R	-1.1E-03	7.0E-04	-2.7E-01	-1.6E+00	9.9E-02	ABI	1.6E-03	2.6E-04	2.7E-02	6.1E+00	1.3E-09
NO WN	-1.9E-03	2.1E-04	-4.1E-01	-8.9E+00	5.8E-19	ABQ	1.4E-03	6.9E-04	1.4E-01	2.0E+00	4.9E-02
LCC	-2.3E-05	3.0E-05	-6.5E-03	-7.8E-01	4.3E-01	ABR	2.7E-03	6.7E-04	1.6E-02	4.0E+00	6.6E-05
MORE THAN 1	-1.3E-05	3.6E-05	-1.8E-03	-3.6E-01	7.2E-01	ABY	3.9E-03	6.7E-04	2.3E-02	5.9E+00	4.3E-09
MS	2.4E-02	2.4E-03	5.2E-02	9.9E+00	5.6E-23	ACK	2.5E-03	4.8E-04	2.1E-02	5.3E+00	1.5E-07
LOWCMS	3.5E-03	3.7E-03	7.1E-03	9.4E-01	3.5E-01	ACT	1.7E-03	2.4E-04	3.1E-02	6.9E+00	6.1E-12
LCMS	1.5E-02	5.0E-03	1.9E-02	3.0E+00	2.7E-03	ACV	1.7E-03	2.1E-04	3.8E-02	8.2E+00	3.6E-16
ALONE	9.9E-05	3.4E-05	2.2E-02	2.9E+00	3.6E-03	ACY	1.5E-03	2.5E-04	3.0E-02	6.1E+00	1.2E-09
7H	2.1E-03	9.5E-04	1.2E-02	2.2E+00	2.7E-02	ADQ	1.6E-03	8.4E-04	1.3E-02	1.9E+00	5.7E-02
AA	2.5E-03	2.1E-04	7.0E-01	1.2E+01	9.1E-32	AEX	2.2E-03	1.6E-04	8.1E-02	1.4E+01	2.2E-42

Table Appendix G. 7. 1 FEM model coefficient values 2007

2007 Coefficient	*Unstand. Coef.*		*Stand. Coef.*	*t*	*Sig.*	*2007 Variables*	*Unstand. Coef.*		*Stand. Coef.*	*T*	*Sig.*
β, γ	*B*	*Std. E.*	*Beta*			*Variable*	*B*	*Std. E.*	*Beta*		
AQ	2.0E-03	2.6E-04	5.8E-02	7.9E+00	4.2E-15	AGS	2.7E-03	1.6E-04	1.1E-01	1.7E+01	2.2E-64
AS	2.3E-03	2.2E-04	2.5E-01	1.1E+01	9.7E-26	AKN	2.0E-03	8.4E-04	1.7E-02	2.4E+00	1.7E-02
B6	2.5E-03	2.2E-04	2.1E-01	1.1E+01	7.3E-30	ALB	1.2E-03	6.9E-04	8.4E-02	1.7E+00	8.1E-02
ALW	9.8E-04	6.7E-04	5.8E-03	1.5E+00	1.4E-01	BUF	9.9E-04	6.9E-04	9.4E-02	1.4E+00	1.5E-01
AMA	1.1E-03	7.0E-04	5.2E-02	1.6E+00	1.2E-01	BUR	1.0E-03	6.9E-04	7.8E-02	1.5E+00	1.5E-01
ANC	2.0E-03	6.9E-04	1.8E-01	2.9E+00	3.6E-03	BWI	1.4E-03	6.9E-04	1.5E-01	2.0E+00	4.6E-02
APF	1.6E-03	6.7E-04	9.6E-03	2.5E+00	1.4E-02	BZN	2.6E-03	1.4E-04	1.5E-01	1.8E+01	3.8E-74
ASE	2.6E-03	1.6E-04	9.7E-02	1.6E+01	5.3E-59	CAE	1.6E-03	6.9E-04	1.1E-01	2.3E+00	1.9E-02
ATL	2.3E-03	6.9E-04	2.7E-01	3.3E+00	9.8E-04	CAK	6.5E-04	6.9E-04	3.8E-02	9.4E-01	3.5E-01
ATW	1.9E-03	1.4E-04	1.2E-01	1.4E+01	1.3E-42	CDV	7.6E-04	9.7E-04	6.3E-03	7.8E-01	4.3E-01
AUS	1.5E-03	6.9E-04	1.6E-01	2.1E+00	3.2E-02	CHA	2.5E-03	1.4E-04	1.4E-01	1.7E+01	2.5E-67
AVL	2.3E-03	1.4E-04	1.2E-01	1.6E+01	1.7E-57	CHO	2.3E-03	1.5E-04	1.0E-01	1.5E+01	5.6E-51
AVP	1.6E-03	1.5E-04	8.2E-02	1.1E+01	1.3E-27	CHS	1.3E-03	6.9E-04	9.1E-02	1.8E+00	6.5E-02
AZO	2.3E-03	1.5E-04	1.2E-01	1.6E+01	1.2E-55	CID	1.1E-03	6.9E-04	7.7E-02	1.6E+00	1.2E-01
BDL	1.3E-03	6.9E-04	1.4E-01	1.9E+00	5.5E-02	CLD	-3.6E-05	2.3E-04	-6.9E-04	-1.5E-01	8.8E-01
BET	2.1E-03	9.7E-04	1.2E-02	2.2E+00	3.0E-02	CLE	1.5E-03	6.9E-04	1.5E-01	2.2E+00	2.8E-02
BFL	1.9E-03	1.6E-04	6.9E-02	1.2E+01	1.0E-31	CLL	1.4E-03	2.0E-04	3.3E-02	6.7E+00	1.5E-11
BGM	1.6E-03	1.5E-04	6.9E-02	1.0E+01	1.2E-25	CLT	1.4E-03	6.9E-04	1.5E-01	2.0E+00	4.3E-02
BGR	2.3E-03	1.5E-04	1.2E-01	1.6E+01	8.2E-58	CMH	1.2E-03	6.9E-04	1.3E-01	1.8E+00	7.5E-02
BHM	1.4E-03	6.9E-04	1.1E-01	2.0E+00	4.9E-02	CMI	1.9E-03	1.8E-04	5.5E-02	1.0E+01	1.3E-25
BIL	2.4E-03	1.4E-04	1.5E-01	1.7E+01	8.4E-65	COS	7.7E-04	6.9E-04	5.8E-02	1.1E+00	2.6E-01
BIS	2.7E-03	1.7E-04	9.2E-02	1.6E+01	2.0E-58	CPR	3.3E-03	2.9E-04	4.8E-02	1.1E+01	1.8E-29
BLI	6.8E-04	7.0E-04	2.0E-02	9.8E-01	3.3E-01	CRP	1.1E-03	6.9E-04	6.2E-02	1.6E+00	1.2E-01
BLV	2.4E-03	6.7E-04	1.4E-02	3.6E+00	3.5E-04	CRW	2.3E-03	1.4E-04	1.3E-01	1.6E+01	4.1E-59
BMI	5.9E-04	6.9E-04	3.2E-02	8.4E-01	4.0E-01	CSG	3.3E-03	6.7E-04	1.9E-02	4.9E+00	9.2E-07
BNA	1.5E-03	6.9E-04	1.6E-01	2.2E+00	2.8E-02	CVG	2.4E-03	6.9E-04	1.9E-01	3.4E+00	5.9E-04
BOI	1.1E-03	6.9E-04	8.3E-02	1.5E+00	1.3E-01	CWA	1.9E-03	1.5E-04	8.3E-02	1.2E+01	2.9E-35
BOS	1.6E-03	6.9E-04	1.9E-01	2.3E+00	2.4E-02	DAB	2.8E-04	7.0E-04	1.3E-02	4.1E-01	6.8E-01
BPT	7.2E-04	6.7E-04	4.2E-03	1.1E+00	2.8E-01	DAL	5.0E-04	7.0E-04	2.5E-02	7.3E-01	4.7E-01
BQK	1.7E-03	6.7E-04	9.9E-03	2.5E+00	1.2E-02	DAY	1.3E-03	6.9E-04	9.4E-02	1.9E+00	5.9E-02
BQN	2.5E-04	7.3E-04	4.4E-03	3.4E-01	7.3E-01	DBQ	1.4E-03	4.0E-04	1.4E-02	3.5E+00	4.5E-04
BRO	1.4E-03	2.8E-04	2.2E-02	5.0E+00	5.0E-07	DCA	1.7E-03	6.9E-04	1.9E-01	2.5E+00	1.4E-02
BRW	3.0E-03	9.7E-04	1.8E-02	3.1E+00	2.1E-03	DEN	1.4E-03	6.9E-04	1.9E-01	2.1E+00	3.7E-02
BTM	1.4E-03	6.7E-04	8.2E-03	2.1E+00	3.8E-02	DFW	1.7E-03	6.9E-04	2.0E-01	2.5E+00	1.3E-02
BTR	1.0E-03	6.9E-04	6.8E-02	1.5E+00	1.4E-01	DHN	3.4E-03	4.8E-04	2.9E-02	7.2E+00	7.3E-13
BTV	8.4E-04	6.9E-04	5.9E-02	1.2E+00	2.2E-01	DLG	1.7E-04	9.7E-04	9.7E-04	1.7E-01	8.6E-01
DLH	1.7E-03	1.6E-04	6.4E-02	1.1E+01	7.2E-27	GPT	9.7E-04	6.9E-04	6.0E-02	1.4E+00	1.6E-01
DRO	2.1E-03	1.7E-04	7.0E-02	1.2E+01	2.6E-35	GRB	9.6E-04	6.9E-04	6.4E-02	1.4E+00	1.7E-01
DSM	1.4E-03	6.9E-04	9.9E-02	2.0E+00	5.0E-02	GRK	2.1E-03	1.5E-04	9.8E-02	1.4E+01	2.1E-44
DTW	1.7E-03	6.9E-04	1.9E-01	2.4E+00	1.7E-02	GRR	1.4E-03	6.9E-04	9.7E-02	2.0E+00	4.8E-02
DUT	5.7E-03	9.5E-04	3.4E-02	6.0E+00	2.3E-09	GSO	1.0E-03	6.9E-04	7.3E-02	1.5E+00	1.4E-01
EAT	1.7E-03	3.5E-04	1.9E-02	4.7E+00	2.5E-06	GSP	1.7E-03	6.9E-04	1.2E-01	2.4E+00	1.5E-02
EGE	9.4E-04	7.0E-04	4.1E-02	1.4E+00	1.8E-01	GTF	2.5E-03	1.6E-04	8.8E-02	1.5E+01	7.4E-51
ELM	1.2E-03	1.7E-04	4.0E-02	6.9E+00	4.7E-12	GTR	2.1E-03	6.7E-04	1.2E-02	3.1E+00	2.2E-03
ELP	1.3E-03	6.9E-04	9.7E-02	1.9E+00	5.7E-02	GUC	9.4E-04	3.2E-04	1.2E-02	2.9E+00	3.3E-03
ENA	1.4E-03	9.5E-04	8.1E-03	1.4E+00	1.5E-01	GUM	6.0E-03	2.6E-04	1.0E-01	2.3E+01	1.5E-111
ERI	1.3E-03	1.5E-04	5.7E-02	8.6E+00	8.5E-18	HDN	1.5E-03	1.5E-04	6.4E-02	9.8E+00	1.6E-22
EUG	1.8E-03	1.4E-04	1.1E-01	1.3E+01	3.8E-39	HHH	1.7E-03	2.0E-04	4.2E-02	8.6E+00	1.2E-17
EVV	2.5E-03	1.5E-04	1.3E-01	1.7E+01	4.1E-66	HLN	2.9E-03	2.4E-04	5.5E-02	1.2E+01	3.2E-34
EWN	1.4E-03	1.8E-04	4.3E-02	8.1E+00	8.2E-16	HNL	2.2E-03	6.9E-04	2.3E-01	3.2E+00	1.5E-03
EWR	1.7E-03	6.9E-04	1.9E-01	2.4E+00	1.7E-02	HOU	1.2E-03	6.9E-04	8.3E-02	1.7E+00	8.3E-02
EYW	8.6E-04	7.0E-04	3.9E-02	1.2E+00	2.2E-01	HPN	1.8E-03	1.4E-04	9.8E-02	1.3E+01	2.5E-36
FAI	2.3E-03	7.0E-04	8.3E-02	3.3E+00	1.1E-03	HRL	9.7E-04	7.0E-04	3.6E-02	1.4E+00	1.6E-01

Table Appendix G. 7. 2 FEM model coefficient values 2007

2007 Coefficient	*Unstand. Coef.*		*Stand. Coef.*	*t*	*Sig.*	*2007 Variables*	*Unstand. Coef.*		*Stand. Coef.*	*t*	*Sig.*
γ	*B*	*Std. E.*	*Beta*			*Variable*	*B*	*Std. E.*	*Beta*		
FAR	2.7E-03	1.5E-04	1.3E-01	1.8E+01	2.0E-73	HSV	1.6E-03	6.9E-04	1.1E-01	2.4E+00	1.8E-02
FAT	1.1E-03	6.9E-04	7.4E-02	1.6E+00	1.1E-01	HTS	1.4E-03	3.2E-04	1.9E-02	4.5E+00	7.4E-06
FAY	2.4E-03	1.6E-04	9.9E-02	1.6E+01	3.4E-55	IAD	1.4E-03	6.9E-04	1.4E-01	2.0E+00	4.3E-02
FCA	2.5E-03	1.5E-04	1.1E-01	1.6E+01	4.5E-58	IAH	1.5E-03	6.9E-04	1.8E-01	2.2E+00	2.7E-02
FLG	1.0E-03	3.0E-04	1.4E-02	3.4E+00	8.0E-04	ICT	1.4E-03	6.9E-04	1.0E-01	2.0E+00	4.6E-02
FLL	1.1E-03	6.9E-04	1.3E-01	1.6E+00	1.2E-01	IDA	2.6E-03	1.6E-04	1.0E-01	1.6E+01	6.4E-59
FLO	1.1E-03	4.0E-04	1.1E-02	2.7E+00	7.3E-03	IFP	-6.9E-04	8.1E-04	-7.0E-03	-8.6E-01	3.9E-01
FNL	2.1E-03	6.7E-04	1.3E-02	3.2E+00	1.6E-03	ILM	1.5E-03	1.5E-04	7.8E-02	1.0E+01	4.5E-25
FNT	5.5E-04	6.9E-04	3.0E-02	7.9E-01	4.3E-01	IND	1.4E-03	6.9E-04	1.6E-01	2.1E+00	3.7E-02
FSD	1.2E-03	6.9E-04	7.7E-02	1.8E+00	7.5E-02	IPT	1.1E-03	6.7E-04	6.7E-03	1.7E+00	8.6E-02
FSM	2.3E-03	2.1E-04	5.1E-02	1.1E+01	4.0E-27	ISP	1.7E-04	7.0E-04	7.2E-03	2.4E-01	8.1E-01
FWA	2.6E-03	1.4E-04	1.5E-01	1.9E+01	4.1E-77	ITH	1.6E-03	2.0E-04	3.8E-02	7.7E+00	1.3E-14
GEG	1.2E-03	6.9E-04	9.4E-02	1.7E+00	8.8E-02	ITO	7.3E-04	7.1E-04	1.8E-02	1.0E+00	3.1E-01
GFK	2.5E-03	2.8E-04	3.8E-02	8.9E+00	5.7E-19	IYK	3.9E-03	6.7E-04	2.3E-02	5.8E+00	8.0E-09
GJT	2.5E-03	1.6E-04	9.2E-02	1.6E+01	1.4E-54	JAC	2.3E-03	1.4E-04	1.4E-01	1.6E+01	3.4E-59
GNV	2.0E-03	1.7E-04	7.0E-02	1.2E+01	1.4E-33	JAN	1.4E-03	6.9E-04	1.0E-01	2.0E+00	4.5E-02
JAX	1.2E-03	6.9E-04	1.2E-01	1.7E+00	9.0E-02	MHT	1.1E-03	6.9E-04	7.0E-02	1.5E+00	1.3E-01
JFK	1.2E-03	6.9E-04	1.1E-01	1.8E+00	7.3E-02	MIA	1.2E-03	6.9E-04	1.2E-01	1.8E+00	7.9E-02
JNU	1.2E-03	7.1E-04	2.8E-02	1.6E+00	1.0E-01	MKE	1.4E-03	6.9E-04	1.4E-01	2.0E+00	5.0E-02
KOA	1.7E-03	6.9E-04	1.1E-01	2.5E+00	1.2E-02	MKG	1.1E-03	4.8E-04	9.3E-03	2.3E+00	2.1E-02
KTN	1.4E-03	7.7E-04	1.7E-02	1.9E+00	6.0E-02	MLB	1.6E-03	2.1E-04	3.6E-02	7.4E+00	1.2E-13
LAN	6.2E-04	7.0E-04	2.8E-02	8.9E-01	3.7E-01	MLI	5.0E-04	6.9E-04	3.4E-02	7.2E-01	4.7E-01
LAS	1.4E-03	6.9E-04	1.7E-01	2.0E+00	5.1E-02	MLU	2.1E-03	1.7E-04	6.9E-02	1.2E+01	3.4E-34
LAW	1.8E-03	4.8E-04	1.5E-02	3.8E+00	1.3E-04	MOB	2.9E-03	1.4E-04	1.7E-01	2.0E+01	5.7E-90
LAX	1.7E-03	6.9E-04	2.3E-01	2.5E+00	1.1E-02	MOT	2.3E-03	3.2E-04	3.0E-02	7.2E+00	5.7E-13
LBB	1.0E-03	6.9E-04	5.2E-02	1.5E+00	1.4E-01	MQT	1.8E-03	2.3E-04	3.5E-02	7.7E+00	1.7E-14
LCH	1.6E-03	4.8E-04	1.4E-02	3.4E+00	7.3E-04	MRY	2.2E-03	1.5E-04	9.7E-02	1.4E+01	9.0E-47
LEX	2.4E-03	1.4E-04	1.5E-01	1.7E+01	1.3E-67	MSN	1.2E-03	6.9E-04	8.5E-02	1.7E+00	8.4E-02
LFT	2.4E-03	1.5E-04	1.1E-01	1.6E+01	1.9E-57	MSO	2.6E-03	1.4E-04	1.4E-01	1.8E+01	4.3E-73
LGA	1.3E-03	6.9E-04	1.5E-01	1.9E+00	6.0E-02	MSP	2.0E-03	6.9E-04	2.3E-01	2.8E+00	4.6E-03
LGB	-8.6E-05	7.0E-04	-3.2E-03	-1.2E-01	9.0E-01	MSY	1.4E-03	6.9E-04	1.6E-01	2.1E+00	3.8E-02
LIH	1.8E-03	6.9E-04	9.7E-02	2.5E+00	1.2E-02	MTJ	1.4E-03	1.8E-04	4.4E-02	8.1E+00	5.9E-16
LIT	1.4E-03	6.9E-04	1.2E-01	2.1E+00	3.6E-02	MYR	7.2E-04	6.9E-04	4.2E-02	1.0E+00	3.0E-01
LMT	1.9E-03	4.8E-04	1.5E-02	3.9E+00	1.1E-04	OAJ	8.0E-04	7.0E-04	2.7E-02	1.1E+00	2.5E-01
LNK	2.1E-03	1.7E-04	6.8E-02	1.2E+01	7.0E-34	OAK	1.1E-03	6.9E-04	9.9E-02	1.6E+00	1.1E-01
LRD	2.4E-03	2.1E-04	5.7E-02	1.2E+01	5.1E-32	OGG	1.9E-03	6.9E-04	1.5E-01	2.7E+00	6.7E-03
LSE	1.9E-03	1.8E-04	5.8E-02	1.1E+01	5.4E-27	OKC	1.5E-03	6.9E-04	1.2E-01	2.1E+00	3.2E-02
LWS	2.0E-03	3.2E-04	2.6E-02	6.2E+00	7.2E-10	OMA	1.2E-03	6.9E-04	1.2E-01	1.8E+00	7.6E-02
LYH	2.4E-03	3.5E-04	2.8E-02	6.8E+00	8.1E-12	OME	1.7E-03	9.7E-04	1.0E-02	1.8E+00	7.2E-02
MAF	1.1E-03	7.0E-04	5.5E-02	1.6E+00	1.1E-01	ONT	1.3E-03	6.9E-04	1.3E-01	1.8E+00	7.1E-02
MBS	1.8E-03	1.6E-04	7.0E-02	1.1E+01	3.8E-30	ORD	1.7E-03	6.9E-04	2.1E-01	2.5E+00	1.4E-02
MCI	1.4E-03	6.9E-04	1.6E-01	2.0E+00	4.9E-02	ORF	1.4E-03	6.9E-04	1.1E-01	2.0E+00	4.8E-02
MCO	1.4E-03	6.9E-04	1.8E-01	2.0E+00	4.5E-02	OTH	1.4E-03	4.8E-04	1.1E-02	2.9E+00	4.3E-03
MDT	9.8E-04	6.9E-04	6.9E-02	1.4E+00	1.6E-01	OTZ	2.0E-03	9.7E-04	1.2E-02	2.1E+00	4.0E-02
MDW	1.0E-03	6.9E-04	6.5E-02	1.5E+00	1.5E-01	PBI	7.8E-04	6.9E-04	7.6E-02	1.1E+00	2.6E-01
MEM	2.0E-03	6.9E-04	1.9E-01	2.8E+00	4.4E-03	PDX	1.4E-03	6.9E-04	1.6E-01	2.0E+00	4.5E-02
MFE	1.1E-03	6.9E-04	5.6E-02	1.6E+00	1.1E-01	PFN	2.6E-03	1.7E-04	9.2E-02	1.6E+01	6.4E-56
MFR	1.9E-03	1.5E-04	9.8E-02	1.3E+01	1.4E-39	PHF	8.3E-04	6.9E-04	4.4E-02	1.2E+00	2.3E-01
MGM	2.6E-03	1.5E-04	1.1E-01	1.7E+01	2.1E-65	PHL	1.4E-03	6.9E-04	1.8E-01	2.1E+00	3.7E-02
PHX	1.4E-03	6.9E-04	1.9E-01	2.0E+00	4.4E-02	SCE	2.1E-03	1.5E-04	9.4E-02	1.4E+01	1.0E-44
PIA	5.0E-04	6.9E-04	2.5E-02	7.2E-01	4.7E-01	SDF	1.3E-03	6.9E-04	1.3E-01	1.9E+00	5.4E-02
PIE	-4.5E-04	7.5E-04	-7.5E-03	-6.0E-01	5.5E-01	SEA	1.6E-03	6.9E-04	2.1E-01	2.3E+00	2.1E-02
PIT	1.2E-03	6.9E-04	1.3E-01	1.8E+00	7.5E-02	SFO	1.5E-03	6.9E-04	1.8E-01	2.1E+00	3.5E-02

