REPUBLIC OF TURKEY
YILDIZ TECHNICAL UNIVERSITY
GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES

A MATHEMATICAL PROGRAMMING MODEL FOR AIRCRAFT FLEET MANAGEMENT

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January, 2019

Abdullah Enes Bolat

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LIST OF SYMBOLS

f	for aircraft type where $(f = 1,...,F)$
a	for age of aircraft where $(a = 0,...,A)$, A is the allowed maximum age in fleet
t	for planning period where $(t = 0,...,T)$, T is the length of planning horizon and 0 is the current year
$T2$	Final planning period, T+1 year
A	Maximum allowable aircraft age
mS	Minimum allowable salvage age
Lp_o	Number of operational lease period for operational lease alternative *o*
La_o	Aircraft age for operational lease alternative *o*
D_{ft}	Demand of aircraft type *f* in period *t*
LC_{fo}	Lease cost of leased aircraft type *f* with operational lease alternative *o*
BC_f	Acquisition cost of owned aircraft type *f*
WC_f	Annual cost of wet leased aircraft type *f*
SC_{fa}	Salvage cost of owned aircraft type *f* with age *a*
OC_{fa}	Operating cost of aircraft type *f* with age *a*
$I0_{ft}$	Number of initial aircraft type *f* which will exit at *t*
B_{fat}	Number of owned aircraft *f* with age *a* in period *t*
NB_{ft}	Number of aircraft *f* with age *a* acquired in period *t*
RB_{fat}	Number of owned aircraft *f* with age *a* sold in period *t*
L_{fat}	Number of operational leased aircraft *f* with age *a* in period *t*
NL_{fot}	Number of aircraft *f* leased in period *t* with option o
W_{ft}	Number of wet leased aircraft *f* in period *t*

LIST OF ABBREVIATIONS

A/C	Aircraft
A.C.M.I	Aircraft Crew Maintenance Insurance
AOC	Airline Operator Certificate
ASK	Available Seat Kilometer
AVR	Aircraft Value Reference
B737	Boeing manufactured 737 type aircraft
E190	Embraer Manufactured E190 type aircraft
FAA	Federal Aviation Administration
IATA	International Air Transport Association
LCC	Low Cost Carrier
M&A	Merger and Acquisition
MBH	Model of Bazargan and Hartman
RPK	Revenue Passenger Kilometers
RPM	Revenue Passenger Miles
YTU	Yıldız Technical University

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ABSTRACT

A MATHEMATICAL PROGRAMMING MODEL FOR AIRCRAFT FLEET MANAGEMENT

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PhD. Thesis

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Airlines operate in a business environment with very low profit margins and fuel prices greatly affect the profitability of airlines. In fact, depending on the type and age of aircraft, the fuel cost can range between 20-25% of the total operating expenses. While crew costs do not typically change with the age of the aircraft, maintenance costs do, as there are more intensive and costly events occurring at later stages of an aircraft's life cycle. Coupled with their higher operating costs, older aircraft are therefore more likely to be favored for replacement if the fuel prices increase at the rates expected. It is clear from the growth in the airline market that airlines will need appropriate fleet replacement and acquisition strategies to cope with the increasing demand for air travel while succesfully competing in a low profit margin industry that is becoming increasingly liberalized.

There are very few articles that jointly considers the subject of fleet planning, aircraft procurement and aircraft phase-out as these decisions are based on strategic plans and decisions and therefore require very confidential data. Nevertheless, the current market situation as reported by various industry leaders has been analyzed. Using the integer linear programming approach existing in the literature, a new model was designed to address the issues that are sometimes over simplified and sometimes unnecessarily complicated. The model made certain improvements to the existing models in literature but did not answer all of the weaknesses noted.