Table Appendix G. 7. 3 FEM model coefficient values 2007

2007 Coefficient	*Unstand. Coef.*		*Stand. Coef.*	*t*	*Sig.*	*2007 Variables*	*Unstand. Coef.*		*Stand. Coef.*	*t*	*Sig.*
γ	*B*	*Std. E.*	*Beta*			*Variable*	*B*	*Std. E.*	*Beta*		
PNS	1.4E-03	6.9E-04	1.1E-01	2.1E+00	3.8E-02	SGF	2.7E-03	1.4E-04	1.7E-01	2.0E+01	8.0E-85
PPG	3.6E-03	8.4E-04	3.0E-02	4.4E+00	1.4E-05	SGU	-1.3E-03	4.9E-04	-1.1E-02	-2.7E+00	8.0E-03
PSC	2.6E-03	1.5E-04	1.1E-01	1.7E+01	4.3E-63	SHV	2.8E-03	1.4E-04	1.6E-01	2.0E+01	7.5E-86
PSE	-3.9E-04	7.4E-04	-6.1E-03	-5.4E-01	5.9E-01	SIT	1.2E-03	7.9E-04	1.2E-02	1.5E+00	1.4E-01
PSG	9.7E-04	9.5E-04	5.7E-03	1.0E+00	3.1E-01	SJC	1.2E-03	6.9E-04	1.2E-01	1.7E+00	8.4E-02
PSP	8.0E-04	6.9E-04	5.4E-02	1.2E+00	2.5E-01	SJT	1.7E-03	4.0E-04	1.7E-02	4.2E+00	3.0E-05
PUW	1.6E-03	6.7E-04	9.4E-03	2.4E+00	1.8E-02	SJU	1.4E-03	6.9E-04	1.1E-01	2.0E+00	4.2E-02
PVD	1.1E-03	6.9E-04	9.8E-02	1.6E+00	1.1E-01	SLC	1.8E-03	6.9E-04	1.9E-01	2.7E+00	7.9E-03
PWM	9.3E-04	6.9E-04	6.9E-02	1.3E+00	1.8E-01	SMF	1.3E-03	6.9E-04	1.4E-01	1.9E+00	5.6E-02
RAP	2.6E-03	1.5E-04	1.2E-01	1.7E+01	4.0E-64	SMX	2.6E-03	4.0E-04	2.7E-02	6.6E+00	3.1E-11
RDD	1.8E-03	2.5E-04	3.2E-02	7.3E+00	3.7E-13	SNA	1.3E-03	6.9E-04	1.4E-01	1.9E+00	5.4E-02
RDM	1.7E-03	1.6E-04	6.9E-02	1.1E+01	2.6E-27	SPI	1.7E-03	2.9E-04	2.4E-02	5.6E+00	2.1E-08
RDU	1.3E-03	6.9E-04	1.5E-01	1.9E+00	6.1E-02	SPN	3.5E-03	8.3E-04	2.9E-02	4.2E+00	2.8E-05
RFD	1.7E-03	4.8E-04	1.4E-02	3.6E+00	3.0E-04	SRQ	4.6E-04	6.9E-04	2.5E-02	6.6E-01	5.1E-01
RIC	1.4E-03	6.9E-04	1.1E-01	2.0E+00	4.3E-02	STL	1.7E-03	6.9E-04	1.8E-01	2.4E+00	1.5E-02
RKS	4.1E-03	4.8E-04	3.4E-02	8.6E+00	9.7E-18	STT	1.3E-03	6.9E-04	7.3E-02	1.9E+00	5.6E-02
RNO	1.1E-03	6.9E-04	1.0E-01	1.6E+00	1.1E-01	STX	1.3E-03	7.1E-04	3.3E-02	1.8E+00	7.0E-02
ROA	2.6E-03	1.4E-04	1.5E-01	1.8E+01	3.9E-74	SUN	2.9E-03	3.2E-04	3.8E-02	9.1E+00	1.1E-19
ROC	2.1E-03	1.4E-04	1.6E-01	1.5E+01	7.0E-53	SUX	2.0E-03	4.0E-04	2.0E-02	5.0E+00	6.8E-07
RST	1.8E-03	1.6E-04	7.1E-02	1.2E+01	6.1E-31	SWF	1.6E-03	1.5E-04	8.4E-02	1.1E+01	3.8E-27
RSW	8.8E-04	6.9E-04	9.2E-02	1.3E+00	2.0E-01	SYR	1.1E-03	6.9E-04	7.4E-02	1.5E+00	1.3E-01
SAN	1.5E-03	6.9E-04	1.9E-01	2.2E+00	3.0E-02	TLH	1.1E-03	6.9E-04	5.9E-02	1.6E+00	1.0E-01
SAT	1.6E-03	6.9E-04	1.8E-01	2.3E+00	2.0E-02	TOL	4.0E-04	7.0E-04	1.4E-02	5.7E-01	5.7E-01
SAV	1.3E-03	6.9E-04	9.1E-02	1.8E+00	6.4E-02	TPA	1.1E-03	6.9E-04	1.3E-01	1.6E+00	1.1E-01
SBA	8.0E-04	6.9E-04	5.0E-02	1.2E+00	2.5E-01	TRI	2.8E-03	1.5E-04	1.2E-01	1.8E+01	2.1E-72
SBN	1.8E-03	1.4E-04	1.1E-01	1.3E+01	6.5E-38	TUL	1.4E-03	6.9E-04	9.8E-02	2.0E+00	4.9E-02
SBP	1.8E-03	1.5E-04	8.4E-02	1.2E+01	1.6E-34	TUS	1.1E-03	6.9E-04	1.0E-01	1.6E+00	1.2E-01
SBY	8.3E-04	4.0E-04	8.4E-03	2.1E+00	3.8E-02	TVC	2.2E-03	1.5E-04	1.0E-01	1.5E+01	1.0E-48
SCC	3.7E-03	9.7E-04	2.2E-02	3.8E+00	1.6E-04	TYR	1.9E-03	2.3E-04	3.8E-02	8.2E+00	2.2E-16
TYS	1.6E-03	6.9E-04	1.1E-01	2.4E+00	1.9E-02	YAK	3.8E-05	8.4E-04	3.1E-04	4.5E-02	9.6E-01
VPS	2.6E-03	1.4E-04	1.4E-01	1.8E+01	1.8E-72	YKM	1.8E-03	2.5E-04	3.2E-02	7.2E+00	8.3E-13
WRG	7.5E-04	9.5E-04	4.4E-03	7.9E-01	4.3E-01	YUM	9.9E-04	2.0E-04	2.5E-02	5.0E+00	4.8E-07
XNA	2.7E-03	1.4E-04	1.7E-01	1.9E+01	9.9E-84						

Table Appendix G. 8. 0 FEM model coefficient values 2008

2008 Coefficient	*Unstand. Coef.*		*Std.. Coef.*	*t*	*Sig.*	*2005 Variables*	*Unstand. Coef.*		*Std.. Coef.*	*t*	*Sig.*
α, β, γ, δ, φ_1, φ_{10}	*B*	*Std. E.*	*Beta*			*Variable*	*B*	*Std. E.*	*Beta*		
A_4	1.4E+02	8.6E+00		1.6E+01	7.9E-59	DIST	2.0E-01	5.3E-03	4.8E-01	3.7E+01	6.2E-296
VERY SHORT	6.4E-04	6.8E-05	6.7E-02	9.4E+00	9.2E-21	CO	-1.0E-03	3.6E-05	-1.4E-01	-2.8E+01	1.3E-170
SHORT	3.4E-04	3.9E-05	7.8E-02	8.6E+00	7.9E-18	DL	-3.0E-03	9.9E-05	-1.4E-01	-3.0E+01	7.1E-199
MEDIUM	5.5E-05	2.1E-05	2.1E-02	2.6E+00	1.0E-02	F9	-3.7E-04	1.1E-04	-1.6E-02	-3.3E+00	8.3E-04
AA	-3.0E-04	1.4E-04	-8.8E-03	-2.1E+00	3.7E-02	FL	-2.0E-03	1.1E-04	-8.2E-02	-1.8E+01	8.8E-74
AB	-1.1E-04	5.3E-05	-1.1E-02	-2.2E+00	3.0E-02	G4	-5.8E-04	2.3E-05	-1.4E-01	-2.5E+01	3.5E-138
AC	-9.7E-05	4.5E-05	-1.1E-02	-2.2E+00	3.1E-02	HA	-2.4E-03	2.5E-04	-4.0E-02	-9.3E+00	1.4E-20
AE	-1.5E-04	4.9E-05	-1.7E-02	-3.1E+00	1.8E-03	HP	-1.0E-03	4.0E-04	-1.0E-02	-2.5E+00	1.1E-02
BB	8.9E-05	3.9E-05	1.2E-02	2.3E+00	2.4E-02	NK	-1.6E-03	1.6E-04	-4.6E-02	-1.0E+01	5.6E-24
CC	-6.3E-05	3.0E-05	-1.3E-02	-2.1E+00	3.9E-02	NW	-1.3E-03	2.3E-04	-2.4E-02	-5.8E+00	6.1E-09

Table Appendix G. 8. 1 FEM model coefficient values 2008

2008 Coefficient	*Unstand. Coef.*		*Stand. Coef.*	*t*	*Sig.*	*2007 Variables*	*Unstand. Coef.*		*Stand. Coef.*	*t*	*Sig.*
γ	*B*	*Std. E.*	*Beta*			*Variable*	*B*	*Std. E.*	*Beta*		
CE	-1.3E-04	5.7E-05	-1.1E-02	-2.2E+00	2.9E-02	OO	-1.1E-03	1.9E-04	-2.9E-02	-5.7E+00	1.1E-08
DD	1.2E-04	4.4E-05	1.6E-02	2.7E+00	7.0E-03	QX	-2.2E-04	2.1E-05	-6.0E-02	-1.0E+01	5.6E-25
DE	-4.2E-04	2.5E-04	-9.9E-03	-1.7E+00	9.2E-02	SY	-8.4E-04	2.7E-05	-1.9E-01	-3.1E+01	1.5E-201
LCC-LCC	-5.6E-04	5.2E-05	-7.3E-02	-1.1E+01	2.9E-27	TZ	-3.4E-03	4.9E-04	-2.8E-02	-6.8E+00	8.4E-12
FSC-LCC	-2.5E-04	2.5E-05	-9.3E-02	-1.0E+01	2.6E-24	U5	-4.9E-04	6.2E-05	-3.5E-02	-7.9E+00	2.2E-15
T-T	1.8E-05	4.9E-05	1.9E-03	3.6E-01	7.2E-01	UA	1.6E-03	1.5E-04	8.7E-02	1.1E+01	1.9E-26
T-B	-9.8E-05	3.0E-05	-1.9E-02	-3.3E+00	1.1E-03	US	1.2E-03	2.8E-04	1.9E-02	4.2E+00	2.4E-05
T-R	-1.5E-04	3.4E-05	-2.5E-02	-4.2E+00	2.4E-05	YV	2.4E-03	1.4E-04	2.4E-01	1.7E+01	4.6E-64
B-B	1.3E-04	4.1E-05	1.8E-02	3.2E+00	1.2E-03	YX	2.5E-03	6.8E-04	1.5E-02	3.6E+00	2.9E-04
B-R	-4.6E-05	2.9E-05	-1.1E-02	-1.6E+00	1.1E-01	ABE	2.5E-03	6.8E-04	1.5E-02	3.7E+00	1.9E-04
N-R	6.2E-06	2.9E-05	1.9E-03	2.1E-01	8.3E-01	ABI	2.3E-03	3.6E-04	2.7E-02	6.3E+00	2.5E-10
NO WN	-8.1E-05	3.4E-05	-1.2E-02	-2.4E+00	1.8E-02	ABQ	1.6E-03	3.0E-04	2.3E-02	5.2E+00	1.6E-07
LCC	2.6E-02	2.5E-03	5.8E-02	1.1E+01	8.3E-27	ABR	1.6E-03	2.0E-04	4.2E-02	8.1E+00	6.1E-16
MORE THAN 1	3.5E-04	3.8E-03	7.2E-04	9.3E-02	9.3E-01	ABY	2.3E-03	3.2E-04	3.4E-02	7.3E+00	4.2E-13
MS	4.2E-02	5.1E-03	5.2E-02	8.3E+00	1.6E-16	ACK	2.8E-03	5.0E-04	2.3E-02	5.5E+00	4.9E-08
LOWCMS	1.6E-04	3.5E-05	3.6E-02	4.7E+00	2.6E-06	ACT	2.1E-03	1.8E-04	7.0E-02	1.2E+01	5.8E-33
LCMS	-4.6E-04	2.1E-05	-1.2E-01	-2.1E+01	1.0E-99	ACV	2.3E-03	1.6E-04	1.0E-01	1.4E+01	1.5E-46
ALONE	-1.6E-03	1.7E-04	-3.9E-02	-9.4E+00	6.6E-21	ACY	4.2E-03	6.8E-04	2.5E-02	6.2E+00	6.2E-10
7H	-6.8E-04	4.8E-05	-7.7E-02	-1.4E+01	1.5E-46	ADQ	2.2E-03	1.4E-04	1.6E-01	1.5E+01	7.4E-53
AA	-3.5E-04	5.4E-05	-3.0E-02	-6.5E+00	1.0E-10	AEX	7.2E-04	6.8E-04	4.2E-03	1.1E+00	2.9E-01
AQ	-2.4E-04	2.7E-05	-4.5E-02	-8.9E+00	6.5E-19	AGS	2.1E-03	1.6E-04	9.8E-02	1.3E+01	1.1E-39
AS	-3.5E-04	1.9E-05	-1.1E-01	-1.9E+01	9.2E-76	AKN	3.3E-03	1.4E-04	2.8E-01	2.3E+01	5.7E-112
B6	-9.0E-04	4.5E-05	-9.4E-02	-2.0E+01	9.1E-88	ALB	2.6E-03	1.6E-04	1.1E-01	1.6E+01	1.8E-60
SCE	2.6E-03	1.4E-04	3.4E-01	1.8E+01	1.0E-73	SJT	2.4E-03	1.4E-04	2.6E-01	1.7E+01	4.4E-63
SDF	2.9E-03	1.5E-04	1.8E-01	2.0E+01	7.2E-85	SJU	2.2E-03	4.1E-04	2.3E-02	5.5E+00	3.2E-08
SEA	-1.4E-03	4.1E-04	-1.4E-02	-3.4E+00	6.1E-04	SLC	2.4E-03	1.4E-04	2.6E-01	1.7E+01	2.6E-62
SFO	3.0E-03	1.5E-04	1.6E-01	2.0E+01	1.6E-84	SMF	1.1E-03	2.7E-04	1.8E-02	4.0E+00	6.3E-05
SGF	2.0E-03	5.0E-04	1.7E-02	4.0E+00	7.3E-05	SMX	4.7E-03	4.9E-04	3.9E-02	9.5E+00	3.4E-21
SGU	2.1E-03	1.4E-04	2.1E-01	1.5E+01	1.3E-51	SNA	1.5E-03	1.5E-04	8.4E-02	1.0E+01	7.2E-24
SHV	8.5E-04	4.9E-04	7.2E-03	1.7E+00	8.0E-02	SPI	2.8E-03	1.4E-04	3.2E-01	2.0E+01	2.0E-86
SIT	2.6E-03	1.4E-04	2.4E-01	1.8E+01	2.6E-72	SPN	2.4E-03	1.5E-04	1.4E-01	1.6E+01	6.9E-58
SJC	2.7E-03	1.4E-04	2.9E-01	1.9E+01	4.9E-81	SRQ	2.1E-03	2.1E-04	5.4E-02	1.0E+01	3.2E-25
ALW	3.2E-03	1.4E-04	3.8E-01	2.2E+01	4.4E-11	BUF	1.7E-03	1.5E-04	1.0E-01	1.2E+01	1.9E-31
AMA	2.0E-03	1.5E-04	1.2E-01	1.3E+01	2.4E-40	BUR	2.2E-03	7.2E-04	1.3E-02	3.0E+00	2.7E-03
ANC	2.4E-03	1.4E-04	2.7E-01	1.7E+01	1.8E-64	BWI	2.3E-03	1.5E-04	1.2E-01	1.5E+01	1.2E-51
APF	2.1E-03	1.5E-04	1.1E-01	1.4E+01	1.8E-42	BZN	2.1E-03	1.6E-04	9.0E-02	1.3E+01	4.2E-39
ASE	1.4E-03	1.5E-04	7.5E-02	9.3E+00	1.1E-20	CAE	2.3E-03	1.4E-04	1.7E-01	1.6E+01	2.8E-59
ATL	2.4E-03	1.6E-04	1.1E-01	1.6E+01	5.2E-54	CAK	2.4E-03	1.4E-04	1.7E-01	1.7E+01	1.3E-61
ATW	2.4E-03	1.4E-04	2.5E-01	1.7E+01	5.0E-66	CDV	-1.9E-04	3.6E-04	-2.2E-03	-5.3E-01	6.0E-01
AUS	2.7E-03	7.2E-04	1.6E-02	3.7E+00	1.8E-04	CHA	2.6E-03	1.4E-04	2.5E-01	1.9E+01	3.6E-76
AVL	1.7E-03	1.7E-04	6.1E-02	1.0E+01	1.1E-23	CHO	1.4E-03	2.4E-04	2.8E-02	5.9E+00	4.6E-09
AVP	1.5E-03	1.6E-04	5.8E-02	8.9E+00	4.8E-19	CHS	2.7E-03	1.4E-04	2.9E-01	1.9E+01	2.4E-78
AZO	2.2E-03	1.7E-04	8.6E-02	1.3E+01	2.9E-41	CID	2.4E-03	1.4E-04	2.6E-01	1.7E+01	1.5E-65
BDL	1.7E-03	6.8E-04	1.0E-02	2.5E+00	1.3E-02	CLD	1.6E-03	2.0E-04	4.1E-02	7.9E+00	4.0E-15
BET	2.3E-03	1.4E-04	1.8E-01	1.6E+01	1.4E-60	CLE	1.9E-03	1.4E-04	1.5E-01	1.3E+01	3.1E-40
BFL	2.2E-03	1.4E-04	1.4E-01	1.5E+01	2.4E-51	CLL	2.8E-03	2.2E-04	6.3E-02	1.3E+01	6.3E-38
BGM	3.0E-03	1.8E-04	9.1E-02	1.6E+01	2.0E-59	CLT	2.3E-03	1.5E-04	1.2E-01	1.5E+01	5.5E-50
BGR	1.5E-03	2.1E-04	3.7E-02	7.2E+00	6.4E-13	CMH	2.4E-03	1.5E-04	1.3E-01	1.6E+01	1.6E-57
BHM	2.3E-03	6.8E-04	1.4E-02	3.3E+00	8.3E-04	CMI	3.0E-03	6.8E-04	1.8E-02	4.5E+00	6.9E-06
BIL	1.7E-03	1.5E-04	9.4E-02	1.1E+01	1.5E-28	COS	3.4E-03	1.4E-04	2.7E-01	2.4E+01	8.5E-122
BIS	2.5E-03	1.4E-04	2.6E-01	1.8E+01	4.7E-73	CPR	1.8E-03	1.6E-04	8.1E-02	1.2E+01	8.4E-31
BLI	2.0E-03	1.4E-04	1.6E-01	1.4E+01	2.3E-46	CRP	1.2E-03	1.6E-04	5.7E-02	7.7E+00	1.8E-14

Table Appendix G. 8. 2 FEM model coefficient values 2008

2008 Coefficient	*Unstand. Coef.*		*Stand. Coef.*	*t*	*Sig.*	*2007 Variables*	*Unstand. Coef.*		*Stand. Coef.*	*t*	*Sig.*
Γ	*B*	*Std. E.*	*Beta*			*Variable*	*B*	*Std. E.*	*Beta*		
BLV	2.8E-03	1.4E-04	3.4E-01	1.9E+01	1.2E-83	CRW	2.1E-03	1.6E-04	9.7E-02	1.3E+01	7.4E-37
BMI	4.2E-04	6.8E-04	2.5E-03	6.2E-01	5.3E-01	CSG	2.4E-03	1.4E-04	1.7E-01	1.7E+01	5.3E-61
BNA	1.4E-03	2.5E-04	2.6E-02	5.5E+00	3.6E-08	CVG	8.8E-04	3.6E-04	1.1E-02	2.5E+00	1.3E-02
BOI	1.5E-03	4.1E-04	1.6E-02	3.8E+00	1.5E-04	CWA	3.0E-03	1.4E-04	3.5E-01	2.1E+01	3.4E-98
BOS	3.4E-03	7.2E-04	2.0E-02	4.8E+00	1.8E-06	DAB	2.7E-03	1.4E-04	3.5E-01	1.9E+01	1.5E-77
BPT	2.5E-03	4.9E-04	2.1E-02	5.0E+00	4.7E-07	DAL	2.9E-03	1.4E-04	3.4E-01	2.0E+01	1.2E-91
BQK	2.2E-03	1.5E-04	1.3E-01	1.5E+01	8.5E-49	DAY	3.2E-03	4.9E-04	2.7E-02	6.5E+00	7.6E-11
BQN	1.7E-03	1.5E-04	1.1E-01	1.2E+01	2.7E-32	DBQ	3.6E-03	6.8E-04	2.1E-02	5.3E+00	1.2E-07
BRO	2.1E-03	1.4E-04	1.9E-01	1.5E+01	3.0E-48	DCA	2.2E-03	2.0E-04	5.6E-02	1.1E+01	5.1E-27
BRW	2.0E-03	1.4E-04	1.5E-01	1.4E+01	7.6E-44	DEN	2.2E-03	1.7E-04	8.3E-02	1.3E+01	3.8E-39
BTM	2.6E-03	1.4E-04	2.8E-01	1.8E+01	3.8E-73	DFW	2.5E-03	1.4E-04	1.9E-01	1.7E+01	7.1E-68
BTR	2.4E-03	1.4E-04	1.5E-01	1.6E+01	2.6E-60	DHN	3.0E-03	1.4E-04	3.3E-01	2.1E+01	2.4E-96
BTV	2.8E-03	1.4E-04	1.9E-01	2.0E+01	2.7E-85	DLG	6.9E-03	6.8E-04	4.1E-02	1.0E+01	3.0E-24
STL	2.2E-03	2.6E-04	3.9E-02	8.6E+00	6.5E-18	TPA	2.2E-03	1.4E-04	2.2E-01	1.6E+01	5.4E-55
STT	1.5E-03	6.8E-04	8.7E-03	2.1E+00	3.2E-02	TRI	2.4E-03	1.6E-04	1.1E-01	1.5E+01	8.3E-51
STX	1.7E-03	1.6E-04	8.2E-02	1.1E+01	2.4E-27	TUL	2.1E-03	2.5E-04	4.0E-02	8.5E+00	2.7E-17
SUN	2.2E-03	1.4E-04	1.6E-01	1.5E+01	1.1E-52	TUS	2.7E-03	1.4E-04	2.0E-01	1.9E+01	5.6E-79
SUX	2.2E-03	1.5E-04	1.2E-01	1.5E+01	3.8E-48	TVC	2.4E-03	1.5E-04	1.4E-01	1.7E+01	5.6E-61
SWF	1.3E-03	1.9E-04	3.9E-02	7.1E+00	1.8E-12	TYR	1.6E-03	6.8E-04	9.4E-03	2.3E+00	1.9E-02
SYR	2.2E-03	1.4E-04	2.6E-01	1.5E+01	1.6E-53	TYS	2.8E-03	1.5E-04	1.8E-01	1.9E+01	2.7E-81
TLH	2.7E-03	1.6E-04	1.1E-01	1.7E+01	1.8E-61	VPS	3.6E-03	7.2E-04	2.1E-02	5.0E+00	7.4E-07
TOL	2.4E-03	1.4E-04	1.9E-01	1.7E+01	6.6E-63	WRG	1.9E-03	2.7E-04	3.1E-02	6.9E+00	4.6E-12
DLH	1.3E-03	3.6E-04	1.5E-02	3.5E+00	4.5E-04	GPT	1.9E-03	1.4E-04	1.3E-01	1.3E+01	1.5E-38
DRO	1.8E-03	1.6E-04	7.8E-02	1.1E+01	2.7E-29	GRB	2.6E-03	1.4E-04	1.7E-01	1.8E+01	1.9E-73
DSM	-2.7E-04	4.9E-04	-2.2E-03	-5.5E-01	5.9E-01	GRK	2.5E-03	1.7E-04	8.6E-02	1.5E+01	3.6E-48
DTW	1.1E-03	1.7E-04	3.9E-02	6.5E+00	8.8E-11	GRR	1.4E-03	3.2E-04	1.8E-02	4.2E+00	2.4E-05
DUT	2.3E-03	1.4E-04	1.7E-01	1.6E+01	6.9E-57	GSO	5.7E-03	2.5E-04	1.1E-01	2.3E+01	4.2E-114
EAT	3.4E-03	6.8E-04	2.0E-02	5.0E+00	7.1E-07	GSP	1.2E-03	1.6E-04	4.8E-02	7.3E+00	3.3E-13
EGE	1.1E-03	1.7E-04	4.2E-02	6.5E+00	6.2E-11	GTF	1.4E-03	2.1E-04	3.5E-02	7.0E+00	2.8E-12
ELM	1.6E-03	1.5E-04	8.8E-02	1.1E+01	2.4E-27	GTR	2.6E-03	2.0E-04	6.4E-02	1.3E+01	4.3E-36
ELP	2.5E-03	1.6E-04	1.1E-01	1.6E+01	1.3E-55	GUC	3.4E-03	1.4E-04	3.6E-01	2.4E+01	2.0E-123
ENA	1.2E-03	1.7E-04	4.4E-02	7.3E+00	4.1E-13	GUM	2.4E-03	1.5E-04	1.7E-01	1.7E+01	4.3E-62
ERI	2.8E-03	1.4E-04	3.3E-01	2.0E+01	5.6E-87	HDN	1.7E-03	1.5E-04	9.6E-02	1.2E+01	8.9E-31
EUG	2.0E-03	1.6E-04	9.2E-02	1.3E+01	7.6E-38	HHH	2.1E-03	1.8E-04	7.3E-02	1.2E+01	1.2E-32
EVV	3.3E-03	1.7E-04	1.2E-01	1.9E+01	8.4E-81	HLN	2.7E-03	1.4E-04	1.9E-01	1.9E+01	3.1E-79
EWN	2.7E-03	1.5E-04	1.4E-01	1.8E+01	3.9E-71	HNL	1.8E-03	4.9E-04	1.5E-02	3.7E+00	2.0E-04
EWR	2.1E-03	1.4E-04	1.4E-01	1.5E+01	2.1E-47	HOU	2.3E-03	6.8E-04	1.4E-02	3.4E+00	6.9E-04
EYW	2.0E-03	1.6E-04	9.2E-02	1.3E+01	1.5E-38	HPN	2.8E-03	1.4E-04	2.9E-01	2.0E+01	3.1E-86
FAI	2.0E-03	1.6E-04	8.8E-02	1.3E+01	4.5E-36	HRL	2.7E-03	1.4E-04	3.2E-01	1.9E+01	1.5E-82
FAR	7.5E-04	2.6E-04	1.3E-02	2.9E+00	3.5E-03	HSV	2.4E-03	1.4E-04	1.9E-01	1.7E+01	2.4E-63
FAT	2.2E-03	1.4E-04	2.6E-01	1.6E+01	8.7E-55	HTS	2.2E-03	1.7E-04	7.5E-02	1.3E+01	2.2E-36
FAY	8.0E-04	2.6E-04	1.4E-02	3.1E+00	1.8E-03	IAD	1.3E-03	3.9E-04	1.6E-02	3.4E+00	5.9E-04
FCA	1.7E-03	6.8E-04	1.0E-02	2.5E+00	1.1E-02	IAH	1.3E-03	1.5E-04	7.0E-02	8.9E+00	6.8E-19
FLG	1.7E-03	1.5E-04	9.5E-02	1.1E+01	1.3E-29	ICT	2.4E-03	1.4E-04	2.8E-01	1.8E+01	4.9E-68
FLL	2.5E-03	1.5E-04	1.4E-01	1.7E+01	1.1E-64	IDA	1.5E-03	1.6E-04	6.7E-02	9.4E+00	7.2E-21
FLO	2.5E-03	2.4E-04	5.0E-02	1.1E+01	7.5E-26	IFP	1.4E-03	1.9E-04	3.9E-02	7.4E+00	1.4E-13
FNL	2.4E-03	1.5E-04	1.4E-01	1.6E+01	6.5E-58	ILM	2.1E-03	2.4E-04	4.7E-02	8.7E+00	5.4E-18
FNT	2.2E-03	1.4E-04	1.7E-01	1.5E+01	3.9E-53	IND	3.5E-03	6.8E-04	2.1E-02	5.2E+00	2.4E-07
FSD	2.2E-03	2.6E-04	3.9E-02	8.6E+00	9.5E-18	IPT	2.1E-03	1.4E-04	1.3E-01	1.5E+01	4.4E-48
FSM	2.1E-03	1.5E-04	1.0E-01	1.4E+01	3.5E-44	ISP	2.4E-03	1.4E-04	1.7E-01	1.7E+01	1.7E-62
FWA	1.7E-03	1.8E-04	5.5E-02	9.4E+00	7.1E-21	ITH	2.2E-03	1.4E-04	2.2E-01	1.5E+01	1.6E-53
GEG	2.0E-03	1.5E-04	1.2E-01	1.3E+01	2.8E-41	ITO	2.4E-03	1.4E-04	2.2E-01	1.7E+01	1.4E-63
GFK	2.1E-03	1.4E-04	1.4E-01	1.5E+01	4.5E-48	IYK	2.0E-03	2.2E-04	4.6E-02	9.0E+00	2.8E-19

Table Appendix G. 8. 3 FEM model coefficient values 2008

2008 Coefficient	*Unstand. Coef.*		*Stand. Coef.*	*t*	*Sig.*	*2007 Variables*	*Unstand. Coef.*		*Stand. Coef.*	*t*	*Sig.*
Γ	*B*	*Std. E.*	*Beta*			*Variable*	*B*	*Std. E.*	*Beta*		
GJT	2.3E-03	1.6E-04	1.1E-01	1.5E+01	6.1E-49	JAC	3.0E-03	1.5E-04	1.7E-01	1.9E+01	9.3E-83
GNV	2.5E-03	1.4E-04	1.8E-01	1.8E+01	2.7E-68	JAN	2.2E-03	3.3E-04	3.0E-02	6.7E+00	1.9E-11
XNA	7.4E-04	2.0E-04	1.9E-02	3.7E+00	2.0E-04	PHX	2.5E-03	1.4E-04	1.9E-01	1.8E+01	4.2E-68
YAK	-3.5E-04	1.6E-05	-1.2E-01	-2.2E+01	2.3E-108	PIA	4.4E-03	5.0E-04	3.7E-02	8.8E+00	2.3E-18
YKM	-7.3E-04	2.2E-05	-2.1E-01	-3.3E+01	1.1E-234	PIE	2.0E-03	6.8E-04	1.2E-02	2.9E+00	3.4E-03
YUM	-1.0E-03	2.7E-05	-2.5E-01	-3.7E+01	1.0E-293	PIT	2.6E-03	1.6E-04	1.2E-01	1.6E+01	9.8E-59
PNS	1.0E-03	3.3E-04	1.3E-02	3.0E+00	2.3E-03	PSP	1.9E-03	1.4E-04	1.4E-01	1.3E+01	6.4E-41
PPG	1.9E-03	6.8E-04	1.1E-02	2.8E+00	4.7E-03	PUW	2.6E-03	1.5E-04	1.4E-01	1.7E+01	3.6E-66
PSC	1.9E-03	1.5E-04	1.2E-01	1.3E+01	1.3E-36	PVD	1.5E-03	2.5E-04	2.9E-02	6.2E+00	6.4E-10
PSE	7.8E-04	4.9E-04	6.5E-03	1.6E+00	1.1E-01	PWM	1.3E-03	1.6E-04	5.6E-02	8.2E+00	2.9E-16
PSG	2.1E-03	1.4E-04	1.9E-01	1.5E+01	1.0E-50	RAP	2.3E-03	1.4E-04	2.8E-01	1.7E+01	3.5E-63
SBP	2.0E-03	1.6E-04	8.9E-02	1.3E+01	7.3E-37	SBY	2.4E-03	1.4E-04	2.3E-01	1.7E+01	7.0E-66
JAX	1.7E-03	1.6E-04	7.5E-02	1.1E+01	8.8E-28	MHT	2.0E-03	2.3E-04	4.2E-02	8.7E+00	2.9E-18
JFK	2.5E-03	1.4E-04	3.2E-01	1.7E+01	1.5E-65	MIA	2.6E-03	1.5E-04	1.4E-01	1.8E+01	1.2E-68
JNU	2.1E-03	3.3E-04	2.8E-02	6.5E+00	7.0E-11	MKE	2.8E-03	3.0E-04	4.1E-02	9.4E+00	7.6E-21
KOA	2.9E-03	1.4E-04	3.9E-01	2.0E+01	6.6E-88	MKG	3.5E-03	4.1E-04	3.5E-02	8.5E+00	2.0E-17
KTN	2.0E-03	1.5E-04	1.1E-01	1.3E+01	7.3E-41	MLB	2.0E-03	1.6E-04	8.6E-02	1.3E+01	8.7E-37
LAN	2.8E-03	6.8E-04	1.7E-02	4.1E+00	3.8E-05	MLI	2.4E-03	1.4E-04	1.8E-01	1.7E+01	1.3E-61
LAS	2.5E-03	1.5E-04	1.5E-01	1.7E+01	1.7E-63	MLU	2.4E-03	1.5E-04	1.2E-01	1.6E+01	1.0E-55
LAW	2.0E-03	1.6E-04	7.9E-02	1.2E+01	3.5E-34	MOB	3.4E-03	1.4E-04	4.0E-01	2.4E+01	4.6E-126
LAX	2.5E-03	1.4E-04	3.0E-01	1.8E+01	4.2E-71	MOT	2.5E-03	1.4E-04	2.7E-01	1.8E+01	1.6E-68
LBB	7.7E-04	1.7E-04	3.0E-02	4.6E+00	4.7E-06	MQT	1.6E-03	2.1E-04	3.9E-02	7.8E+00	6.8E-15
LCH	2.8E-03	1.5E-04	1.6E-01	1.8E+01	1.6E-74	MRY	3.6E-03	6.8E-04	2.1E-02	5.2E+00	1.6E-07
LEX	2.4E-03	1.4E-04	1.8E-01	1.7E+01	1.9E-61	MSN	1.7E-03	1.5E-04	9.1E-02	1.1E+01	8.2E-30
LFT	2.6E-04	4.9E-04	2.2E-03	5.2E-01	6.0E-01	MSO	1.7E-03	1.6E-04	6.8E-02	1.0E+01	1.3E-24
LGA	1.7E-03	1.8E-04	5.7E-02	9.9E+00	7.4E-23	MSP	2.1E-03	1.4E-04	1.7E-01	1.4E+01	9.5E-47
LGB	1.9E-03	2.5E-04	3.5E-02	7.6E+00	3.0E-14	MSY	3.1E-03	1.5E-04	2.3E-01	2.1E+01	3.8E-98
LIH	2.1E-03	1.9E-04	5.9E-02	1.1E+01	8.0E-28	MTJ	2.5E-03	1.4E-04	2.0E-01	1.8E+01	1.7E-70
LIT	1.3E-03	3.2E-04	1.8E-02	4.1E+00	4.3E-05	MYR	2.3E-03	1.4E-04	2.4E-01	1.7E+01	6.9E-62
LMT	2.0E-03	3.6E-04	2.3E-02	5.5E+00	4.6E-08	OAJ	3.0E-03	7.2E-04	1.8E-02	4.1E+00	3.6E-05
LNK	2.3E-03	1.6E-04	1.1E-01	1.5E+01	2.3E-51	OAK	2.3E-03	1.4E-04	2.2E-01	1.6E+01	2.4E-59
LRD	1.8E-03	1.7E-04	6.6E-02	1.1E+01	7.3E-27	OGG	2.9E-03	1.4E-04	3.6E-01	2.1E+01	2.5E-94
LSE	2.5E-03	1.4E-04	3.0E-01	1.8E+01	3.0E-71	OKC	2.4E-03	1.4E-04	1.8E-01	1.7E+01	4.4E-61
LWS	2.5E-03	1.4E-04	3.2E-01	1.7E+01	5.1E-67	OMA	8.5E-04	3.6E-04	1.0E-02	2.4E+00	1.7E-02
LYH	2.0E-03	1.4E-04	1.4E-01	1.4E+01	2.3E-43	OME	3.0E-03	7.2E-04	1.8E-02	4.2E+00	2.8E-05
MAF	2.3E-03	1.5E-04	1.5E-01	1.5E+01	1.3E-52	ONT	1.9E-03	1.4E-04	1.8E-01	1.3E+01	2.9E-41
MBS	3.1E-03	1.4E-04	3.0E-01	2.2E+01	9.3E-107	ORD	2.4E-03	1.4E-04	2.9E-01	1.7E+01	5.0E-63
MCI	2.2E-03	1.6E-04	1.1E-01	1.4E+01	4.6E-45	ORF	2.2E-03	1.7E-04	8.6E-02	1.3E+01	4.9E-41
MCO	1.8E-03	1.5E-04	9.0E-02	1.2E+01	6.4E-32	OTH	-3.0E-04	6.8E-04	-1.8E-03	-4.4E-01	6.6E-01
MDT	2.4E-03	1.6E-04	1.0E-01	1.5E+01	2.1E-49	OTZ	1.9E-03	1.5E-04	1.1E-01	1.3E+01	2.3E-37
MDW	2.0E-03	1.5E-04	1.3E-01	1.4E+01	1.5E-41	PBI	2.6E-03	1.4E-04	3.1E-01	1.8E+01	3.3E-74
MEM	2.3E-03	1.4E-04	2.2E-01	1.6E+01	2.8E-57	PDX	2.5E-03	1.4E-04	3.2E-01	1.7E+01	7.4E-66
MFE	2.3E-03	1.4E-04	2.3E-01	1.6E+01	6.6E-59	PFN	1.6E-03	1.5E-04	8.7E-02	1.1E+01	3.9E-27
MFR	1.1E-03	2.2E-04	2.6E-02	5.2E+00	2.0E-07	PHF	-8.1E-05	3.1E-04	-1.4E-03	-2.6E-01	7.9E-01
MGM	1.8E-03	1.4E-04	1.2E-01	1.2E+01	8.9E-35	PHL	2.3E-03	1.4E-04	2.5E-01	1.7E+01	1.0E-60
RDD	1.3E-03	4.1E-04	1.3E-02	3.1E+00	2.0E-03	RST	2.6E-03	1.4E-04	3.0E-01	1.8E+01	7.5E-75
RDM	2.3E-03	1.4E-04	1.8E-01	1.6E+01	6.7E-60	RSW	2.2E-03	1.4E-04	1.5E-01	1.5E+01	3.3E-51
RDU	3.0E-03	4.1E-04	3.1E-02	7.5E+00	9.7E-14	SAN	1.8E-03	1.5E-04	1.1E-01	1.2E+01	5.3E-33
RFD	2.2E-03	1.4E-04	1.9E-01	1.5E+01	5.3E-51	SAT	1.7E-03	1.5E-04	1.1E-01	1.2E+01	6.9E-32
RIC	2.5E-03	1.5E-04	1.5E-01	1.7E+01	4.9E-66	SAV	1.8E-03	1.6E-04	7.2E-02	1.1E+01	5.8E-28
RKS	2.1E-03	1.4E-04	1.5E-01	1.5E+01	9.0E-48	SBA	5.3E-04	4.1E-04	5.5E-03	1.3E+00	1.9E-01
RNO	1.9E-03	1.8E-04	6.2E-02	1.1E+01	9.8E-27	ROC	2.5E-03	1.4E-04	3.2E-01	1.8E+01	3.7E-71
ROA	2.0E-03	1.4E-04	2.1E-01	1.4E+01	3.0E-47	SBN	3.6E-03	7.2E-04	2.2E-02	5.0E+00	4.8E-07

Appendix H: CFEM model results at different markets

In order to examine the effects that LCC's produce when entering routes only operated by FSC's, the CFEM mathematical model (Section 4.5) has been used to analyze the relation between airlines fares and route distances at different markets. Markets have been classified according to the analysis shown in Appendix F.

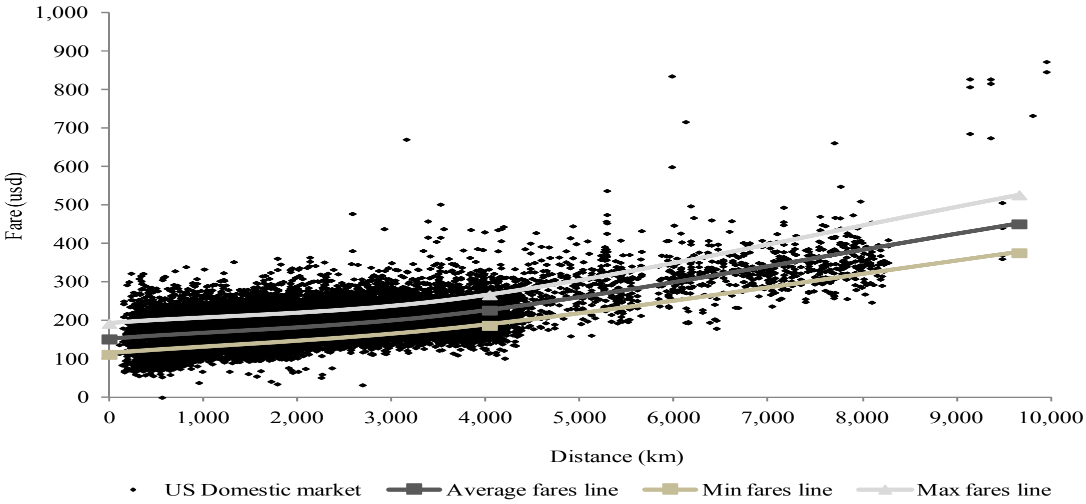


Figure Appendix H. 1 US 2005 domestic market model result

In Figure Appendix H. 1 to Figure Appendix H. 3 three examples of how the model calculates the min, max and average fares lines for the LCC, FSC and the total market. In Table Appendix H. 1, the CFEM model coefficient values are presented for the LCC, FSC and the complete market. The LCC market was 50 usd cheaper than the FSC. After crossing D*, LCC and FSC fares per km get closer. Fare dispersion between both markets reduces as distance increase.

The LCC market average fares line (Figure Appendix H. 2) is approximately the same line as the US 2005 market min fares line (Figure Appendix H. 3). The LCC market shows the lowest average dispersion (±25 usd) comparing with the FSC market (±37.55 usd) and with the complete US 2005 market (±40 usd) (Figure Appendix H. 1).

Table Appendix H. 1 US CFEM model coefficient values for year 2005

Market	D* (km)	m_1	b_1	m_2	b_2	Δm_1	Δb_1	Δm_2	Δb_2
US 2005	4,035	0.03	152.33	0.06	66.30	-0.0001	40.00	0.01	14.06
FSC	3,950	0.03	160.19	0.06	83.30	-0.0004	37.55	0.01	13.71
LCC	4,145	0.03	110.29	0.09	65.91	-0.0001	25.00	0.01	-1.65

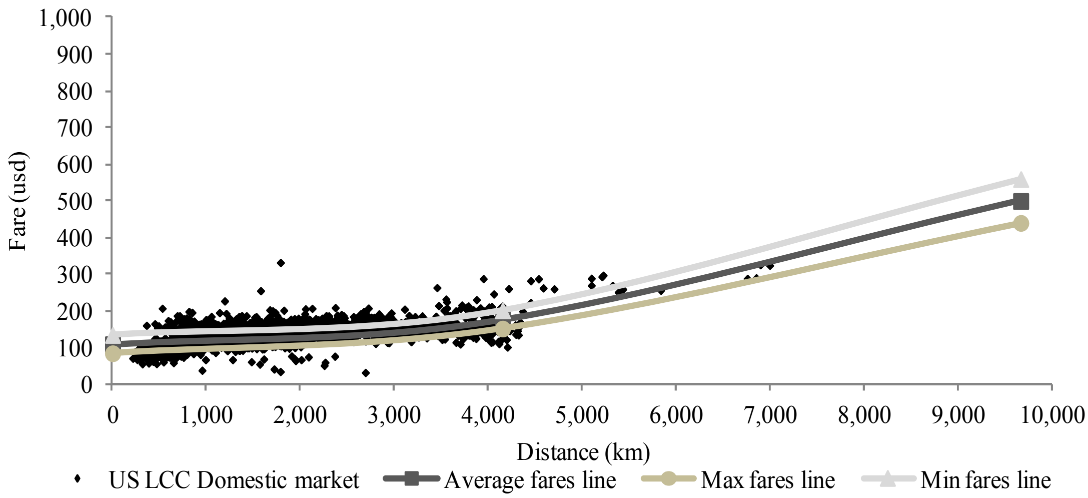


Figure Appendix H. 2 LCC 2005 domestic market model result

In the case of the FSC market, the average fares line (Figure Appendix H. 3) very low fares can be found, as much as the LCC market. This means, FSC's can low fares close to the LCC's average fares line.

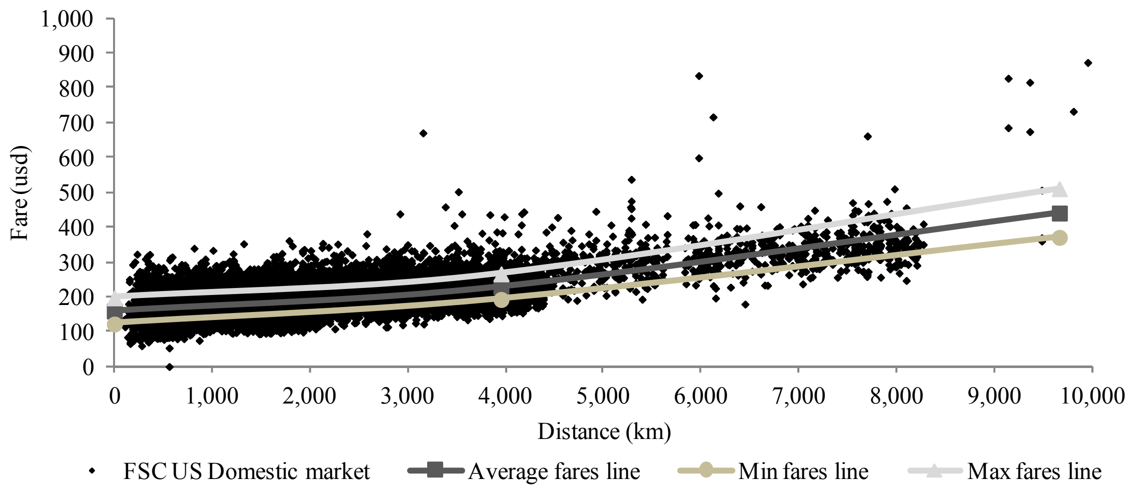


Figure Appendix H. 3 FSC 2005 domestic market model result

In Table Appendix H. 2, the model coefficient values for the competition markets (FSC-FSC, LCC-LCC and FSC-LCC) are presented. The FSC-FSC market is more expensive than the LCC-LCC market, 80 usd. This market is also more expensive than the FSC-LCC market, 40 usd. The FSC-LCC market is cheaper than the FSC-FSC market, 40 usd.

Table Appendix H. 2 US CFEM model coefficient values for year 2005, competition

Market	D* (km)	m_1	b_1	m_2	b_2	Δm_1	Δb_1	Δm_2	Δb_2
FSC-FSC	3,929	0.03	165.65	0.06	103.01	-0.0001	35.30	0.01	12.52
LCC-LCC	4,550	0.04	84.93	0.07	-7.38	-0.0001	19.65	0.01	-6.74
FSC-LCC	4,101	0.03	128.64	0.09	-40.14	-0.0020	29.25	0.02	-20.85

The FSC-FSC routes dispersion is greater than the other competition markets, ±35.30 usd. Dispersion decreases after crossing the segment division point (D*), ±12.52 usd. The LCC-LCC market average fares dispersion is ±29.25 usd. After D*, the dispersion becomes negative. Thus, more dispersion between fares is expected at the long-haul routes.

In Figure Appendix H. 4 to Figure Appendix H. 6, fares increase slightly more than in the short-haul routes after D*. FSC-FSC routes fares increase slower than LCC-LCC routes fares and FSC-LCC routes fares.

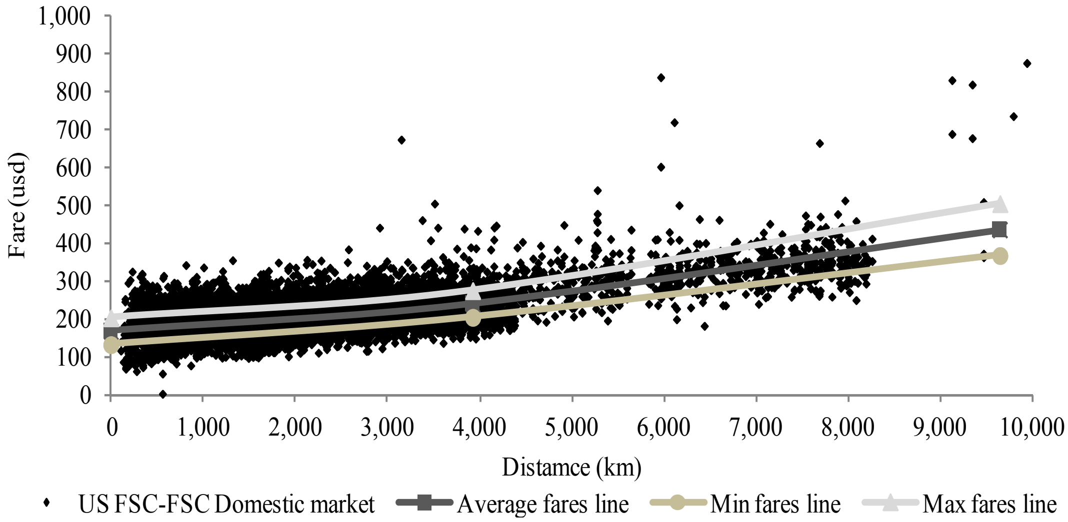


Figure Appendix H. 4 FSC-FSC market model result

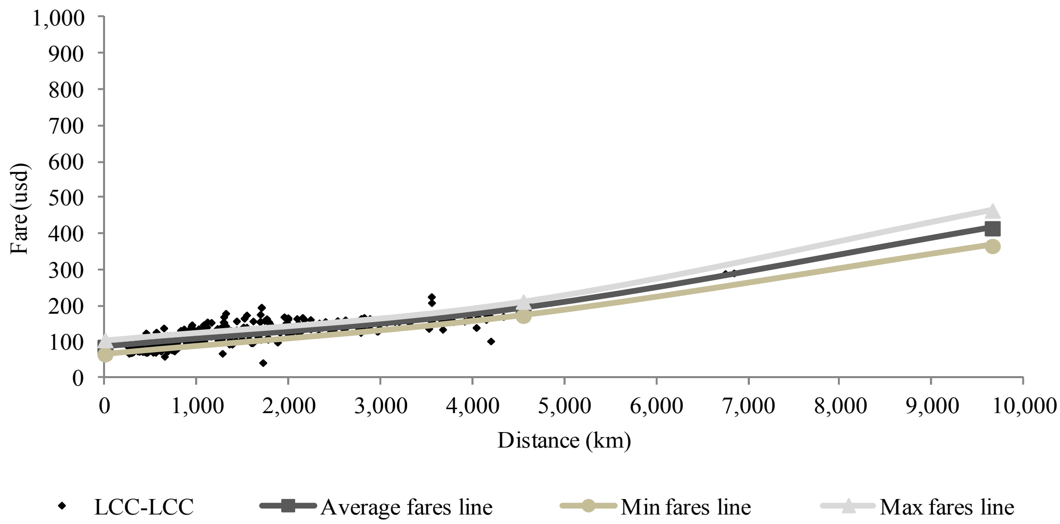


Figure Appendix H. 5 LCC-LCC market model result

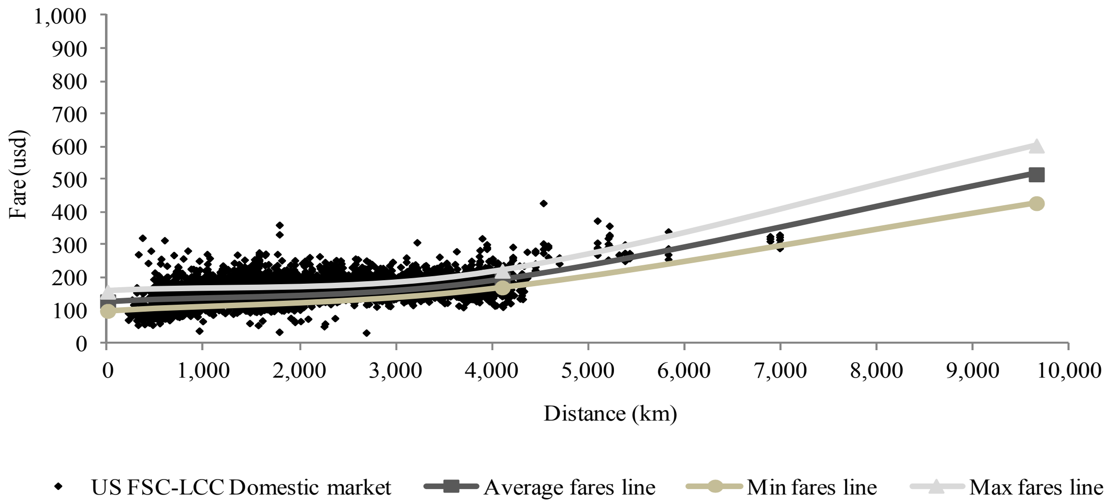


Figure Appendix H. 6 FSC-LCC market model result

In Figure Appendix H. 7, the model fares cumulative normal distribution function for the complete market is presented at 322km route distance. The LCC effect is shown by Figure Appendix H. 7. The presences of LCC's reduce the average fare dispersion and lower fares.

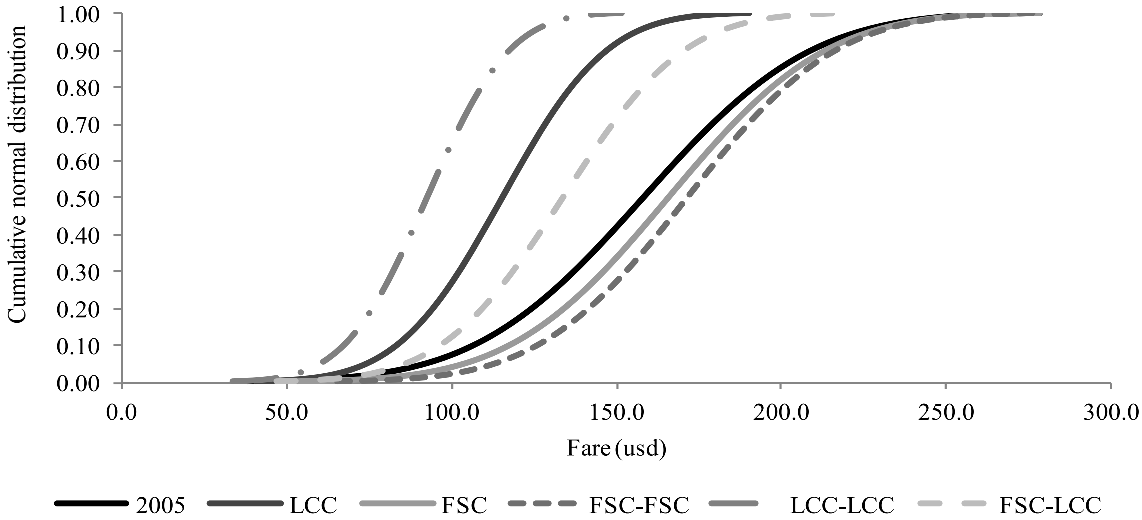


Figure Appendix H. 7 Market fares cumulative normal distribution at 322km

LCC-LCC routes were the cheapest. The FSC-LCC fares cumulative normal distribution function shows that the presence of LCC's made FSC's lower fares. FSC's fares were more expensive than LCC's fares. The FSC-FSC routes are the most expensive.

The average max fares at 322km route distance are: 220.78 usd for the FSC-LCC market, 190.41 usd for the LCC market, and 151.41 usd the LCC-LCC. The average min fares are 47.10 usd, 40.57 usd and 33.56 usd for the FSC-LCC, LCC and LCC-LCC markets respectively.

The FSC-FSC market average max fare at 322km route distance is 277.43 usd. In the case of the FSC market, the market average max fare at 322km is 278.30 usd. The average min fares are 65.66 usd, 38.38 usd and 53.43 usd for the FSC-FSC, FSC, and the complete US market respectively.

In Figure Appendix H. 8, the CFEM model cumulative normal distribution functions at 4,827km route distance are shown for different markets. The LCC's effect for the long-haul routes is shown in Figure Appendix H. 8. As distance increase the dispersion at all the markets decrease and the difference between LCC's and FSC's fares decrease. LCC's found more difficult than FSC's to lower fares in long-haul routes because FSC's fares per km are already low.

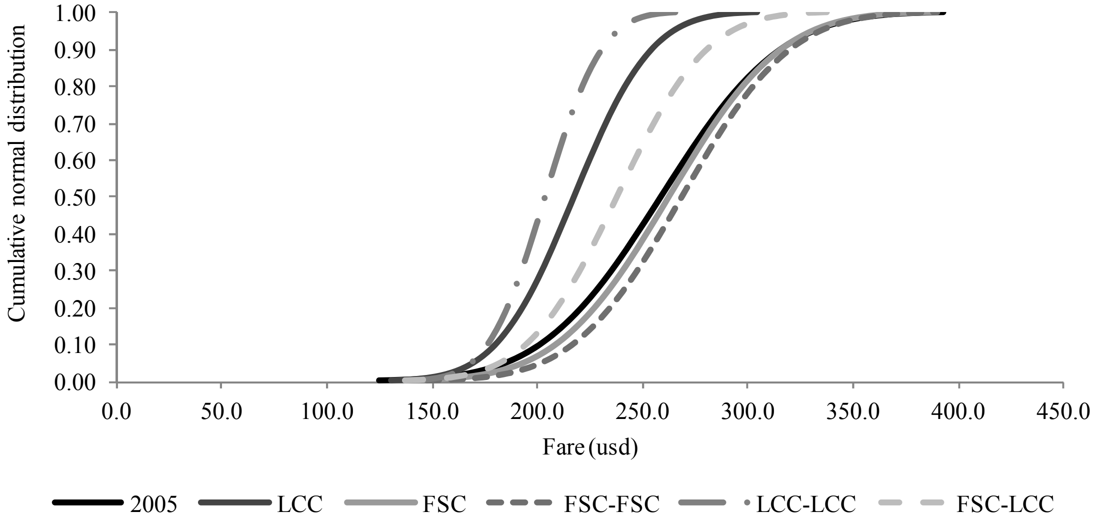


Figure Appendix H. 8 Market fares cumulative normal distribution at 4,827km

The model estimates the average max fare for the FSC-LCC, LCC and LCC-LCC markets at 338.67 usd, 304.26 usd and 267.45 usd respectively for a 4,827km (3,000mi) route. The model estimates the average min fare for the FSC-LCC, LCC and LCC-LCC at 137.32 usd, 130.23 usd and 140.31 usd respectively. The model estimates the average max fares for the FSC-FSC, FSC and all the US market at 389.71 usd, 387.56 usd and 392.96 usd respectively. Finally, the model estimates the min average fares for the FSC-FSC, FSC and all the US market at 147.05 usd, 137.02 usd and 124.71 usd respectively.

In Figure Appendix H. 9, the CFEM model fares cumulative distribution function at 402km distance, for all the airlines operating the domestic US air transport, is presented. In general, the model estimates FSC's fares to be the max fares on the market. Continental (CO) and American West (HP) showed the max average route fare and the min average route fare at 402km route distance. In Table Appendix H. 3 the CFEM model average, max and min fares are presented at 402km. In Table Appendix H. 4, the CFEM model average, max and min fares are presented at 4,827km.

Table Appendix H. 3 CFEM results max and min fares at 402km routes

Fare	AA	US	UA	DL	CO	WN	NK	FL	DH	B6
Min	66.74	43.89	78.54	64.15	17.29	36.81	42.37	45.46	26.30	65.56
Max	265.18	286.06	248.14	279.62	302.31	126.22	110.90	205.00	184.20	109.03

Table Appendix H. 4 CFEM results max and min fares in usd for 4,827km routes

Fare	AA	US	UA	DL	CO	WN	NK	FL	DH	B6
Min	140.09	133.63	172.83	125.99	128.44	113.50	159.41	122.74	143.87	128.73
Max	355.85	303.74	380.99	351.02	436.09	213.22	254.25	254.25	181.97	299.56

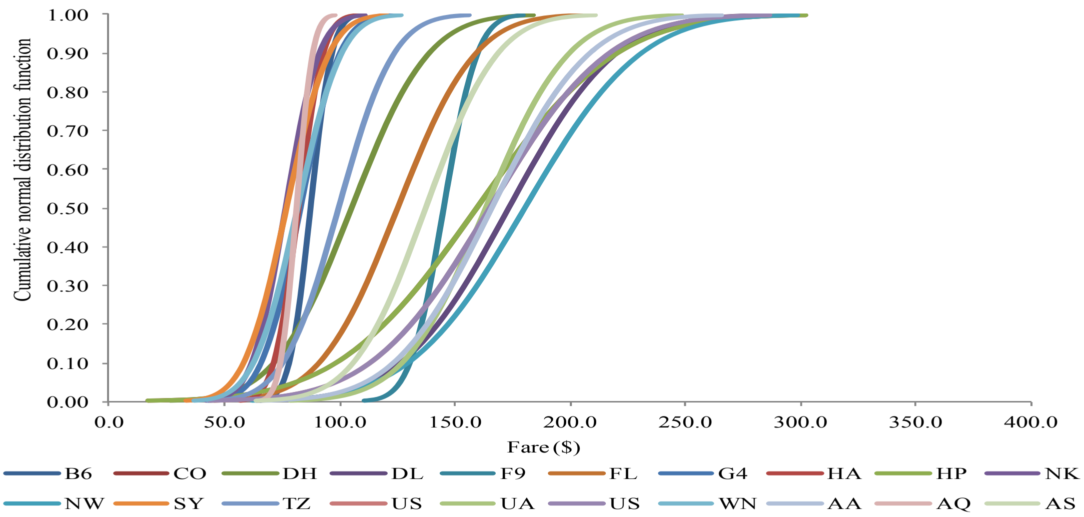


Figure Appendix H. 9 Airline fares cumulative normal distribution at 402km

The CFEM model analysis shows that FSC's can lower fares in short-haul markets to counteract the presence of LCC's. In long-haul markets, LCC's fares are low. It makes difficult for LCC's to operate in long-haul routes. Thus, few long-haul markets are operated by LCC's.

In Figure Appendix H. 10, the airports types' fares cumulative normal distribution function at 402km and 4,827km is presented. The model results for a short-haul route (Figure Appendix H. 10, left side) show that in general all airports types' fares are close to each other. The cheapest airport type is B with 278 usd max and 11 usd min fares. The most expensive airports are the smallest ones (Type E), with max 267.59 usd and min 73.48 usd fares.

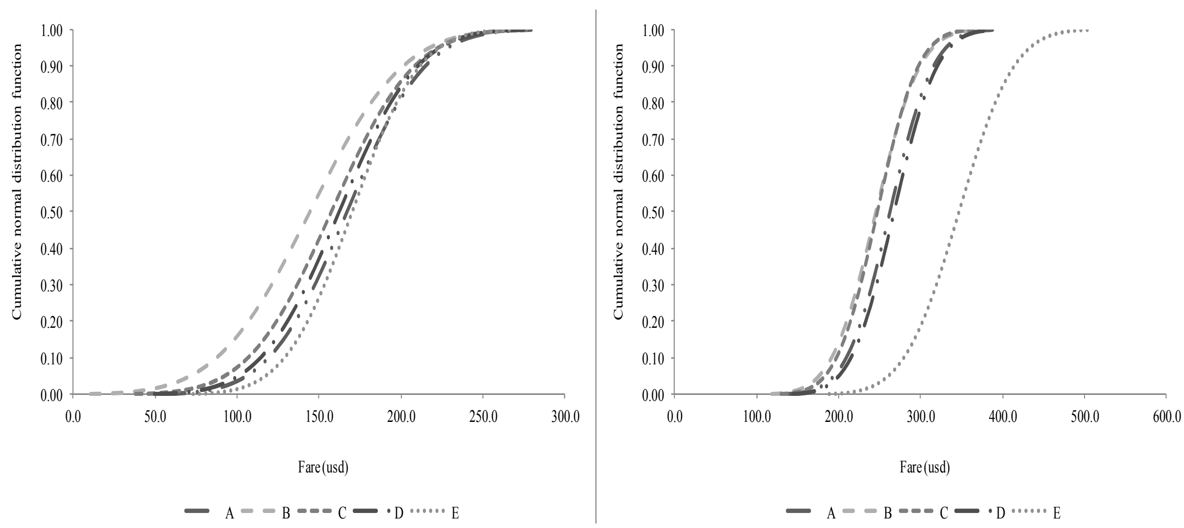


Figure Appendix H. 10 Airport fares cumulative normal distribution at 402km (left) and at 4,827km (right)

The model results for a short-haul route (Figure Appendix H. 10, left side) show that Airports B and C charge the lowest fares. Airports A and D fares are very close to B and C with fares between 137.02 usd and 387.56 usd at 4,827km route distances. Small airports show very expensive route average fare in long-haul markets. Their average fares are between 188 usd and 506 usd at 4,827km.

Appendix I: Grey prediction algorithm

A sequence of historical data observed over time is called a time series. It is needed to estimate the sequences of the observations growth into the future to forecast a time series. The easiest way to find a time series pattern is by plotting the historical data over time. Different time series patterns can be found: horizontal, seasonal, trend and cyclical [Talliri and Ryzin, 2005]. A horizontal pattern shows up when the data values oscillate around the mean. A seasonal pattern happens when the data is influenced by seasonal factors such as quarter of the year, month, or week day. Cyclical patterns exist when the observations rise and do not fall in a fixed period. Finally, a trend pattern happens when a long term increase/decrease in the data values exists [Makridakis, Wheelwright, Hyndman, 1998] [Wells and Young, 2004].

Grey models are used to predict the future values of a time series. A grey model has internal characteristics or mathematical equations that describe known and unknown information. According with Kayakan, Ulutas and Kaynak [2010] a grey model is written by GM (n, m) where n is the order of the differential equation and m the number of variables. GM (1, 1) is the most widely used in the literature, pronounced as “Grey model first order one variable”. The differential equations have time unstable coefficients. In other words, the model is renewed as the new data become available to the prediction model. This makes GM robust with respect to noise and lack of information comparing with other methods. The model can be used only for positive data, principal limitation. The primitive data points are smooth by an operator named Accumulating Generator Operator (AOG). The differential equation is solved to obtain the n step ahead predicted value of the system. Using the prediction, the Inverse Accumulating Generation Operator (IAGO) is applied to find the predicted values of original data.

The Grey model, as Kayakan, Ulutas and Kaynak [2010] described in their paper with minor corrections, is as follow:

Consider a time series data $Q_r^{(0)}$ that denotes the estimation value to forecast for example the number of passengers of an airline route. In Chapter 4, the model is used to estimate the CPI index, thus the variable $Q_r^{(0)}$ changes to $CPI_r^{(0)}$.

$$Q_r^{(0)} = \left(Q_r^{(0)}(1), Q_r^{(0)}(2), \cdots, Q_r^{(0)}(n)\right), \quad n \geq 4 \tag{I.1}$$

Where:

n = sample size of the data, at least four [-]

$Q_r^{(0)}$ is a non-negative sequence and n is the sample size of the data. Then applying the Accumulative Generator Operator (AGO) the following sequence $Q_r^{(1)}$ is obtained. The sequence $Q_r^{(1)}$ is monotonically increasing.

$$Q_r^{(1)} = \left(Q_r^{(1)}(1), Q_r^{(1)}(2), \cdots, Q_r^{(1)}(n)\right), \quad n \geq 4 \tag{I.2}$$

Where:

$$Q_r^{(1)}(k) = \sum_{i=1}^{k} Q_r^{(0)}(k) = Q_r^{(0)}(k), \quad k = 1, 2, 3 \ldots n \tag{I.3}$$

The generated mean sequence $X_r^{(1)}$ of $Q_r^{(1)}$ is defined as:

$$X_r^{(1)} = \left(X_r^{(1)}(1), X_r^{(1)}(2), \cdots, X_r^{(1)}(n)\right), \quad n \geq 4 \tag{I.4}$$

Where:

$X_r^{(1)}$ = is the mean value of the next data [pax]

$$X_r^{(1)}(k) = 0.5\, Q_r^{(1)}(k) + 0.5\, Q_r^{(1)}(k-1), \quad k = 2, 3 \ldots n \tag{I.5}$$

The solution by least square method (OLS) of the grey differential equation of GM (1, 1) is as follows:

$$Q_r^{(0)}(k) = \frac{b}{a\, X_r^{(1)}(k)} \tag{I.6}$$

The whitening equation is as follows:

$$\frac{dQ_r^{(0)}(t)}{dt} + a\, X_r^{(1)}(t) = b \tag{I.7}$$

$[a, b]^T$ is a sequence of variables where a solve the b estimation problem and can be found as follows:

$$[a, b]^T = (B^T B)^{-1} B^T Q^T \tag{I.8}$$

Where:

$$Q^T = \left[Q_r^{(0)}(2),\ Q_r^{(0)}(3), \cdots, Q_r^{(0)}(n)\right]^T \tag{I.9}$$

$$B^T = \begin{bmatrix} -X_r^{(0)}(2), & -X_r^{(0)}(2), & \cdots & -X_r^{(0)}(2) \\ 1 & 1 & \cdots & 1 \end{bmatrix}^T \tag{I.10}$$

According with equation I.7, the solution of $Q_r^{(1)}(t)$ at time k:

$$Q_{r_p}^{(1)}(k+1) = \left[Q_r^{(0)}(1) - \frac{b}{a}\right] e^{-ak} + \frac{b}{a} \tag{I.11}$$

The pax flow estimated Q_r (t) at time k is equal to:

$$Q_{r_p}^{(0)}(k+1) = \left(Q_{r_p}^{(1)}(k+1) - Q_{r_p}^{(1)}(k)\right) \tag{I.12}$$

In order to improve the accuracy of the model predictions, an error modification of the GM based on the Fourier series is explicated.

Considering equation I.11 and the predicted values given by the GM (1, 1) model the error sequence of $Q_r^{(0)}$ can be determined as:

$$\epsilon_r^{(0)} = \left(\epsilon_r^{(0)}(2), \epsilon_r^{(0)}(3), \cdots, \epsilon_r^{(0)}(n)\right) \quad \text{(I.13)}$$

Where:

$$\epsilon_r^{(0)}(k) = Q_r^{(0)}(k) - Q_{r_p}^{(0)}(k), \qquad k = 2, 3 \ldots n \quad \text{(I.14)}$$

Now, expressing the error residual in equation I.14 as Fourier series:

$$W_t = \epsilon_{r_p}^{(0)}(k) \cong 0.5\, a_0 + \sum_{i=1}^{z}\left[a_i \cos\left(\frac{2\pi i}{T}k\right) + b_i \sin\left(\frac{2\pi i}{T}k\right)\right], \qquad k = 2, 3 \ldots n \quad \text{(I.15)}$$

Where:

$$T = n - 1 \quad \text{(I.16)}$$

$$z = \left(\frac{n-1}{2}\right) - 1 \quad \text{(I.17)}$$

Rewriting equation I.15 as follows:

$$\epsilon_{r_p}^{(0)} \cong PC \quad \text{(I.18)}$$

Where:

$$P = \begin{bmatrix} 0.5 & \cos\left(2\frac{2\pi}{T}\right) & \sin\left(2\frac{2\pi}{T}\right) & \cos\left(2\frac{2\pi 2}{T}\right) & \sin\left(2\frac{2\pi 2}{T}\right) & \cdots & \cos\left(2\frac{2\pi z}{T}\right) & \sin\left(2\frac{2\pi z}{T}\right) \\ 0.5 & \cos\left(3\frac{2\pi}{T}\right) & \sin\left(3\frac{2\pi}{T}\right) & \cos\left(3\frac{2\pi 2}{T}\right) & \sin\left(3\frac{2\pi 2}{T}\right) & \cdots & \cos\left(3\frac{2\pi z}{T}\right) & \sin\left(3\frac{2\pi z}{T}\right) \\ \cdots & & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ 0.5 & \cos\left(n\frac{2\pi}{T}\right) & \sin\left(n\frac{2\pi}{T}\right) & \cos\left(n\frac{2\pi 2}{T}\right) & \sin\left(n\frac{2\pi 2}{T}\right) & \cdots & \cos\left(n\frac{2\pi z}{T}\right) & \sin\left(n\frac{2\pi z}{T}\right) \end{bmatrix} \quad \text{(I.19)}$$

$$C = [a_0 a_1 b_1 a_2 b_2 \cdots a_z b_z]^T \quad \text{(I.20)}$$

$$C \cong (P^T P)^{-1} P^T \epsilon_r^{(0)} \quad \text{(I.21)}$$

Finally, the Fourier series correction can be solved as follow:

$$Q_{r_{pf}}^{(0)}(k) = Q_{r_p}^{(0)}(k) - \epsilon_{r_p}^{(0)}(k), \qquad k = 2, 3 \ldots n \quad \text{(I.22)}$$

The final pax flow estimated Q_r (t) at time k is equal to:

$$Q_r(t) = Q_{r_{pf}}^{(0)}(k) \quad \text{(I.23)}$$

Appendix J: Demand function model coefficient values and ANOVA test results

Table Appendix J. 1 Demand function model ANOVA test results 2005

Annova						
Model	*Demand Model*	*Sum of Squares*	*df*	*Mean Square*	*F*	*Sig.*
2005	Regression	34,819.47	29.00	1,200.67	557,521.61	.000a
	Residual	37.26	17,302.00	0.00		
	Total	34,856.73	17,331.00			

Table Appendix J. 2 Demand function model ANOVA test results 2006

Annova						
Model	*Demand Model*	*Sum of Squares*	*df*	*Mean Square*	*F*	*Sig.*
2006	Regression	35,479.25	26.00	1,364.59	660,814.92	.000a
	Residual	35.37	17,129.00	0.00		
	Total	35,514.63	17,155.00			

Table Appendix J. 3 Demand function model ANOVA test results 2007

Annova						
Model	*Demand Model*	*Sum of Squares*	*df*	*Mean Square*	*F*	*Sig.*
2007	Regression	35,511.06	27.00	1,315.22	622,058.23	.000a
	Residual	36.15	17,100.00	0.00		
	Total	35,547.21	17,127.00			

Table Appendix J. 4 Demand function model ANOVA test results 2008

Annova						
Model	*Demand Model*	*Sum of Squares*	*df*	*Mean Square*	*F*	*Sig.*
2008	Regression	34,412.24	27.00	1,274.53	575,795.99	.000a
	Residual	37.02	16,723.00	0.00		
	Total	34,449.26	16,750.00			

Table Appendix J. 5 Demand function model coefficient values 2005[19]

2005	*Unstandardized Coefficients*		*Standardized Coefficients*	*t*	*Sig.*
Variable	*B*	*Std. Error*	*Beta*		
ln A_5	0.1726	9.81E-03		1.76E+01	9.74E-69
α_5	-0.0309	7.15E-04	-1.43E-02	-4.32E+01	0.00E+00
δ_5	-0.0083	1.85E-03	-1.61E-03	-4.50E+00	6.96E-06
ω_5	-0.0052	7.39E-04	-5.33E-03	-6.97E+00	3.22E-12
ρ_5	0.0070	6.19E-04	7.64E-03	1.13E+01	2.90E-29
θ_5	0.9996	3.59E-04	9.98E-01	2.79E+03	0.00E+00
π_{AA}	-0.0014	2.40E-04	-1.77E-03	-5.89E+00	3.85E-09
π_{AQ}	-0.0068	1.66E-03	-1.03E-03	-4.09E+00	4.38E-05
π_{B6}	-0.0053	5.64E-04	-2.48E-03	-9.44E+00	4.02E-21
π_{CO}	0.0124	1.05E-03	3.00E-03	1.18E+01	3.52E-32
π_{DL}	0.0060	3.03E-04	5.55E-03	1.98E+01	3.45E-86
π_{AS}	0.0000	0.00E+00	-1.28E-03	-4.22E+00	2.40E-05
π_{F9}	0.0102	7.71E-04	3.38E-03	1.33E+01	5.06E-40
π_{FL}	0.0089	5.45E-04	4.29E-03	1.63E+01	1.50E-59
π_{G4}	0.0132	1.88E-03	1.77E-03	7.06E+00	1.75E-12
π_{NK}	0.0112	1.65E-03	1.71E-03	6.81E+00	1.03E-11
π_{NW}	0.0015	2.50E-04	1.83E-03	6.14E+00	8.49E-10
π_{SY}	0.0128	2.05E-03	1.56E-03	6.25E+00	4.09E-10
π_{U5}	0.0116	2.15E-03	1.35E-03	5.40E+00	6.83E-08
π_{UA}	-0.0010	2.28E-04	-1.28E-03	-4.22E+00	2.40E-05
π_{US}	-0.0041	3.02E-04	-3.84E-03	-1.34E+01	7.38E-41
π_{WN}	-0.0125	3.44E-04	-1.09E-02	-3.63E+01	1.12E-277
π_{YV}	NA	NA	NA	NA	NA
π_{YX}	0.0023	9.47E-04	6.01E-04	2.38E+00	1.74E-02
π_{CX}	NA	NA	NA	NA	NA
π_{DH}	0.0062	8.28E-04	1.90E-03	7.46E+00	9.10E-14
π_{E9}	NA	NA	NA	NA	NA
π_{HP}	0.0130	4.04E-04	8.63E-03	3.22E+01	2.83E-221
π_{OO}	-0.1397	9.74E-03	-3.65E-03	-1.43E+01	2.35E-46
π_{PN}	NA	NA	NA	NA	NA
π_{QX}	0.0070	6.73E-03	2.60E-04	4.04E+00	2.97E-02
π_{TZ}	0.0117	1.56E-03	1.89E-03	7.55E+00	4.64E-14
π_{XP}	0.0121	9.53E-03	3.16E-04	1.27E+00	2.05E-02
π_{HA}	0.0034	1.39E-03	6.24E-04	4.46E+00	1.39E-02
π_{NA}	0.0199	5.49E-03	9.03E-04	3.63E+00	2.86E-04
π_{7H}	NA	NA	NA	NA	NA
π_{99}	NA	NA	NA	NA	NA

[19] The coefficient parameter is equal "NA", when airlines did not report to the DOT US Consumer Report database.

Table Appendix J. 6 Demand function model coefficient values 2006[20]

2006	*Unstandardized Coefficients*		*Standardized Coefficients*	*t*	*Sig.*
Variable	*B*	*Std. Error*	*Beta*		
ln A_5	0.1695	1.00E-02		1.69E+01	8.39E-64
α_5	-2.67E-02	7.01E-04	-1.21E-02	-3.81E+01	3.02E-304
δ_5	-1.37E-02	1.77E-03	-2.74E-03	-7.74E+00	1.08E-14
ω_5	-5.72E-03	7.33E-04	-5.82E-03	-7.81E+00	6.01E-15
ρ_5	8.36E-03	6.13E-04	9.06E-03	1.36E+01	4.67E-42
θ_5	9.99E-01	3.54E-04	9.97E-01	2.82E+03	0.00E+00
π_{AA}	9.74E-04	6.03E-04	1.24E-03	3.62E+00	1.06E-02
π_{AQ}	-2.95E-03	1.96E-03	-3.84E-04	-3.51E+00	1.32E-02
π_{B6}	4.67E-03	7.51E-04	2.36E-03	6.22E+00	5.17E-10
π_{CO}	-1.03E-02	9.09E-04	-3.52E-03	-1.13E+01	2.09E-29
π_{DL}	-6.05E-03	6.25E-04	-5.93E-03	-9.69E+00	3.76E-22
π_{AS}	6.90E-04	5.96E-04	9.92E-04	3.16E+00	2.47E-02
π_{F9}	-8.34E-03	8.68E-04	-3.09E-03	-9.61E+00	8.06E-22
π_{FL}	-5.20E-03	7.25E-04	-2.88E-03	-7.18E+00	7.45E-13
π_{G4}	-1.35E-02	1.69E-03	-2.08E-03	-8.01E+00	1.18E-15
π_{NK}	-1.01E-02	1.86E-03	-1.39E-03	-5.44E+00	5.54E-08
π_{NW}	-1.38E-03	6.08E-04	-1.61E-03	-2.27E+00	2.31E-02
π_{SY}	-1.30E-02	2.06E-03	-1.59E-03	-6.33E+00	2.54E-10
π_{U5}	-1.24E-02	2.41E-03	-1.28E-03	-5.14E+00	2.78E-07
π_{UA}	1.48E-04	6.02E-04	1.92E-04	3.25E+00	5.00E-02
π_{US}	-1.20E-03	6.20E-04	-1.23E-03	-1.94E+00	5.00E-02
π_{WN}	8.59E-03	6.32E-04	8.30E-03	1.36E+01	7.56E-42
π_{YV}	NA	NA	NA	NA	NA
π_{YX}	-3.32E-03	9.97E-04	-9.76E-04	-3.33E+00	8.60E-04
π_{CX}	NA	NA	NA	NA	NA
π_{DH}	NA	NA	NA	NA	NA
π_{E9}	-8.35E-03	8.37E-03	-2.41E-04	-3.00E+00	3.18E-02
π_{HP}	-1.16E-02	6.77E-04	-7.66E-03	-1.71E+01	6.26E-65
π_{OO}	1.33E-01	4.65E-03	7.42E-03	2.87E+01	3.96E-177
π_{PN}	NA	NA	NA	NA	NA
π_{QX}	NA	NA	NA	NA	NA
π_{TZ}	-1.37E-02	2.04E-03	-1.69E-03	-6.74E+00	1.68E-11
π_{XP}	NA	NA	NA	NA	NA
π_{HA}	NA	NA	NA	NA	NA
π_{NA}	NA	NA	NA	NA	NA
π_{7H}	NA	NA	NA	NA	NA
π_{99}	NA	NA	NA	NA	NA

[20] The coefficient parameter is equal "NA", when airlines did not report to the DOT US Consumer Report database.

Table Appendix J. 7 Demand function model coefficient values 2007[21]

2007	*Unstandardized Coefficients*		*Standardized Coefficients*	*t*	*Sig.*
Variable	*B*	*Std. Error*	*Beta*		
$\ln A_5$	0.2391	9.78E-03		2.44E+01	1.23E-129
α_5	-2.10E-02	7.18E-04	-9.50E-03	-2.92E+01	2.87E-183
δ_5	-3.34E-02	1.75E-03	-7.04E-03	-1.91E+01	2.00E-80
ω_5	-4.52E-03	7.36E-04	-4.65E-03	-6.14E+00	8.44E-10
ρ_5	7.33E-03	6.17E-04	8.04E-03	1.19E+01	1.97E-32
θ_5	9.98E-01	3.61E-04	9.96E-01	2.76E+03	0.00E+00
π_{AA}	1.44E-03	6.18E-04	1.81E-03	2.34E+00	1.94E-02
π_{AQ}	-6.10E-03	1.96E-03	-8.03E-04	-3.11E+00	1.86E-03
π_{B6}	7.26E-03	7.62E-04	3.70E-03	9.53E+00	1.82E-21
π_{CO}	-8.41E-03	8.73E-04	-3.21E-03	-9.63E+00	6.68E-22
π_{DL}	-4.67E-03	6.48E-04	-4.23E-03	-7.21E+00	5.82E-13
π_{AS}	2.78E-03	6.09E-04	4.00E-03	4.56E+00	5.10E-06
π_{F9}	-7.44E-03	8.72E-04	-2.81E-03	-8.53E+00	1.61E-17
π_{FL}	-3.89E-03	7.22E-04	-2.32E-03	-5.39E+00	6.98E-08
π_{G4}	-9.49E-03	1.40E-03	-1.86E-03	-6.77E+00	1.32E-11
π_{NK}	-3.90E-03	1.71E-03	-5.97E-04	-2.27E+00	2.30E-02
π_{NW}	-2.02E-03	6.21E-04	-2.32E-03	-3.25E+00	1.17E-03
π_{SY}	-1.16E-02	2.07E-03	-1.43E-03	-5.61E+00	2.11E-08
π_{U5}	-1.10E-02	2.41E-03	-1.16E-03	-4.57E+00	4.85E-06
π_{UA}	1.15E-03	6.15E-04	1.48E-03	1.86E+00	6.25E-02
π_{US}	-3.75E-03	6.20E-04	-4.44E-03	-6.04E+00	1.57E-09
π_{WN}	1.00E-02	6.47E-04	9.88E-03	1.55E+01	8.51E-54
π_{YV}	5.08E-03	8.41E-03	1.48E-04	3.60E+00	5.00E-02
π_{YX}	-4.56E-03	9.82E-04	-1.41E-03	-4.65E+00	3.36E-06
π_{CX}	NA	NA	NA	NA	NA
π_{DH}	NA	NA	NA	NA	NA
π_{E9}	NA	NA	NA	NA	NA
π_{HP}	-8.96E-03	1.07E-03	-2.45E-03	-8.36E+00	6.81E-17
π_{OO}	1.53E-01	4.68E-03	8.58E-03	3.26E+01	7.50E-226
π_{PN}	NA	NA	NA	NA	NA
π_{QX}	NA	NA	NA	NA	NA
π_{TZ}	-1.51E-02	1.77E-03	-2.22E-03	-8.54E+00	1.43E-17
π_{XP}	NA	NA	NA	NA	NA
π_{HA}	-3.28E-04	1.41E-03	-6.32E-05	-5.23E+00	4.16E-02
π_{NA}	NA	NA	NA	NA	NA
π_{7H}	NA	NA	NA	NA	NA
π_{99}	NA	NA	NA	NA	NA

[21] The coefficient parameter is equal "NA", when airlines did not report to the DOT US Consumer Report database.

Table Appendix J. 8 Demand function model coefficient values 2008[22]

2008	*Unstandardized Coefficients*		*Standardized Coefficients*	*t*	*Sig.*
Variable	*B*	*Std. Error*	*Beta*		
ln A_5	0.2320	9.97E-03		2.33E+01	7.71E-118
α_5	-2.16E-02	7.33E-04	-9.76E-03	-2.95E+01	3.11E-186
δ_5	-3.14E-02	1.73E-03	-6.72E-03	-1.82E+01	3.08E-73
ω_5	-4.86E-03	7.56E-04	-5.02E-03	-6.42E+00	1.39E-10
ρ_5	7.72E-03	6.33E-04	8.51E-03	1.22E+01	5.41E-34
θ_5	9.98E-01	3.74E-04	9.96E-01	2.67E+03	0.00E+00
π_{AA}	3.02E-03	6.38E-04	3.77E-03	4.73E+00	2.23E-06
π_{AQ}	-6.50E-03	2.31E-03	-7.44E-04	-2.82E+00	4.86E-03
π_{B6}	1.08E-02	7.87E-04	5.62E-03	1.38E+01	6.25E-43
π_{CO}	-6.69E-03	8.98E-04	-2.58E-03	-7.45E+00	9.84E-14
π_{DL}	-3.96E-03	6.78E-04	-3.34E-03	-5.85E+00	5.06E-09
π_{AS}	2.28E-04	6.29E-04	3.25E-04	6.36E+00	4.17E-02
π_{F9}	-6.68E-03	8.03E-04	-3.24E-03	-8.32E+00	9.71E-17
π_{FL}	-7.58E-03	7.31E-04	-4.80E-03	-1.04E+01	3.89E-25
π_{G4}	-9.35E-03	1.41E-03	-1.91E-03	-6.63E+00	3.50E-11
π_{NK}	8.41E-03	1.78E-03	1.29E-03	4.72E+00	2.33E-06
π_{NW}	-2.07E-03	6.45E-04	-2.39E-03	-3.22E+00	1.30E-03
π_{SY}	-1.29E-02	2.06E-03	-1.66E-03	-6.24E+00	4.55E-10
π_{U5}	-1.07E-02	2.13E-03	-1.34E-03	-5.03E+00	4.94E-07
π_{UA}	2.81E-03	6.36E-04	3.61E-03	4.41E+00	1.02E-05
π_{US}	-5.28E-03	6.38E-04	-6.63E-03	-8.28E+00	1.32E-16
π_{WN}	9.37E-03	6.60E-04	9.57E-03	1.42E+01	1.73E-45
π_{YV}	-3.92E-03	6.46E-03	-1.55E-04	-6.07E-01	5.00E-02
π_{YX}	-1.11E-03	1.01E-03	-3.57E-04	-4.11E+00	2.69E-02
π_{CX}	NA	NA	NA	NA	NA
π_{DH}	NA	NA	NA	NA	NA
π_{E9}	NA	NA	NA	NA	NA
π_{HP}	NA	NA	NA	NA	NA
π_{OO}	1.60E-01	4.64E-03	9.53E-03	3.44E+01	7.68E-251
π_{PN}	NA	NA	NA	NA	NA
π_{QX}	-5.98E-03	6.91E-03	-2.20E-04	-2.87E+00	3.87E-02
π_{TZ}	-1.30E-02	3.25E-03	-1.03E-03	-4.00E+00	6.43E-05
π_{XP}	NA	NA	NA	NA	NA
π_{HA}	1.15E-04	1.41E-03	2.33E-05	4.08E+00	4.35E-02
π_{NA}	NA	NA	NA	NA	NA
π_{7H}	NA	NA	NA	NA	NA
π_{99}	NA	NA	NA	NA	NA

[22] The coefficient parameter is equal "NA", when airlines did not report to the DOT US Consumer Report database.

Appendix K: Optimization model parameters values

Tp	= 24	[hrs]
WTD	= 0	[hrs]
WTO	= 0	[hrs]
ξ	= 4	[-]
WACC	= 0.08	[-]
VA	= 0	[usd]
$freq_{max}$	= 10 and 70	[usd]
C_3	= 0.04 for landing at airport destination and 0.42 for taking off at airport origin	[1/min]
t_0	= -5.01 for landing at airport destination and 3.14 for taking off at airport origin	[min]
α_1	= 1.31 for landing at airport destination and 0.66 for taking off at airport origin	[-]
β_1	= 0.67 for landing at airport destination and 0.28 for taking off at airport origin	[-]
λ_1	= 0.04 for landing at airport destination and 1.29 for taking off at airport origin	[-]
λ_2	= 0.19 for landing at airport destination and 1.78 for taking off at airport origin	[-]
V_{WTD}	= V_C	[km/hr]
D_{SA}	= 160.93	[km]
WPax	= 89	[kg/pax]
NBags	= 1	[bag/pax]
WBags	= 21	[kg/bag]
D*	= 4,101 (Chapter 4, CFEM model result)	[km]
JFP	= 598.73 (Table 3.3) considering the jet fuel density equal to 0.785 kg/l [A318 manual]	[usd/ton]
ρ_{Air}	= 1.22	[kg/m^3]
α_{AT}	= 14 for taking off and menus 4 for landing	[°]
V_w	= 0	[km/hr]
D_{Tin}	= 5	[km]
$V_{taxiing}$	= 32.18 km/hr [FAA, 2010a]	[km/hr]
D_{TO}	= 5	[km]
RL	= 7	[km]
AIRSIDE	= E	[-]
Ђ	= 24	[hrs]
λ_{max}	= 1,000,000	[mov]
Mov	= 0	[mov]
$Ꝏ_{max}$	= 1,000,000	[mov]
Pg	= 0	[mov]
$CapS_{af}$	= 100,000,000	[pax]
$CapD_{sf}$	= 100,000,000	[pax]
AC	= 100,000,000	[pax]
U	= 24*7=156 hrs	[hrs/week]
maintenance	= 0	[hrs/week]

ENAIR $_{t=0}$ = 0 [-]
Cargo = 1.099 [Federal Express Cargo Carrier, FEDEX] [usd/kg/km]

Table Appendix K. 1 Aircraft velocities, price and wing area

x	*Vc*	*Vmax*	*M*	*Price*	*Sw*	*x*	*Vc*	*Vmax*	*M*	*Price*	*Sw*
A318	840	948.48	0.82	65.2	122.6	B737-900	908	948	0.82	85.8	124.58
A319	840	948.48	0.82	77.7	122.6	B787-3	913	983	0.85	155.5	325
A320	840	948.48	0.82	85	122.6	B747-8	948	994	0.86	308	524.9
A321	840	948.48	0.82	99.7	123	B767-200ER	854	914	0.79	144.1	283.3
A330-200	860	994.75	0.86	200.8	361.6	B787-800	913	983	0.85	171.5	325
A330-300	860	995	0.86	261.8	361.6	B787-900	913	983	0.85	205.5	325
A340-300	880	995	0.86	238	361.6	B767-300ER	850	900	0.78	164.3	283.3
A340-500	960	995	0.86	261.8	439.4	B777-200	893	972	0.84	232.3	427.8
A340-600	960	995	0.86	275.4	439.4	B777-300ER	893	972	0.84	284.1	427.8
A350-800	983	1,029	0.89	236.6	460	EMB135	834	902	0.78	19	51.18
A350-900	983	1,029	0.89	267.6	460	ERJ140	833	902	0.78	22	51.18
A350-1000	983	1,029	0.89	299.7	460	EMB145	833	902	0.78	24.5	51.18
A380	983	1,029	0.89	375.3	846	E170	833	948	0.82	33	72.72
B737-600	908	948	0.82	56.9	124.58	E175	833	948	0.82	35.5	72.72
B737-700	908	948	0.82	67.9	124.58	E190	833	948	0.82	39.5	92.5
B737-800	908	948	0.82	80.8	124.58	E195	833	948	0.82	42	92.5

Table Appendix K. 2 Aircraft short-haul simulation seats, payload and load capacities

x	*Smax*	*S opt.*	*Nbags*	*Payload*	*OEW*	*Load*	*MTW*	*x*	*Smax*	*S opt.*	*Payload*	*OEW*	*Load*	*MTW*
A318	149	136	1	14.96	39.5	54.46	68.4	B737-900	200	200	22.99	44.68	67.67	85.37
A319	156	156	1	17.16	40.3	57.46	75.9	B787-3	330	330	36.3	101	137.3	170.55
A320	180	180	1	19.8	42.1	61.9	78.4	B747-8	524	524	57.64	211.9	269.54	443.61
A321	220	220	1	24.2	48.1	72.3	93.9	B767-200ER	255	255	28.05	82.38	110.43	179.62
A330-200	380	380	1	41.8	120.5	162.3	238.9	B787-800	250	250	27.5	109.77	137.27	228.38
A330-300	375	375	1	41.25	123.1	164.35	233.9	B787-900	290	290	31.9	115	146.9	247.66
A340-300	375	375	1	48.4	120.9	169.3	277.4	B767-300ER	350	350	38.5	90.01	128.51	187.33
A340-500	375	375	1	41.25	170.4	211.65	381.2	B777-200	440	440	48.4	145.15	193.55	348.36
A340-600	440	440	1	48.4	176.36	224.76	381.2	B777-300ER	550	550	60.5	167.83	228.33	352.44
A350-800	258	258	1	28.38	104.65	133.03	259.9	EMB135	37	37	4.07	11.5	15.57	20.1
A350-900	316	316	1	34.76	106.53	141.29	268.9	ERJ140	44	44	4.84	11.81	16.65	21.2
A350-1000	350	350	1	38.5	108.4	146.9	308.9	EMB145	50	50	5.5	12.59	18.09	24.2
A380	853	765	1	84.15	276.8	360.95	562	E170	80	70	7.7	21.8	29.5	37.36
B737-600	130	130	1	14.3	36.38	50.68	65.77	E175	88	88	9.68	21.81	31.49	38.95
B737-700	148	132	1	14.52	37.65	52.17	70.31	E190	106	106	11.66	28.08	39.74	51.96
B737-800	184	184	1	20.24	41.41	61.65	79.33	E195	118	118	12.98	28.97	41.95	52.45

Table Appendix K. 3 Aircraft short-haul simulation weights, tank, cargo capacities

x	*MTOW*	*MLW*	*MZFW*	*ToutF*	*Tank max*	*UF*	*Cargo*
A318	68	57.5	54.5	0.4	19	13.54	-
A319	75.5	62.5	62.5	0.4	23.7	18.04	-
A320	78	66	62.5	0.4	23.7	16.1	-
A321	93	77.8	73.8	0.9	23.57	20.7	-
A330-200	238	182	170	0.9	109.19	75.7	-
A330-300	233	187	175	0.9	76.56	68.65	-
A340-300	276.5	192	183	0.9	115.4	107.2	-
A340-500	380	246	232	1.2	174.94	168.35	-
A340-600	380	265	251	1.2	160.53	155.24	-
A350-800	259	193	181	0.9	108.33	108.33	17.64
A350-900	268	205	192	0.9	108.33	108.33	18.38
A350-1000	308	233	220	0.9	122.46	122.46	38.64
A380	560	386	361	2	251.2	199.05	-
B737-600	65.54	55.11	51.94	0.23	20.89	14.87	-
B737-700	70.08	58.6	52.2	0.23	20.89	17.91	-
B737-800	79.02	66.36	62.73	0.32	20.89	17.36	-
B737-900	85.14	71.35	67.72	0.23	23.82	17.47	-
B787-3	170.1	161	151.03	0.45	38.15	32.8	-
B747-8	442.25	309.35	291.21	1.36	194.66	172.71	-
B767-200ER	179.17	136.08	117.93	0.45	73.36	68.74	-
B787-800	227.93	172.37	161.03	0.45	101.89	90.66	-
B787-900	247.21	191.64	180.3	0.45	101.89	100.31	-
B767-300ER	186.88	145.15	133.81	0.45	73.36	58.37	-
B777-200	347.45	223.17	209.11	0.91	145.54	145.54	8.36
B777-300ER	351.54	251.29	237.68	0.91	145.54	123.21	-
EMB135	20	18.5	16	0.1	5.12	4.43	-
ERJ140	21.1	18.7	17.1	0.1	5.19	4.45	-
EMB145	24.1	20	18.5	0.1	6.03	6.01	-
E170	37.2	32.8	29.6	0.16	9.43	7.7	-
E175	38.79	34	31.7	0.16	9.43	7.3	-
E190	51.8	44	40.9	0.16	13	12.06	-
E195	52.29	45.8	42.6	0.16	13.9	10.34	-

Table Appendix K. 4 Aircraft long-haul simulation seats, payload and load capacities

x	*Smax*	*S optimum*	*Payload*	*OEW*	*Load*	*MTW*
A318	149	71	7.81	39.5	47.31	68.4
A319	156	127	13.97	40.3	54.27	75.9
A320	180	111	12.21	42.1	54.31	78.4
A321	220	146	16.06	48.1	64.16	93.9
A330-200	380	248	27.28	120.5	147.78	238.9
A330-300	375	264	29.04	123.1	152.14	233.9
A340-300	440	347	38.17	120.9	159.07	277.4
A340-500	375	284	31.24	170.4	201.64	381.2
A340-600	440	380	41.8	176.36	218.16	381.2
A350-800	258	479	52.69	104.65	157.34	259.9
A350-900	316	549	60.39	106.53	166.92	268.9
A350-1000	350	753	82.83	108.4	191.23	308.9
A380	853	337	37.07	276.8	313.87	562
B737-600	130	79	8.69	36.38	45.07	65.77
B737-700	148	70	7.7	37.65	45.35	70.31
B737-800	184	119	13.09	41.41	54.5	79.33
B737-900	215	129	14.19	44.68	58.87	85.37
B787-3	330	275	30.25	101	131.25	170.55
B747-8	524	375	41.25	211.9	253.15	443.61
B767-200ER	255	183	20.13	82.38	102.51	179.62
B787-800	250	275	30.25	109.77	140.02	228.38
B787-900	290	379	41.69	115	156.69	247.66
B767-300ER	350	239	26.29	90.01	116.3	187.33
B777-200	440	333	36.63	145.15	181.78	348.36
B777-300ER	550	353	38.83	167.83	206.66	352.44
EMB135	37	21	2.31	11.5	13.81	20.1
ERJ140	44	27	2.97	11.81	14.78	21.2
EMB145	50	31	3.41	12.59	16	24.2
E170	80	35	3.85	21.8	25.65	37.36
E175	88	52	5.72	21.81	27.53	38.95
E190	106	68	7.48	28.08	35.56	51.96
E195	118	73	8.03	28.97	37	52.45

Table Appendix K. 5 Aircraft short-haul simulation weights, tank, cargo capacities

x	*MTOW*	*MLW*	*MZFW*	*ToutF*	*Tank max*	*UF*	*Cargo (15%)*	*Range max*
A318	68	57.5	54.5	0.4	19	19	7.1	1,313.12
A319	75.5	62.5	62.5	0.4	23.7	21.23	8.14	3,179.87
A320	78	66	62.5	0.4	23.7	23.69	8.15	1,490.13
A321	93	77.8	73.8	0.9	23.57	23.57	9.62	2,072.63
A330-200	238	182	170	0.9	109.19	90.22	22.17	6,650.64
A330-300	233	187	175	0.9	76.56	76.56	22.82	5,221.06
A340-300	276.5	192	183	0.9	115.4	115.4	23.86	11,310.72
A340-500	380	246	232	1.2	174.94	174.94	30.25	15,796.83
A340-600	380	265	251	1.2	160.53	160.53	32.72	12,994.84
A350-800	259	193	181	0.9	108.33	101.66	23.6	15,768.59
A350-900	268	205	192	0.9	108.33	101.08	25.04	14,672.82
A350-1000	308	233	220	0.9	122.46	116.77	28.68	16,367.13
A380	560	386	361	2	251.2	246.13	47.08	9,050.30
B737-600	65.54	55.11	51.94	0.23	20.89	20.48	6.76	4,138.90
B737-700	70.08	58.6	52.2	0.23	20.89	20.89	6.8	4,961.96
B737-800	79.02	66.36	62.73	0.32	20.89	20.89	8.18	4,185.90
B737-900	85.14	71.35	67.72	0.23	23.82	23.82	8.83	3,874.75
B787-3	170.1	161	151.03	0.45	38.15	38.15	19.69	4,063.62
B747-8	442.25	309.35	291.21	1.36	194.66	189.1	37.97	14,067.90
B767-200ER	179.17	136.08	117.93	0.45	73.36	73.36	15.38	11,292.79
B787-800	227.93	172.37	161.03	0.45	101.89	87.91	21	12,636.59
B787-900	247.21	191.64	180.3	0.45	101.89	90.52	23.5	13,262.60
B767-300ER	186.88	145.15	133.81	0.45	73.36	70.58	17.45	8,555.14
B777-200	347.45	223.17	209.11	0.91	145.54	145.54	27.27	15,478.38
B777-300ER	351.54	251.29	237.68	0.91	145.54	144.88	31	11,468.25
EMB135	20	18.5	16	0.1	5.12	5.12	2.07	2,571.20
ERJ140	21.1	18.7	17.1	0.1	5.19	5.19	2.22	2,511.44
EMB145	24.1	20	18.5	0.1	6.03	6.03	2.4	3,404.71
E170	37.2	32.8	29.6	0.16	9.43	9.43	3.85	3,526.04
E175	38.79	34	31.7	0.16	9.43	9.43	4.13	3,206.60
E190	51.8	44	40.9	0.16	13	13	5.33	4,756.69
E195	52.29	45.8	42.6	0.16	13.9	13.9	5.55	3,942.36

Table Appendix K. 6 Airport turnaround station and en-route station times [Boeing, Airbus and Embraer manuals]

x	*Turnaround station*	*En-route station*	*x*	*Turnaround station*	*En-route station*
A318	38	19	B737-900	40	23
A319	41	21	B787-3	43	43
A320	48	23	B747-8	110.5	98.2
A321	56	25	B767-200ER	35	20
A330-200	60	44	B787-800	43	43
A330-300	64	48	B787-900	43	43
A340-300	70	43	B767-300ER	40	25
A340-500	63	40	B777-200	45	25
A340-600	74	46	B777-300ER	52	35
A350-800	62	34	EMB135	14	11
A350-900	62	34	ERJ140	15.5	11.5
A350-1000	62	34	EMB145	18	12
A380	126	90	E170	14.5	11
B737-600	29	15	E175	15.5	11.5
B737-700	32	18	E190	17.5	12
B737-800	37	20	E195	19	12

Appendix L: Aircraft and Airports classifications

Aircraft have been classified according with Table 6.4. The dimensions of the aircraft limit the aircraft operation to certain airports. Aircraft operate airports according with their dimensions. Table Appendix L. 1, Table Appendix L. 2, Table Appendix L. 3, Table Appendix L. 4, Table Appendix L. 5, Table Appendix L. 6, Table Appendix L. 7, Table Appendix L. 8, Table Appendix L. 9 and Table Appendix L. 10 indicate the airports runways and taxiways dimensions in relation to aircraft dimensions and designations. Then, airports can be classified based on their dimensions in relation with the aircraft FAA code. Thus, airports can serve aircraft that have and FAA code (Table Appendix L. 1) [FAA, 1989] [ACC, 2008] smaller or equal to its FAA airport reference code.

Table Appendix L. 1 Aircraft Dimensions and Designations [FAA, 1989] [ACC, 2008]

Aircraft	*Wingspan*	*Length*	*Tail Height*	*FAA Code*	*ICAO Code*	*Aircraft*	*Wingspan*	*Length*	*Tail Height*	*FAA Code*	*ICAO Code*
A318	33.91	31.45	12.93	III	C	B737-900	34.32	42.11	12.6	III	C
A319	34.1	33.84	12.02	III	C	B787-3	60	57	17	V	E
A320	33.91	37.57	11.9	III	C	B747-8	68.4	76.3	19.4	VI	F
A321	33.91	37.57	11.8	III	C	B767-200ER	47.57	48.52	16.3	IV	D
A330-200	60.3	58.37	17.18	V	E	B787-800	60	57	17	V	E
A330-300	60.3	63.66	17.18	V	E	B787-900	63	63	17	V	E
A340-300	60.3	63.66	16.99	V	E	B767-300ER	47.57	54.95	16.03	IV	D
A340-500	63.45	67.93	17.53	V	E	B777-200	60.93	63.73	18.76	V	E
A340-600	63.45	75.36	17.93	V	E	B777-300ER	60.93	73.86	18.76	V	E
A350-800	64	60.6	16.9	VI	E	EMB135	20.04	26.33	6.76	II	B
A350-900				VI	E	ERJ140	20.04	28.45	6.76	II	B
A350-1000				VI	E	EMB145	20.04	29.87	6.76	II	C
A380	79.75	72.73	24.1	VI	F	E170	26	29.9	9.85	III	C
B737-600	34.31	31.25	12.58	III	C	E175	26	31.68	9.73	III	C
B737-700	34.31	33.64	12.58	III	C	E190	28.72	25.76	10.57	III	C
B737-800	34.32	39.47	12.6	III	C	E195	28.72	38.65	10.55	III	C

Runway Protection Zone (PPZ)

Table Appendix L. 2 Airport classification depending on the larger aircraft geometry [FAA, 1989]

Airport Geometry					
Approach visibility	*Facilities expected to serve*	*Length (m)*	*Inner Width (m)*	*Outer Width (m)*	*RPZ (acres)*
Visual and not lower than 1,600 m	Small Aircraft	300	75	135	8,035
	Aircraft Approach A & B	300	150	210	13,770
	Aircraft Approach C & D	510	150	1,010	29,465
Not lower than 1,200 m	All	510	300	1,510	48,978
Lower than 1,200 m	All	750	300	1,750	78,914

Table Appendix L. 3 Runway separation for aircraft approach A & B [FAA, 1989]

Runway design visual runways and runways with not lower than 1,200 m approach visibility minus					
ITEM	*Airplane Design Group (m)*				
	I (Small)	I	II	III	IV
Holdline	38	60	60	60	75
Taxiway / Taxilane / Certerline 3	45	67.5	72	90	120
Aircraft Parking Area	37.5	60	75	120	150
Runway design visual runways and runways with lower than 1,200 m approach visibility minus					
ITEM	*Airplane Design Group (m)*				
	I (Small)	I	II	III	IV
Holdline	53	75	75	75	75
Taxiway / Taxilane / Certerline 3	60	75	90	105	120
Aircraft Parking Area	120	120	120	120	150

Table Appendix L. 4 Runway separation for aircraft approach C & D [FAA, 1989]

Runway design visual runways and runways with not lower than 1,200 m approach visibility minus						
ITEM	*Airplane Design Group (m)*					
	I	II	III	IV	V	VI
Holdline	75	75	75	75	75	85
Taxiway / Taxilane / Certerline 3	90	90	120	120	150	150
Aircraft Parking Area	120	120	150	150	150	150
Runway Design visual runways and runways with lower than 1,200 m approach visibility minus						
ITEM	*Airplane Design Group (m)*					
	I	II	III	IV	V	VI
Holdline	75	75	75	75	75	85
Taxiway / Taxilane / Certerline 3	120	120	120	120	168	168
Aircraft Parking Area	150	150	150	150	150	150

Table Appendix L. 5 Taxiways and taxilane separation standards [FAA, 1989]

ITEM	*Airplane Design Group (m)*					
	I	II	III	IV	V	VI
Parallel Taxiway / Taxi centerline	21	32	46.5	65.5	81	99
Fixed or Movable Objects	13.5	20	28.5	39.5	48.5	59
Parallel Taxilane Centerline	195	29.5	42.5	60	74.5	91
Fixed or Movable Objects	12	17.5	24.5	34	42	51

Runway Design

Table Appendix L. 6 Airport classification depending on the runway design for A & B [FAA, 1989] [ACC, 2008]

Runway design visual runways and runways with not lower than 1,200 m approach visibility minus					
ITEM	*Airplane Design Group*				
	I (Small)	I	II	III	IV
Runway Width	18	18	23	30	45
Runway Shoulder Width	3	3	3	6	7.5
Runway Blast Pad With	24	24	29	42	60
Runway Blast Pad Length	18	30	45	60	60
Runway safety area with	36	36	45	90	150
Runway safety area length prior to landing	72	72	90	180	180
Runway safety area beyond RW	72	72	90	180	300
Runway object free area W	75	120	150	240	240
Runway object free area L	72	72	90	180	300
Runway design visual runways and runways with lower than 1,200 m approach visibility minus					
ITEM	*Airplane Design Group*				
	I (Small)	I	II	III	IV
Runway Width	23	30	30	30	45
Runway Shoulder Width	3	3	3	6	7.5
Runway Blast Pad With	29	36	36	42	60
Runway Blast Pad Length	18	30	45	60	60
Runway safety area with	90	90	90	120	150
Runway safety area length prior to landing	180	180	180	180	180
Runway safety area beyond RW	180	180	180	240	300
Runway object free area W	240	240	240	240	240
Runway object free area L	180	180	180	240	300

Table Appendix L. 7 FAA Airport classification depending on the runway design for C & D facilities expected to serve approach visibility minus [FAA, 1989] [ACC, 2008]

Runway Design standards for aircraft approach						
ITEM	*Airplane Design Group (meters)*					
	I	II	III	IV	V	VI
Runway Width	30	30	30	45	45	60
Runway Shoulder Width	3	3	6	7.5	10.5	12
Runway Blast Pad With	36	36	42	60	66	84
Runway Blast Pad Length	30	45	60	60	120	120
Runway safety area with	150	150	150	150	150	150
Runway safety area length prior to landing	180	180	180	180	180	180
Runway safety area beyond RW	300	300	300	300	300	300
Runway object free area W	240	240	240	240	240	240
Runway object free area L	300	300	300	300	300	300

Taxiway and Taxilane Design

Table Appendix L. 8 FAA Taxiway dimensional standards [FAA, 1989]

ITEM	*Airplane Design Group*					
	I	*II*	*III*	*IV*	*V*	*VI*
Taxiway Width	7.5	10.5	15	23	23	30
Taxiway Edge Safety Margin	1.5	2.25	3	4.5	4.5	6
Taxiway Pavement Fillet Configuration	3	3	6	7.5	10.5	12
Taxiway Shoulder Width	15	24	36	52	65	8
Taxiway Object Free Area Width	27	40	57	79	97	118
Taxilane Object Free Area Width	24	35	49	68	84	102

Table Appendix L. 9 FAA Taxiway fillet dimensions [FAA, 1989]

ITEM	*Airplane Design Group*					
	I	*II*	*III*	*IV*	*V*	*VI*
Radius of taxiway turn	22.5	22.5	30	45	45	51
Length of Lead-in to Fillet	15	15	45	75	75	75
Fillet Radius for Tracking Centreline	18	16.5	16.5	25.5	25.5	25.5
Fillet Radius for Judgmental Over steering Symmetrical Widening	18.75	17.25	20.4	31.5	31.5	33
Fillet Radius for Judgmental Over steering One Side Widening	18.75	17.25	18	29	29	30

Table Appendix L. 10 FAA Wingtip clearance standards [FAA, 1989]

ITEM	*Airplane Design Group*					
	I	*II*	*III*	*IV*	*V*	*VI*
Taxiway Wingtip Clearance	6	8	10.5	13.5	16	19
Taxiway Wingtip Clearance	4.5	5.5	6.5	8	9.5	11

Appendix M: Airlines employee data

Table Appendix M. 1 US Airlines Employee data for year 2010 [web.mit.edu/airlinedata]

Code	*Airline*	*Management*	*Pilots*	*General Services*	*Maintenance*	*Handling*	*Aircraft control*	*Employees*
AA	AMERICAN AIRLINES	54	7,934	14,918	12,621	193	184	65,506
CO	CONTINENTAL AIRLINES	42	4,199	8,505	3,877	-	116	37,760
DL	DELTA AIRLINES	494	10,701	18,279	7,315	3,409	578	76,742
NW	NORTHWEST AIRLINES	21	4,204	6,748	1,225	424	1,387	29,828
UA	UNITED AIRLINES	40	5,527	12,787	4,172	748	158	46,289
US	US AIRWAYS	207	3,967	6,982	3,528	5,815	161	30,876
B6	JETBLUE AIRWAYS	34	1,828	2,093	558	105	165	11,211
FL	AIRTRAN AIRWAYS	70	1,622	2,013	375	1,197	76	8,229
AS	ALASKA AIRLINES	15	1,218	2,527	654	314	226	8,649
F9	FRONTIER AIRLINES	50	674	1,546	245	47	-	4,309
G4	ALLEGIANT AIR	18	328	403	237	-	26	1,585
HA	HAWAIIAN AIRLINE	46	436	1,068	298	320	92	3,802
VX	VIRGIN AMERICA	20	428	2	132	6	32	1,770
WN	SOUTHWEST AIRLINES	1,008	6,423	8,755	1,645	6,119	282	35,089

Table Appendix M. 2 US Airlines Employee data for year 2010 [web.mit.edu/airlinedata]

Code	*Airline*	*Pax Handling*	*Stats*	*Traffic Solicitors*	*Cargo Handling*	*Other*	*Trainees and Instructors*	*Pax*
AA	AMERICAN AIRLINES	12,027	6,274	114	10,842	110	235	86,202,910
CO	CONTINENTAL AIRLINES	11,943	971	-	1,191	6,838	78	43,568,824
DL	DELTA AIRLINES	19,589	734	1,369	1,416	12,312	546	111,236,895
NW	NORTHWEST AIRLINES	6,865	513	502	701	6,984	254	41,115,120
UA	UNITED AIRLINES	16,646	5,925	25	13	45	203	54,098,276
US	US AIRWAYS	4,579	2,356	1,104	183	1,926	68	51,852,657
B6	JETBLUE AIRWAYS	4,618	414	130	23	1,076	167	24,217,344
FL	AIRTRAN AIRWAYS	1,652	14	35	-	1,148	27	24,720,902
AS	ALASKA AIRLINES	1,871	301	78	650	719	76	16,514,862
F9	FRONTIER AIRLINES	1,630	74	-	-	-	43	9,241,888
G4	ALLEGIANT AIR	117	35	27	-	38	37	5,228,648
HA	HAWAIIAN AIRLINE	813	159	67	448	32	23	8,423,956
VX	VIRGIN AMERICA	414	27	5	-	110	31	1,680,328
WN	SOUTHWEST AIRLINES	7,210	867	14	374	2,303	89	106,307,073

Appendix N: Q_r and F_r calculation for pax connections

The purpose is to use the optimization model to maximize the net present value (NPV) between two short-haul low-cost networks connecting by two hubs. The link with the highest pax flow is used to connect both airline networks, both airports can be used as hubs.

The total number of pax willing to fly from an airport ORI to an airport DES can be connected in order to increase the total number of pax flow on long haul links. It will help to increase the demand of transportation allowing operating larger aircraft. It can be beneficial since long-haul routes do not allow to minimize operation costs as it can be done in short-haul (Chapter 2). Then, the optimization model has to allow passengers connections to compare with direct flies. Direct flies will require extra number of aircraft to connect all airports, and the investment will be higher. Although, direct flies allow airlines operate small aircraft that are cheaper than larger aircraft. The disadvantage can be in the number of frequencies needed to transport the pax flow demand. Larger aircraft do it in fewer flights than smaller aircraft. The model needs to compare pax connections with direct flights to find the optimal solution in long-haul links.

The passenger flow between each node from network A and network B has to be calculated by using the CFEM and PEM model between each airport/city from network A and network B assuming direct flights.

The passenger flow is connected by two airports, one from network A and one from network B. It increases the pax flow demand in both network links. The total demand and the total fare crossing each link can be calculated using Equation Appendix N.1.

$$TQ_{L(r),t} = \left\{\sum_{k=0}^{max-ORI(r)-1}\left\{\left(\sum_{i=1}^{I} Q_{[i,max-k],t}{}^{*}\right)\left[\text{roundup}\left(\frac{y_{[max-k,max]}+y_{[max-k,DES(r)]}}{2}\right)\right]\right\}\right\} + Q_{[ORI(r),DES(r)],t}{}^{*} \quad (N.1)$$

Where:

I = total number of nodes to connect with airline partner, from A to B, I is equal to the number of networks in B and vice versa [-]

ORI = origin airport/city number [-]

DES = destination/city airport number [-]

max = maximum number of nodes to connect, number of nodes in network A plus number of nodes to connect in network B [-]
$TQ_{L(r),t}$ = Total number of passenger demand between airport ORI(r) and DES(r) [pax]
$y_{x,L(r),t}$ = Decision variable that indicates if a connection between both airports exist in $MAT_{x,t,j}$ [-]

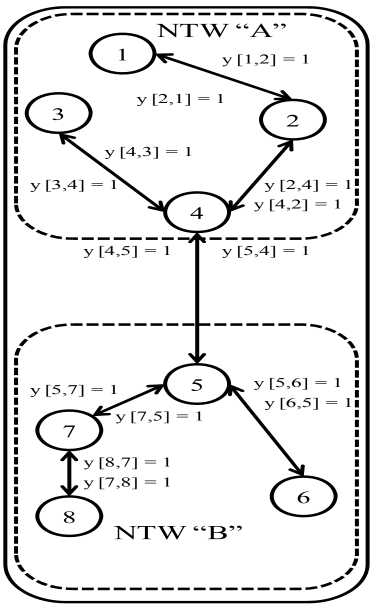
Equation Appendix N.1 calculates the pax flow between two airline networks or routes. The total pax flow flying to network B is calculated using Equation Appendix N.1 from network A to network B. The total pax flow flying to network A is calculated using Equation Appendix N.1 from network B to network A (Figure Appendix N. 1), and the airports number have to be changed in an opposite way. Then, airport origin number 1 is on the side of the Network B if the total pax flow wants to be calculated for the links on Network A. Equation Appendix N.1 is not to calculate pax flow connecting inside one airline network.

Equation Appendix N.1 allows connecting the demand from an airport origin to an airport destination. The link with the highest pax flow demand, between two short-haul networks, is used to connect both networks. The maximum number of possible connections is five. It is assumed that it is highly unlikely that any pax will fly more than five links from airport origin to airport destination. The increment of pax flow in each link is because of the existing demand between airports on both networks (Figure Appendix N. 1).

The total fare is calculated as the sum of each link for a passenger trip with connections. The CFEM model calculates the fare of a link based on the lowest average fare according with the behavior of the LCC market. In this thesis, it has been assumed that the sums of low cost fares are cheaper than the total fare for a similar trip using a FSC. Equation Appendix N.2 must be used as Equation Appendix N.1 has been explained. The total fare crossing each link can be calculated using the next equation:

$$TF_{L(r),t} = \left\{\sum_{k=0}^{max-ORI(r)-1}\left\{\left(\sum_{i=1}^{I} F_{[i,max-k],t}\right)\left[\text{roundup}\left(\frac{y_{[max-k,max]}+y_{[max-k,DES(r)]}}{2}\right)\right]\right\}\right\} + F_{[ORI(r),DES(r)],t} \quad (N.2)$$

Where:
$F_{L(r),t}$ = Fare between airport ORI and DES [usd]
$TF_{L(r),t}$ = Total fare for connecting flights [usd]



Decision matrix y x,r,t		Airport Destination							
		1	2	3	4	5	6	7	8
Airport Origin	1	0	1	0	0	0	0	0	0
	2	1	0	0	1	0	0	0	0
	3	0	0	0	1	0	0	0	0
	4	0	1	1	0	1	0	0	0
	5	0	0	0	1	0	1	1	0
	6	0	0	0	0	1	0	0	0
	7	0	0	0	0	1	0	0	1
	8	0	0	0	0	0	0	1	0
Matrix Qr		Airport Destination							
		1	2	3	4	5	6	7	8
Airport Origin	1	0	1	0	0	5	6	7	8
	2	1	0	0	2	5	6	7	8
	3	0	0	0	4	5	6	7	8
	4	0	2	3	0	5	6	7	8
	5	1	2	3	4	0	6	7	0
	6	1	2	3	4	5	0	0	0
	7	1	2	3	4	5	0	0	8
	8	1	2	3	4	0	0	7	0
Matrix TQr		Airport Destination							
		1	2	3	4	5	6	7	8
Airport Origin	1	0	27	0	0	0	0	0	0
	2	5	0	0	28	0	0	0	0
	3	0	0	0	30	0	0	0	0
	4	0	14	15	0	104	0	0	0
	5	0	0	0	40	0	30	67	0
	6	0	0	0	0	15	0	0	0
	7	0	0	0	0	25	0	0	40
	8	0	0	0	0	0	0	17	0

Figure Appendix N. 1 TQ_r and TF_r for connecting flights between two networks

Glossary

Glossary Chapter 3

a	= airline	[-]
A_1	= constant value	[usd/km/seat]
A_2	= constant value	[-]
AOC_u	= Aircraft operation cost per pax	[usd/pax]
B_0	= constant value	[-]
B_1	= constant values	[km^{-1}]
C_0	= constant value	[tons]
C_1, C_2	= constant values	[tons/km]
D_r	= distance or range	[km]
Drag	= aircraft drag force	[N]
e	= engine type	[-]
ETF_e	= engines thrust force	[N]
ETF_{STL}	= Engine Thrust for steady level (STL)	[N]
f	= costs factors per route per passenger per km range	[usd/km/pax]
f_{DOCa}	= DOC airlines operating costs factors per route per pax per km [AviationDB]	[usd/km/pax]
f_{IOCa}	= IOC airlines operating costs factors per route per pax per km [AviationDB]	[usd/km/pax]
$F_{OCF,a}$	= Airlines operating costs factors OCF per route per pax per km [AviationDB]	[usd/km/pax]
g	= gravitational constant	[km/hr^2]
g	= gravitational constant	[m/s^2]
JFP	= Jet fuel price	[usd/l]
%JFC	= Jet fuel cost percentage of total AOC	[-]
LF	= Pax load factor	[-]
Lift	= aircraft lift force	[N]
$Load_x$	= aircraft load	[tons]
m_f	= mass fuel flow	[g/sec]
M_x	= Mach number for aircraft type x	[-]
NBags	= Total number of bags available per pax (LCC's = 1, FSC's = 2)	[-]
O_0	= constant distance	[km]
O_1	= constant number of seats	[seats]
O_2	= model cost coefficient	[usd/km/seat]
OCF	= airline operation costs type OCF, OCF can be any cost in Figure 3.1	[usd/pax]
OEW	= Aircraft operation empty weight	[tons]
Payload	= Aircraft payload before landing	[tons]
R	= Total number of routes in the study	[-]
Range	= possible aircraft flying distance	[km]
r	= route link	[-]
r	= route from airport origin ORI to airport DES	[-]

SFC	= engine specific fuel consumption	[g/kN/sec]
S_x	= aircraft number of seats	[seats]
t	= time in years, months, day	[-]
TMF	= Total airline km flown during one day [AviationDB]	[usd/km]
$UFe_{x,r}$	= jet fuel volume to fly a route link distance to closest emergency airport	[tones]
UF_r	= Usable fuel or quantity of fuel needed for aircraft propulsion to fly D_r, it represents the aircraft jet fuel volume consumption to fly a route with distance D_r	[tons]
$UF_{x,r}$	= jet fuel volume to fly a route distance D_r	[tones]
$V_{C,x}$	= cruise velocity	[km/hr]
W	= Aircraft weight before takeoff (TO) or landing (DES)	[tons]
WBags	= 21 kg per bag	[-]
WPax	= 89 kg per pax [Peeters, Middel and Hoolhorst, 2005]	[kgs]
W_α	= aircraft average weight	[tones]
x	= Aircraft type x	[-]
α_{AT}	= Aircraft angle of attack	[-]
α_1, β_1	= coefficients	[-]
α_2, β_2	= coefficients	[-]
$\beta_{2\ DOCa}$	= direct operating costs coefficients	[-]
$\beta_{2\ IOCa}$	= indirect operating costs coefficients	[-]

Glossary Chapter 4

b	= coefficients	[usd]
Comp	= airline competition type (FSC, LCC, FSC-FSC, FSC-LCC, LCC-LCC)	[-]
D*	= Distance division segment point	[km]
D_L*	= Distance division segment point between long and medium-haul	[km]
D_r	= Route distance	[km]
D_S*	= Distance division segment point between medium and short-haul	[km]
F_{Comp}	= airline route competition type Comp average fare	[usd]
F_{est}	= average fare estimation or prediction	[usd]
F_{est}	= Route fare estimation	[usd]
F_r	= Route r average fare	[usd]
F_{real}	= Real route fare database	[usd]
$F_{r,0}$	= Average fare present value	[usd]
$F_{r,t}$	= Average price in year t	[usd]
INF	= inflation rate	[-]
j	= number of segments	[-]
m	= coefficients	[usd / km]
Q_r	= Route r number of passengers	[pax]
r	= route	[-]
R	= Total number of routes in the market under study	[-]
RComp	= Airlines competition type Comp, total number of routes	[-]
SIFL	= SIFL factor	[usd/km/pax]
t	= time in future (forecast number of year)	[-]
Δm	= coefficients	[usd / km]
Δb	= coefficients	[usd]

Glossary Chapter 5

a	= Airline	[-]
A_5	= Constant value	[pax/km/usd^2]
D	= Distance	[km]
est	= estimation	[-]
GDP	= Gross Domestic product	[usd]
GDP_{state}	= Total Gross Domestic Product (GDP) generated by the state[23]	[usd]
$\%IC_H$	= log-normal distribution percentage at IC_H (Table 5.6)	[-]
%IC	= IC log-normal distribution percentage at IC (Table 5.6)	[-]
K	= Constant value	[pax]

[23] The US Census Bureau GDP and POP data per state [US Census Bureau, 2005-2008]

K = The year until the forecast wants to be performed [-]
Q_H = Airport route relationship highest average Q_r at IC_H (existing data) [pax]
Qreal,r = Actual pax flow between airports in the cities [pax]
$Q_{r,IC}$ = Airport route relationship average Q_r at IC (interval class data calculation) [pax]
n = sample size of the data, minimum four [-]
NS_r = total number of seats supply on route r [pax]
PAX = Total number of passenger flying to or from airport/city ORI or DES [pax]
PAX_{state} = Total number of passenger flying to or from state ORI or DES [pax]
POP = Population [pax]
POP_{state} = total number of person living on the state [person or pax]
S = number of seats (Table Appendix C. 1) [pax]
TQr = Total pax demand between airports connecting two cities [pax]
TQreal,r = Actual pax flow between two cities [pax]
$TQ_{U,r}$ = Possible induced demand or possible market size [pax]
$X_r^{(1)}$ = is the mean value of the next data [pax]
α_5, δ_5, ω_5, ρ_5, θ_5, π_a = constant exponent values [-]
ΔQ_r = The expected growth from $Q_2^{(0)}$ to $Q_k^{(0)}$. IATA expected growth, 21.05 [-]
ΔTQ = Number of times than $TQ_{U,r}$ must be higher than $TQ_{real,r}$ to represent an opportunity to open new services [-]
μ = Log-normal distribution average [-]
σ = Standard deviation [-]
ς = Smooth parameter [-]

Glossary Chapter 6

A = total number of airlines serving an airport [-]
a = airline operating a link ϵ {United Airlines = 1, American Airlines = 2, etc.} [-]
AC = Airport max number of pax during a T_{dhp} depending on its LOS [pax]
af ϵ {check-in, wait/circulate, hold room, baggage claim, GIS} [-]
AIRSIDE = Airport FAA code based on runways and taxiways dimensions and separations [-]
AMI = Aircraft FAA dimensions and designations code (Table Appendix L. 1) [-]
a_0 = airline fixed cost per pax [usd/pax]
B_0 = constant value (Table 3.4) [-]
B_1 = constant values (Table 3.4) [km^{-1}]
$CapD_{sf}$ = number of pax served (dynamic capacity) [pax]
$CapS_{af}$ = number of pax in airport facility f (static capacity) [pax]
Cargo = aircraft amount of cargo capacity per flight haul [tons]
C_L = Aircraft type x ground lift coefficient [-]
Cost = total link cost in time t for aircraft type x [usd]
C_3 = constant factor [1/min]
C_0 = constant value (Table 3.4) [tons]
C_1, C_2 = constant values (Table 3.4) [tons/km]
C_4 = employee type constant factor [pax/person]
D* = Distance point dividing short-haul and long-haul [km]
D_r = route distance [km]
Drag = drag force [N]
D_{Tin} = Average distance from terminal apron/gate to the runway landings position on route r [km]
D_{TO} = Average distance from terminal apron/gate to the runway takeoff position on route r [km]
d_{xjk} = min distance required between aircraft x_j and takeoff of aircraft x_k [km]
Employee = number of employees required to operate the network [person]
ENAIR = total number of aircraft in the airline fleet in time t [-]
F_r = average fare per link [usd]
g = gravity [m/s^2]
G = Aircraft type x available gates at an airport in time t [mov]
GR_{DES} = Aircraft ground roll distance require for takeoff at any airport [km]
GRs = Aircraft ground roll safety distance require during takeoff to allow maneuvering in case of any emergency [km]
GR_{TO} = Aircraft ground roll distance require for takeoff at any airport [km]
i, k = integer counters [-]

IET	= average minimal inter-arrival time at an airport in time t, a route link consist on an airport ORI or takeoff airport (TO) and an airport DES or landing airport DES	[mov/hrs]
IRR	= Route j internal Rate of return	[-]
J	= total airline sub-networks j or airline route j	[-]
j	= 1, ..., J (counter, number of routes)	[-]
$JFP_{ORI(r)}$	= average jet fuel price at airport origin link r	[usd/ton]
$JFP_{DES(r)}$	= average jet fuel price at airport destination link r	[usd/ton]
L	= [ORI(r), DES(r)] = link vector, it determines the link airport ORI and airport DES	[-]
LBT	= Link block time	[hrs]
Load	= max design zero fuel weight plus OEW	[tons]
Lift	= lift force	[N]
M	= aircraft velocity in match speed	[-]
Ma_D	= Aircraft type x available gates at airport DES in time t	[mov]
maintenance	= aircraft maintenance time per week	[hrs/week]
Mov	= total number of aircraft movements at an airport in time t, a route link consist on an airport ORI or takeoff airport and an airport DES or landing airport	[mov]
MS	= airline a1 market share	[-]
MTOW	= aircraft max takeoff weight design	[tons]
NAIR	= total number of aircraft required to operate NTW in time t	[-]
NBags	= Total number of pax available per pax (LCC's = 1, FSC's = 2)	[bag/pax]
N_{DES}	= number of airports destination	[-]
Ng	= Number of gates where an aircraft type x can park at an airport in time t	[mov]
N_{ORI}	= number of airports origin	[-]
OD(r)	= the equation is for airport ORI or DES separately (ORI(r) or DES(r))	[-]
OEW	= Aircraft operation empty weight	[tons]
Payload	= max design zero fuel weight minus OEW	[tons]
PAX	= airport total number of pax in time t	[pax]
$p_{d,t}$	= probability of having any gap between aircraft type x_i and x_j movements at airport in time t	[-]
Pg	= number of gates/stands occupied at an airport in time t	[mov]
Price	= aircraft type price in time t	[usd]
p_{xi}, p_{xj}	= proportions of aircraft types x_i and x_j at the airport traffic in time t	[km]
p_x	= proportion of aircraft type x serving an airport in time t	[-]
Q_{NTW}	= optimum number of passengers to serve in the designed network	[pax]
R	= total links per airline route j	[-]
r	= 1, ..., J (counter, number of links)	[-]
Range	= aircraft max range carrying a W_{TO}	[km]
RL	= Airport runway ORI(r) or DES(r) (OD(r)) length in time t (airport ORI and airport DES can increase the runways lengths in future years if enough space exist to do so)	[km]
sf	ϵ {checking counters, security and GIS, desks, departure gates desks, baggage claim system}	[-]
st_{sf}	= average service time per pax	[hrs/pax]
STE	= aircraft engine static thrust or thrust at zero airspeed	[N]
S_W	= Wing area, aircraft type x	[m^2]
T	= total period of time	[-]
t	= 1, ..., T (counter, number of years)	[-]
T_{dhp}	= design hour period, normally 15 minutes [ACRP Report 25, 2010]	[hrs]
t_{flying}	= aircraft x flying time	[hr]
$tgap_{xij}$	= airport minimal time gaps allowing aircraft x_k takeoffs between aircraft x_i and x_j landings	[hrs]
Tin	= average taxi-in time operation on route r	[hrs]
TODES	= aircraft takeoff (TO) or landing (DES) ϵ {TO, DES}	[-]
Tout	= average taxi-out time operations on route r	[hrs]
Tp	= time interval during which passengers expressed a desire to travel	[hrs]
TQ	= airlines total route pax flow	[-]
Tr	= Aircraft turnaround time at an airport in time t	[hr]
TrB	= Aircraft board pax time at an airport in time t	[hr]
TrD	= Aircraft deplane pax time at an airport in time t	[hr]
TrF	= Aircraft fuelling time at an airport	[hr]
TrP	= Aircraft position air bridge or stairs time at an airport in time t	[hr]
TrR	= Aircraft remove air bridge or stairs time at an airport in time t	[hr]
TrS	= Aircraft service galley time at an airport	[hr]
TrSoF	= Aircraft service galley time at an airport in time t	[hr]

t_{TODES} = takeoff (TO) or landing (DES) time [hr]
t_0 = landing or takeoff time with most probability to happen at an airport [min]
t_1 = time [min]
u = facility f number of servers [-]
U = Aircraft maximum utilization time equal to 24*7=156 hrs [hrs/week]
$UF_{L(r-1)}$ = aircraft amount of jet fuel to fly the previous link [tons]
UF_{max} = aircraft max amount of jet fuel volume per flight haul [tons]
UF_m = aircraft amount of jet fuel in its tank after flying link r-1 [tons]
$UFT_{L(r-1)}$ = aircraft amount of jet fuel carried in the previous link [tons]
VA = Total value of assets [usd]
V_C = average cruise speed according with the aircraft type x manual [km/hr]
V_{DESxi} , V_{DESxj} = aircraft type x_i and x_j landing speed [km/hr]
V_S = Stall speed [km/hr]
$V_{taxiing}$ = Aircraft taxing constant velocity , 32.18 km/hr [FAA, 2010a] [km/hr]
V_{TO} = average takeoff speed [km/hr]
V_w = average wind speed on route r [km/hr]
V_{WTD} = Aircraft average waiting time cruise speed on the air = V_C [km/hr]
WACC = Weight average cost of capital for airline a [-]
WBags = 21 kg per bag [kg/bag]
WPax = 89 kg per pax [Peeters, Middel and Hoolhorst, 2005] [kg/pax]
WTD = average flying and waiting time at an airport destination DES [hrs]
WTr = Aircraft turnaround schedule delay/buffer time at an airport in time t [hr]
WVS_{xii} = wake vortex separation between aircraft type x_i and x_j [km]
y = decision variable {0, 1} [-]
$y_{x,i,k,t,0}$ = Decision variable {1, 0} [-]
y_1 = decision variable {0, 1} [-]
y_2 = decision variable {0, 1} [-]
y_3 = decision variable {0, 1} [-]
y_5 = decision variable {0, 1} [-]
y_6 = decision variable {0, 1} [-]
y_7 = aircraft type turnaround decision variable {0, 1} [-]
y_8 = aircraft type turnaround decision variable {0, 1} [-]
y_9 = aircraft type turnaround decision variable {0, 1} [-]
y_{10} = decision variable {0, 1} [-]
x = aircraft type {Airbus; Boeing; Embraer; etc.} [-]
$Å_{af}$ = area of airport facility af [m^2]
$Å_{0af}$ = square meter per pax allowed at each airport facility depending on the LOS it wants to provide to pax using the airport (Table 6.7) [m^2/pax]
α_{AT} = Aircraft max angle of attack at takeoff or landing [°]
α_1, β_1 = exponent values for landing or takeoff before and after schedule time [-]
λ = airport runway landing and takeoffs capacity in time t, a route link consist on an airport ORI or takeoff airport and an airport DES or landing airport [mov]
λ_{DES} = airport runway landing capacity in an airport, a route link consist on an airport ORI or takeoff airport and an airport DES or landing airport [mov]
λ_{max} = airport maximum runway landing and takeoffs capacity per time t, a route link consist on an airport ORI or takeoff airport and an airport DES or landing airport [mov]
λ_1, λ_2 = probability density function and probability distribution factors for landing and takeoffs before and after schedule time [-]
Γ = pax perception of travelling in cost unit [usd/hrs/pax]
ξ = value that determine the pax schedule delay to the average headway [-]

ρ_{Air} = air density, the International civil aviation authority (ICAO) standard air density at sea level is 1.22 [ICAO, 1993] [kg/m^3]
μ_1 = coefficient of rolling friction [-]
ɭ = length of all aircraft approaching path at an airport [km]
Ъ = total number of hours an airport is open for services during time t [hrs]
$Ꝏ_{max}$ = capacity of an airport apron area and terminal gates/stands for aircraft type x in time t [mov]
§ = is an empirical constant (1 < § < 2) [-]

Glossary Appendix N

DES = destination/city airport number [-]
$F_{L(r),t}$ = Fare between airport ORI and DES [usd]
I = total number of nodes to connect with airline partner, from A to B, I is equal to the number of networks in B and vice versa [-]
max = maximum number of nodes to connect, number of nodes in network A plus number of nodes to connect in network B [-]
ORI = origin airport/city number [-]
$TF_{L(r),t}$ = Total fare for connecting flights [usd]
$TQ_{L(r),t}$ = Total number of passenger demand between airport ORI(r) and DES(r) [pax]
$y_{x,L(r),t}$ = Decision variable that indicates if a connection between both airports exist in $MAT_{x,t,j}$ [-]

Samenvatting

Het openen van een nieuwe passagiersdienst (pax) vraagt een grote investering van een luchtvaartmaatschappij. Het is daarom nodig om goed te onderzoeken of de inkomsten uit de nieuwe dienst zullen opwegen tegen de investering.

Ontwerp en analyse van de haalbaarheid van luchtvaartnetwerken kunnen worden gedaan met behulp van de modellen welke tijdens dit onderzoek zijn ontwikkeld. Met de modellen kunnen routes worden gevonden waarop, binnen bestaande beperkingen, zinvol nieuwe diensten kunnen worden aangeboden, gebaseerd op operationele kosten, passagiersaanbod, beschikbare capaciteit van vliegtuigen en vliegvelden.

Met het optimaliseringsmodel, gebaseerd op maximalisering van de netto contante waarde (E. Net Present Value, NPV), kunnen luchtvaartmaatschappijen nagaan of de routes en de verbindingen van nieuwe netwerken een zinvolle investering zijn.

In een literatuuronderzoek is gezocht naar business modellen, strategieën, voordelen en nadelen. Gebruikelijk worden er vier business modellen voor het vervoer van passagiers onderscheiden: full service carriers (FSC’s), low cost carriers (LCC’s), chartermaatschappijen en regionale maatschappijen.

In werkelijkheid heeft iedere luchtvaartmaatschappij een eigen business model. Ook kan worden geconcludeerd dat voor lange afstanden het low-cost vervoer niet concurrend is met full-service vervoer en chartervervoer.

Het vervoerstarief is de belangrijkste parameter. Maatschappijen kunnen het tarief gebruiken om een plaats te veroveren in een markt en om de passagiersstroom te verhogen. Andere parameters in een model of methode voor het kiezen van de te exploiteren routes zijn de aard van de markt waarop men zich wil richten, de netwerkstructuur, omvang en robuustheid van het netwerk, het optimale aantal passagiers, bezettingsgraad van de vliegtuigen, karakteristieken van de vliegtuigen, omvang van de vloot, beladingsgraad van de vliegtuigen, passagierscapaciteit, bedieningsfrequentie, cyclustijden en infrastructuur en capaciteiten van vliegvelden.

In dit onderzoek zijn twee modellen ontwikkeld voor de operationele kosten, uitgaande van econometrische en technische uitgangspunten. De twee modellen zijn met elkaar vergeleken met gegevens uit de praktijk. Uit de resultaten blijkt dat de operationele kosten met de modellen erg betrouwbaar kunnen worden berekend. Het Aircraft Generic Equation (AGE) model (Hoofdstuk 3) is het meest geschikte model uit dit onderzoek, omdat er verschillende kosten van vliegtuiggebruik worden onderscheiden. Met het AGE model kunnen de operationele kosten per vlucht per vliegtuig worden berekend. De berekening is gebaseerd op belading en afstand en is erg nauwkeurig voor het vaststellen van de benodigde hoeveelheid brandstof die nodig is voor het vliegen van een gegeven verbinding met een gegeven type vliegtuig. Het AGE model is in Hoofdstuk 7 gebruikt voor het berekenen van de operationele kosten in de daar onderzochte cases.

Het tweede model (Airline Operating Cost model, AOC) is een translog functie; zie Hoofdstuk 3. Het belangrijkste voordeel van het model is de mogelijkheid om verschillende operationele kosten per route per pax te berekenen. Met behulp van het model kunnen alle invloeden van de tarieven op de operationele kosten worden nagegaan. Met het AOC model kunnen verschillende business modellen met elkaar worden vergeleken. Een nadeel is dat in het model niet wordt onderscheiden dat verschillende soorten vliegtuigen ook verschillende operationele kosten hebben.

In Hoofdstuk 4 is een model voorgesteld voor de berekening van het laagste gemiddelde tarief. Doel van het model is het bepalen van routes waarop mogelijk een dienst kan worden geopend. Het berekenen van het routetarief is een belangrijk management tool.

Uit literatuuronderzoek volgt een aantal parameters welke mogelijk van invloed zijn op de luchtvaarttarieven (zie Tabel 4.2). In Hoofdstuk 4 zijn twee wiskunde modellen ontwikkeld voor het bepalen van luchtvaarttarieven: het Fare Estimation Model (FEM) en het Competitive Fare Estimation Model (CFEM).

In het FEM model zijn het AOC model (Hoofdstuk 3) en luchthavenkosten, sociale, economische en competatieve factoren samengevoegd. Statistische toetsen (ANOVA, t-toets, F-toets) bevestigen dat met het model tarieven kunnen worden berekend en dat de parameters van het model invloed hebben op luchtvaarttarieven. Voor een nieuw type maatschappij kan met het FEM model een schatting worden gemaakt van de operationele kosten door vergelijking van het business model met andere, bekende business modellen.

Met het FEM model kunnen tarieven nauwkeurig worden berekend. Maar het doel is het identificeren van routes waarop een luchtvaartmaatschappij nieuwe diensten kan aanbieden. Met het FEM kunnen gemiddelde tarieven worden berekend, maar niet een interval waarop de tarieven naar verwachting zullen liggen. Dit is belangrijk, want in een markt met meerdere spelers moet een luchtvaartmaatschappij ook rekening houden met de mogelijke tarieven van andere maatschappijen bij de keuze van mogelijke nieuwe diensten. Het CFEM model is ontwikkeld om de mogelijke minimale en maximale tarieven van andere maatschappijen te berekenen (Hoofdstuk 4).

Het CFEM model berekent het concurrerende tarief met behulp van coëfficienten welke zijn gecalibreerd voor de FSC-LCC markt. Voor een bestaande maatschappij moet dit tarief worden vergeleken met het gemiddelde tarief uit het FEM model. Uit de vergelijking volgt of berekening van het gemiddelde tarief met behulp van het CFEM model mogelijk is. Voor een nieuwe maatschappij kan met het FEM model een berekening worden gemaakt van de operationele kosten welke nodig zijn voor de berekening van het gemiddelde tarief in het CFEM model.

Met de CFEM methode worden routes bepaald waarop een luchtvaartmaatschappij mogelijk diensten kan gaan aanbieden, op basis van het meest concurrerende tarief.

Het is niet voldoende om routes te vinden waarop het passagiersaanbod hoog genoeg is om een nieuwe dienst aan te bieden. De voorspelde passagiersvraag is belangrijk voor economische beslissingen in de planning van het netwerk, de toewijzing van de vloot, nieuwe routes en investeringen. Het is erg belangrijk om te weten of de passagiersvraag hoger is dan de vraag waaraan al wordt voldaan door andere maatschappijen, voordat kan worden besloten tot het openen van een nieuwe dienst.

De vraag waaraan niet wordt voldaan is niet bekend. Het schattingsmodel voor de niet-voldane vraag (Passenger Estimation Model, PEM) (Hoofdstuk 5) simuleert de passagiersstroom door de beschrijving van de passagiersstroom met ca. 18.000 datapunten. Er is gebleken dat de binnenlandse passagiersvraag in de Verenigde Staten beter kan worden beschreven door een log-normale verdeling (formule 5.6). De database is verdeeld is vijf verschillende types vliegvelden, gebaseerd op het aantal vervoerde pax per dag. De resultaten bevestigen dat de pax stroom kan worden gesimuleerd met een log-normale verdeling.

De routes waarop mogelijk nieuwe diensten kunnen worden aangeboden worden gekozen op grond van de volgende criteria. Routes waarop de actuele omvang van de pax stroom hoger is dan die volgens de berekeningen met het PEM, model zijn geen optie voor het aanbieden van een nieuwe dienst. Er kan worden aangenomen dat op deze routes al wordt voldaan aan de vraag. Maar routes waarop de actuele omvang van de pax stroom lager is dan die volgens de berekeningen met het PEM model, bieden wel een mogelijkheid voor het aanbieden van nieuwe diensten. Er kan worden aangenomen dat op deze routes nog niet wordt voldaan aan de vraag.

Als een route is geselecteerd met behulp van de CFEM en de PEM modellen, betekent dat niet dat daarop een nieuwe dienst kan worden aangeboden. De routekeuze in een luchtvaartnetwerk is onderhevig aan meer beperkingen dan alleen het vinden van routes met hoge opbrengst en hoge niet-voldane vraag. Capaciteiten, karakteristieken en beperkingen van vliegtuigen en vliegvelden zijn belangrijke beperkingen waarmee rekening moet worden gehouden bij de keuze van routes waarop diensten kunnen worden aangeboden. Luchtvaartmaatschappijen moeten zich er van overtuigen dat de routes en de verbindingen in hun netwerken goede investeringen zijn.

Het optimaliseringsmodel in dit proefschrift combineert de performance van vliegtuigen en de capaciteit van vliegvelden met twee financiele modellen: Netto Contante Waarde (E. Net Present Value, NPV) en Interne Opbrengstvoet (E. Internal Rate of Return, IRR). Ook Rentabiliteit (E. Return On Investment, ROI) wordt gebruikt bij het vergelijken opbrengsten van vliegtuigen en netwerken bij de noodzakelijke investeringen. De rentabiliteit is geen beperking, en is geen onderdeel van het optimaliseringsmodel. Berekening van de ROI is van belang bij het analyseren van de efficientie van verschillende vliegtuigen, na de optimalisatie.

Voor de maximalisering van de netto contante waarde (NPV) van een netwerk is een voorspelling van de passagiersvraag nodig. Het NPV optimaliseringsmodel wordt behandeld in Hoofdstuk 6. In het onderzoek is een aangepaste versie van het Grey model (GM) gebruikt voor de langetermijn voorspelling van de pax stromen. Het Grey model is gekozen omdat het geschikt is voor gegevensmodellen met onbekende parameters, en omdat er weinig data nodig is voor het benaderen van het gedrag van niet bekende systemen.

In het model wordt de frequentie van een verbinding beïnvloed door de ‘pax perceptie’, d.w.z. de bereidheid van de pax om een verbinding te gebruiken. De bedieningsfrequentie van een verbinding wordt groter als de pax perceptie groter wordt; de frequentie wordt lager als de pax perceptie lager wordt. De frequentie is ook afhankelijk van de operationele kosten van het vliegtuig. De berekende frequentie minimaliseert de operationele kosten per verbinding.

Met het model kunnen voor elk type vliegtuig twee verschillende soorten netwerken worden onderzocht. Er kan een netwerk worden onderzocht waarin geen verbindingen met negatieve opbrengst voorkomen. Maar het is ook relevant om verbindingen met negatieve kosten toe te laten, als een maatschappij daarmee een hogere opbrengst (netto contante waarde) over het hele netwerk kan realiseren.

Met een routegenerator worden een routenummer en een taknummer toegekend aan iedere mogelijke tak die is geselecteerd door het CFEM model en het PEM model. Het doel is om de door het vliegtuig te volgen route te bepalen. De routegenerator verwijdert verbindingen (takken) met negatieve NPV, maar zonder de samenhang van de route te verbreken.

Met dit algorithme worden twee doelstellingen nagestreefd. Ten eerste: Het aantal vervoerde pax wordt verhoogd. Alle mogelijke routes met positieve NPV zijn kandidaat voor het openen van een dienst. Ten tweede: takken met negatieve opbrengst worden verwijderd, om zo de takken te bepalen die de opbrengst van een route positief maken, terwijl zo veel mogelijk verbindingen worden gevlogen.

De routegenerator genereert niet altijd alle mogelijke verbindingen tussen steden/vliegvelden in een netwerk. Het is dus mogelijk dat een andere combinatie, met minder routes en takken, een hogere NPV geeft, maar minder pax vervoert, dan de beste combinatie uit routegenerator. Doel van dit proefschrift is het vinden van routes waarop mogelijk een nieuwe dienst kan worden geopend en het ontwerp van netwerken door het maximaliseren van de NPV van het netwerk en het aantal vervoerde passagiers. Er wordt geprobeerd om diensten uit te voeren op de takken van het netwerk welke zijn geselecteerd door het CFEM model en het PEM model, als de NPV indiceert dat een dienst op die tak een goede investering is.

Het model wijst aan elke route in een netwerk het optimale type vliegtuig toe. Het model bevat ook strategieën voor lange-afstandsvervoer en korte-afstandsvervoer. Daardoor kunnen met het model scenarios voor lange-afstandsvervoer en voor korte-afstandsvervoer worden gesimuleerd.

De resultaten geven aan dat direkte vluchten waarop vracht wordt vervoerd meer opbrengen dan het vervoer van passagiers via hubs. Dat betekent dat het voor een luchtvaartmaatschappij erg lastig is om netwerken voor goedkoop vervoer over lange afstanden te onderhouden. Door de netwerken van regionaal opererende low cost carriers te koppelen via hubs kan de NPV van netwerken worden vergroot. De cases studies in Hoofdstuk 7 laten zien dat het vervoer van vracht het lange-afstandsvervoer profijtelijk maakt, maar dit type vervoer wordt al uitgevoerd door full service carriers en maatschappijen voor vrachtvervoer.
De cases studies in Hoofdstuk 7 laten zien dat er niet een ideaal vliegtuig is, maar het is wel mogelijk om voor elk netwerk het optimale type vliegtuig te vinden.

Summary

Airlines invest a lot of money before opening new pax transportation services, for this reason, airlines have to analyze if their profits will overcome the amount of money they have to invest to open new services.

The design and analysis of the feasibility of airlines networks can be done by using the models developed in this thesis. It is possible to identify routes that are opportunities to open services, based on airline operating costs, passenger demand, aircraft and airport capacities and constraints.

The optimization model based on the maximization of the net present value (NPV) allows airlines to make sure that a set of routes and links forming new networks represent an investment.

The different airline business models, strategies, advantages and disadvantages were identified from the literature review. In general, four generic passenger business models are commonly recognized: full service carriers (FSC's), low cost carriers (LCC's), charter airlines and regional airlines.

In reality, each airline has its own business model. As a main conclusion, it is also possible to say that the low-cost long-haul airline business is not competitive against full-service long haul and charter airlines businesses.

The fare is the most important parameter or variable. Airlines can use it as a tool to get into the market, and increase passenger flow. Other parameters that airlines must consider in a model or methodology that determine what routes to operate are the target market, network structure, size and power of the route network, optimum number of passengers to attend, aircraft utilization, aircraft physical characteristics, size of the fleet, aircraft route load factor, seat capacity, frequency, turnaround times and airport capacities and infrastructure.

Two airline operating cost models were developed based on econometric and engineering approaches. Both models were compared with real data. They were found to be highly

accurate to calculate airline and aircraft operating costs. First, the AGE model (Chapter 3) is the most suitable model for the purpose of this research because it differentiates between aircraft operating costs. The AGE model can calculate route aircraft operating costs per flight per aircraft. It is based on load and range and it is highly accurate to calculate the total jet fuel volume needed to fly a certain route link by any aircraft type. The AGE model was used to generate operating costs data in the studied cases of Chapter 7.

The second model is a translog function (AOC model), also developed in Chapter 3. It most important advantage is the possibility to calculate different operating costs per route per pax. It allows studying each operating cost effect on fares. The AOC model represents some advantages analyzing airlines market behaviour such as airlines business models competition. The disadvantage is that it does not consider that different aircraft types have different costs.

A model that determines the lowest possible average route fare was proposed in Chapter 4. The model purpose is to identify routes that could be an opportunity to open services. Calculating a route fare is an important managerial tool.

Different parameters have been identified as possible airfare determinants based on the literature (Table 4.2). Two mathematical models were developed in Chapter 4. Both models determine airline fares: the fare estimation model (FEM) and the competitive fare estimation model (CFEM) methodology.

The FEM model is a union between the AOC model (Chapter 3) and airport fees, social, economic and competitive factors. The statistic tests (ANOVA, t test and F test) confirm that the model can calculate fares and its variables have an influence on airline fares. In the case of a new airline, the FEM model can assume its operating cost factor by comparing with a similar airline business model because it is unknown.

Although, the FEM model calculates airline routes fares highly accurate. The objective is to calculate the most convenient fare to identify routes where an airline can open new services. The FEM model can calculate the average route fare but not the range in between airlines route fares are expected to be. This is important, under competition airlines need to know how cheap the other airlines fares can be. Airlines can identify routes to open new service by knowing the other airlines possible min and max route fares. The CFEM model has been developed to calculate these ranges (Chapter 4).

The CFEM model calculates the competitive fare using coefficients calibrated for the FSC-LCC market. In the case of an existing airline, this value needs to be compared with the FEM model average fare calculation. The comparison tells us if the CFEM model average fare calculation is possible. In the case of a new airline, the FEM model can calculate the operating cost factor needed to achieve the CFEM average fare value. Thus, both models complement each other.

The CFEM methodology determines what routes represent an opportunity to open services by an airline based on the calculation of the most competitive fare.

Nevertheless, it is not enough to find routes where the pax demand is high or good enough to open services. The forecast of the air pax demand is important for economic decisions of network planning, fleet assignment, new routes and investment. For those routes, it is very important to know if the induced demand is higher than the demand that is already transported by the other airlines operating the route before making the decisions of opening new services.

In reality, the induced demand cannot be known. The induced demand estimation model (PEM) simulates the pax flow behaviour (Chapter 5) by describing the distribution of the pax flow behaviour using approximately 18,000 routes data points. It was found that the log-normal distribution function (Equation 5.6) is the function that describes the US Domestic market behaviour better. The database was divided into five different airports types depending on the total number of pax transported per day. The results confirmed that the pax flow can be simulated by the log-normal distribution function.

The routes that represent an opportunity to open new services are selected using the next criteria. Routes where the actual number of pax flow is higher than the PEM model calculations do not represent an opportunity to open services. In these routes, it is believed that most of the demand is already being attended. On the other hand, routes where the actual number of pax flow is smaller than the PEM model calculations represent an opportunity to open services. In these routes, it is believed that part of the demand has not been attended.

Even when one route has been selected by the CFEM and PEM models, it does not mean that they represent an opportunity to open services. The routes selection of an airline network have more constraints than just finding routes that are very expensive and have a high number of induced passenger demand. Aircraft and airport capacities, characteristics, and limitations are main constraints to consider when selecting routes that represent an opportunity to open services. Airlines have to make sure that their set of routes and the links forming their networks represent an investment.

In this thesis, the optimization model integrates aircraft performances and airport capacities with two financial methods: net present value (NPV) and internal rate of return (IRR). The return on investment (ROI) is also used to compare which aircraft and network generates more benefits for their required investment. The ROI is not a constraint, and it is not part of the optimization model. The importance of calculating the ROI is analyzing the efficiency between aircraft after optimization.

The maximization of an airline network net present value (NPV) requires forecasting the pax demand for future years. The NPV optimization model is presented in Chapter 6. In this thesis, a Grey model (GM) modified version has been used to forecast routes pax flow for the long-term. The GM model was selected because it has the capacity to forecast data that have unknown parameters and it requires few data to approximate the behaviour of unknown systems.

In the model, frequency is affected by the pax perception of travelling. This value represents the pax willingness for travelling the link. The number of frequencies increases on a link if the perception value increases. It decreases if the perception value decreases. The number of frequencies is also related to the aircraft operating costs. Reason why, the frequency calculated minimizes operating costs per route link.

The model can analyze two different airlines network (NTW) cases for each aircraft type. On one side, the model allows studying a network without links with negative profits. On the other side, allowing aircraft to operate links with negative profits is relevant because an airline can earn more money. The generation of both types of networks is important to compare if different sets of routes with a different set of links results into higher net present values.

A route generation algorithm assigns a route number and a link number to each possible link previously selected by the CFEM and PEM model. The objective is to determine the aircraft path. The algorithm considers the elimination of those routes that do not break the flying path only when a route NPV is negative. This algorithm achieves two things. One, it increases the number of pax transported by the airline. All possible routes are considered for open services when the NPV of a route is positive. Two, the route will eliminate routes with negative profits to find the links that make it profitable, whilst flying the maximum possible number of connections.

The generation algorithm does not generate all possible routes between the city/airports in an airline network by purpose. Then, it is possible that another combination, with less routes and links, has a higher NPV than the route generator best combination, but transporting less number of passengers. The objective of this thesis is to find routes that represent a good opportunity to open services and design airlines networks by maximizing the network NPV and the total number of passengers transported in the network. It means to provide service to most of the links selected by the CFEM and PEM model, if the NPV still suggesting a good investment.

The model assigns the optimum aircraft type to each route in an airline network. The model also applied short-haul and long-haul strategies. It allows the model simulating short-haul and long-haul scenarios.

The results indicated that direct flights carrying cargo are a better business than connecting passengers through hubs. It means that it is very difficult to create an airline company that operates long-haul low-cost networks. The long-haul low-cost model connecting LCC's companies in different regions through hubs allows increasing airlines networks net present values. The cases studied in Chapter 7 have shown that carrying cargo is what allows long-haul airlines to earn more money, but this business is already operated by FSC's and cargo companies.

Finally, the cases studied in Chapter 7 show that there are not an ideal aircraft. It is possible to find the optimum aircraft for each network.

Resumen

Para abrir nuevas rutas de transporte de pasajeros, las aerolíneas deben invertir grandes sumas de dinero, por lo que tienen que asegurar que los beneficios esperados superarán la inversión realizada.

La aplicación de los modelos desarrollados en esta tesis permite identificar rutas con oportunidades para abrir nuevos servicios, tomando como base costos de la aerolínea, demanda de pasajeros, capacidad y costos de operación de distintos aviones, así como capacidades y restricciones aeroportuarias.

El modelo de optimización desarrollado en esta investigación, basado en la maximización del valor presente neto (NPV), permite asegurar que las rutas identificadas permitirán recuperar la inversión necesaria para ofrecer los nuevos servicios.

Mediante una extensa revisión bibliográfica, se identificaron diferentes modelos de negocio, estrategias, ventajas y desventajas usadas por las aerolíneas. En general, cuatro modelos de negocio de transporte de pasajeros son reconocidos: compañías con servicio completo (FSC), compañías de bajo costo (LCC), aerolíneas charter y aerolíneas regionales.

En realidad, cada aerolínea tiene su propio modelo de negocio. Como conclusión principal, es posible decir que el modelo de bajo costo para distancias largas no es competitivo con los servicios ofrecidos por aerolíneas de servicio completo.

El precio es el parámetro más importante o variable. Las líneas aéreas pueden usarlo como una herramienta para entrar en el mercado, y aumentar el flujo de pasajeros. Otros parámetros que las compañías aéreas deben tener en cuenta para determinar qué rutas conviene operar son el mercado objetivo, la estructura, el tamaño y la potencia de la red de rutas, el número óptimo de pasajeros esperados, las características físicas de los aviones a utilizar, el tamaño de la flota, el factor de uso de las rutas, la frecuencia de vuelos, así como la capacidad e infraestructura de los aeropuertos y los tiempos de entrada y salida.

En esta tesis se desarrollaron dos modelos de costos de operación basados en principios econométricos y de ingeniería. Al comparar con datos reales, ambos modelos presentaron alta precisión para calcular costos de operación de líneas aéreas y de los aviones. El modelo AGE (capítulo 3) es más apropiado para el propósito de esta investigación debido a que determina costos de operación para distintas rutas operadas con diferentes aviones. Se basa en la carga y la distancia de vuelo y es muy preciso para calcular el volumen de combustible necesario para volar una ruta con cualquier tipo de avión. Este modelo se utilizó para generar los datos de costos operativos en los casos estudiados del capítulo 7.

El segundo modelo (modelo AOC), también desarrollado en el Capítulo 3, es de tipo multiplicativo y su ventaja más importante es la de calcular los costos de operación por pasajero por cada ruta de vuelo, lo que permite entender el efecto de los costos de operación sobre las tarifas. También permite analizar el comportamiento del mercado para distintos modelos de negocio. La desventaja es que no se considera el costo que los diferentes tipos de avión imponen en cada ruta.

En el Capítulo 4 se propone un modelo que determina la tarifa promedio más baja posible de una ruta. El propósito de este modelo es identificar las rutas que podrían ser una oportunidad para abrir nuevos servicios. Este modelo es una herramienta de gestión importante.

También en el Capítulo 4 se desarrollaron dos modelos para determinar las tarifas aéreas: el modelo FEM y el modelo CFEM. Ambos modelos están basados en los distintos parámetros identificados en la literatura técnica como determinantes para el precio de los pasajes aéreos.

El modelo de estimación de tarifas (FEM) es una combinación del modelo de costo de operación AOC (capítulo 3) con los derechos por uso de aeropuerto y los factores sociales, económicos y competitivos. El análisis estadístico (ANOVA, t de Student y F de Fisher) confirma que las variables que usa este modelo tienen influencia en el cálculo de las tarifas aéreas. Para una línea aérea nueva, el modelo FEM estima el factor de costo de operación mediante la comparación con una línea aérea con modelo de negocio similar.

El modelo FEM calcula las tarifas de las rutas aéreas con muy buena precisión, pero no el intervalo entre tarifas de rutas operadas por distintas aerolíneas. Para identificar rutas para abrir nuevos servicios, las aerolíneas necesitan conocer que tan barato puede ser la tarifa más competitiva, por lo que en el mismo Capítulo 4 se ha desarrollado el modelo CFEM para estimar los valores mínimos y máximos de una ruta.

El modelo de CFEM calcula el intervalo de precios competitivos utilizando coeficientes calibrados con datos de rutas FSC-LCC. En el caso de una línea aérea existente, la estimación puede ser comparada con el cálculo FEM para la tarifa media. En el caso de una nueva línea aérea, el modelo FEM debe usarse para calcular el factor de costo de operación necesario para estimar con el modelo CFEM el intervalo competitivo de precios. Por lo tanto, ambos modelos se complementan entre sí.

La metodología CFEM determina qué rutas representan una oportunidad para abrir los servicios de una compañía aérea basada en el cálculo de la tarifa más competitiva.

Sin embargo, no es suficiente encontrar las rutas donde la demanda de pasajeros es alta o suficientemente buena para abrir nuevos servicios. La estimación de la demanda de pasajeros es importante para las decisiones económicas de planeación de la red, asignación de la flota, nuevas rutas y la inversión, pero antes de tomar las decisiones de la apertura de nuevos servicios es necesario saber si la demanda no atendida es mayor que la demanda ya atendida por otras líneas aéreas que operan la ruta.

En realidad, la demanda insatisfecha no puede ser conocida. El modelo de estimación de la demanda insatisfecha (PEM) simula el flujo de pasajeros con una distribución ajustada al comportamiento de pasajeros en 18,000 rutas (Capítulo 5). Se encontró que la función de distribución log-normal (Ecuación 5.6) es la función que mejor describe el comportamiento del mercado interno de los Estados Unidos. La base de datos fue dividida en cinco tipos de aeropuertos, dependiendo del número total de pasajeros transportados por día. Los resultados confirmaron que el flujo de personas puede ser simulado por la función de distribución log-normal.

Las rutas que representan una oportunidad para abrir nuevos servicios se seleccionan con siguiente criterio. Las rutas con más pasajeros que el flujo estimado por el modelo PEM no representan una oportunidad para abrir los servicios. En esas rutas, la demanda ya es atendida por otras aerolíneas. En caso contrario, las rutas en las que el número de pasajeros es menor que los cálculos del modelo PEM representan una oportunidad para abrir nuevos servicios. En estas rutas, se presume que parte de la demanda no ha sido atendida.

Aún cuando una ruta haya sido seleccionada por los modelos CFEM y PEM, no necesariamente representa una oportunidad para abrir nuevos servicios. La decisión debe tomar en cuenta restricciones adicionales al precio y a la demanda no atendida. La capacidad y característica de las aeronaves y de los aeropuertos, son las limitaciones principales a considerar para seleccionar las rutas que representan una oportunidad para abrir nuevos servicios. Las compañías deben asegurarse de que el conjunto de rutas a atender representan una inversión positiva.

En esta tesis, el modelo de optimización aeronaves, aeropuertos, precios y tamaño de la demanda de servicios con dos métodos de cálculo financiero: el valor presente neto (VPN) y la tasa interna de retorno (TIR). El retorno de la inversión (ROI) se utiliza para comparar qué aeronaves y qué rutas genera más beneficios para la inversión a realizar. El retorno de la inversión no es una restricción, y no es parte del modelo de optimización, se utiliza para analizar la eficiencia entre las aeronaves después de la optimización.

La maximización del VPN de una red de rutas requiere de estimación de la demanda de pasajeros para los próximos años. El modelo de optimización del VPN se presenta en el capítulo 6. En esta tesis, se ha propuesto una modificación al modelo de Grey (GM) para estimar el número de de pasajeros a largo plazo. Se decidió utilizar el GM porque tiene la capacidad para predecir datos que tienen parámetros desconocidos y requiere de pocos datos iniciales.

En el modelo, la frecuencia de vuelos en una ruta es afectada por la percepción a viajar. Este valor representa la voluntad de las personas para viajar en la ruta. El número de frecuencias aumenta si aumenta el valor de la percepción y disminuye en caso contrario. El número de frecuencias también está relacionado con los costos de operación de los aviones, por lo que, la frecuencia calculada minimiza los costos de operación por ruta.

El modelo puede analizar dos diferentes tipos de redes para diferentes tipos de avión. En el primer tipo de análisis, el modelo permite no permite rutas con balances negativos. En el segundo caso, permite analizar redes completas con rutas con beneficios negativos, pues el resultado global puede ser benéfico para la aerolínea. La generación de ambos tipos de redes es importante para encontrar cual es el conjunto de rutas que maximiza el VPN de una red de interconexiones aéreas.

Un algoritmo de generación de redes asigna un número de ruta y un número de enlace a cada posible vínculo seleccionado previamente con los modelos CFEM y PEM. El objetivo es determinar la ruta de la aeronave. El algoritmo considera la eliminación de aquellos enlaces con VPN negativo que no rompen la ruta de vuelo. Este algoritmo consigue dos cosas: uno, que aumenta el número de personas transportadas por la aerolínea al tomar en cuenta todos los enlaces posibles cuando el VPN de la ruta es positivo. Dos, elimina enlaces con beneficios negativos que no rompen una ruta de vuelo para hacerla más rentable.

El algoritmo de generación no genera todas las rutas posibles entre ciudades / aeropuertos en una red global. Entonces, es posible que exista otra combinación, con menos rutas y enlaces, que tenga un mayor VPN, pero que transporte menos pasajeros. El objetivo de esta tesis es encontrar las rutas que representan una buena oportunidad para abrir nuevos servicios e identificar redes de rutas aéreas que maximicen el VPN y el número total de pasajeros transportados en las redes diseñadas por el modelo. Esto significa que para dar servicio a la mayoría de los enlaces seleccionados por el CFEM y el modelo PEM, el VPN debe asegurar una buena inversión.

El modelo asigna el tipo de aeronave óptima para cada ruta en una red global de aerolíneas. El modelo toma en cuenta estrategias de aerolíneas de corto y largo alcance y permite analizar escenarios de vuelo de cualquier distancia.

Los resultados indicaron que los vuelos directos que llevan carga son un mejor negocio que el transporte de pasajeros en tránsito a través de *hubs*. Esto significa que es muy difícil crear una compañía aérea que opere vuelos de larga distancia a bajo costo. El modelo largo-alcance bajo-costo que permite conectar aerolíneas de bajo costo en diferentes regiones a través de *hubs* ha permitió incrementar el VPN de las compañías aéreas. Los ejemplos estudiados en el capítulo 7 han demostrado que el transporte de carga es lo que permite a las compañías aéreas de largo alcance ganar más dinero, pero este negocio ya está operado por empresas FSC y de carga.

Finalmente, los casos estudiados en el capítulo 7 muestran que no hay un avión ideal, pero es posible encontrar la aeronave óptima para cada red.

Biography

Rafael Bernardo Carmona Benitez was born on May 6, 1980 in Mexico City, Mexico. In 2000, Rafael moved to study abroad at Cranfield in England for one year. Back from England, Rafael studied Industrial Engineering and Operational Research at the Instituto Tecnológico Autónomo de México, ITAM (Mexican Autonomy Institute of Technology). He designed a solar tracker device as dissertation project. During his studies, Rafael worked as project manager assistant at FRO Engineers for 2 years. Later, his aspirations took him into a transnational company after his graduation in 2004. He worked as junior project manager in business and administration at the department of Power Transmission and Distribution Energy Automation (PTD EA) of Siemens Latin America. At Siemens, Rafael was responsible for financial projects management. Rafael moved back to England after nearly 2 years of working at Siemens. In England, Rafael studied the master in materials for sustainable energy technologies at the University of Birmingham, Engineering School. Then, Rafael decided to study the feasibility of the air passenger transportation system because he believes that two major businesses correlate: energy and transportation. To do so, The Mexican National Council of Science and Technology (CONACyT) sponsored him to develop his studies related to the air passenger transportation industry at Delft University of Technology starting on January 2008. Rafael Bernardo Carmona Benitez interests are working for an airline company, consultancy companies, the International Civil Aviation Authority Organization (ICAO), ONG's such as the World Bank or United Nations (UN), and to establish a company for engineering consultancy projects.

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