For data collection and case study in this research, a carrier based in Istanbul, Turkey was used to design and validate the model. IBM-ilog Studio IDE 12.7.1 software with CPLEX optimization engine was used to program and run the model. Running this model in the case study showed that the model uses both purchasing and leasing options to answer the increasing demand. The model was then modified for wide-body aircraft and the model prefers fuel efficient new generation aircraft over the existing type.

Sensitivity analysis of the model was performed. The results showed that the current solutions were not very sensitive and therefore robust against the increases in IRR rates. Direction for future research was then proposed to cover the shortcomings of the model that was presented in the thesis.

Key words: Fleet Replacement, Mathematical Model, Airline Industry, Operating Costs and Ownership Costs, Optimization

ÖZET

HAVAYOLU FİLO YÖNETİMİ İÇİN BİR MATEMATİKSEL PROGRAMLAMA MODELİ

Abdullah Enes BOLAT

Endüstri Mühendisliği Anabilim Dalı

Doktora Tezi

Tez Danışmanı: Doç. Dr. Fahrettin ELDEMİR

Havayolları çok düşük kar marjları olan iş çevrelerinde çalışırlar ve yakıt fiyatları havayolları karlılığını büyük ölçüde etkiler. Dahası, uçak tip ve yaşına bağlı olarak yakıt maliyeti toplam operasyon maliyetinin yüzde 20 ile 25 civarındadır. Ekip maliyeti uçak yaşına bağlı olarak değişmezken, uçağın ömür döngüsünün son safhalarında daha yoğun bakımların ortaya çıkmasıyla bakım maliyeti değişmektedir. Yakıt fiyatlarının yükselmesinin beklendiği yüksek fiyat senaryosunda, yüksek bakım maliyetleri ile de ortaya çıkınca, eski uçakların değiştirilmesi tercih edilmektedir. Havayolları piyasasının büyümesinden dolayı artan talep ile endüstrideki liberizasyon sonucu değişen rekabetci yapının oluşturduğu düşük kar ortamında mücadele edebilmek için havayolları uygun filo yenilemesi ve satınalma stratejileri yapmak zorundadırlar.

Filo planlama, uçak satınalma ve filodan çıkarma kararlari stratejik planlara ve kararlara bağlı oldukları için ve çok hassas verilere ve analizlere gereksinim duydukları için, bu konularında çok az makale bulunmaktadır. Buna rağmen, bu çalışmada birçok endüstri liderlerinin raporlarına göre mevcut piyasa durumu analiz edilmiştir. Literatürdeki tamsayılı doğrusal model yaklaşımı kullanılarak bazen çok basitleştirilmiş bazen de gereksizce komplike hale getirilmiş konular içeren yeni bir model geliştirilmiştir. Literatürdeki mevcut modellerin tüm eksikliklerini gidermese de bu model belli iyileştirmeler yapmaktadır.

Model dizayn etme ve doğrulamak için İstanbuldaki bir havayolu baz alınarak veri toplanmış ve vaka çalışması yapılımıştır. CPLEX optimization motorlu IBM-ilog Studio IDE 12.7.1 yazılımı kullanılmıştır. Bu modelin koşturulması sonucunda artan talebi karşılamak için her iki satınalma ve kiralama opsiyonlarının kullanıldığını görülmüştür. Model daha sonra geniş gövde uçkları için geliştirilmiş ve model çözüldüğünde yeni nesil yakıt tasarruflu uçakları tercih ettiği gözlemlenmiştir. Model'in duyarlılık analizi de yapılmıştır ve sonuçlar modelin çözümlerinin faiz oranlarına duyarlı olmadığı görülmüştür. Son olarak bu modelde ele alınmayan konular için de gelecek araştırmalarda neler yapılabilir tartışılmıştır.

Anahtar Kelimeler: Filo Yenileme, Matematik Model, Havayolu Endüstrisi, Opearasyon Maliyeti ve Sahiplenme Maliyeti, Optimizasyon

CHAPTER 1

INTRODUCTION

The airline market and the aircraft market are two markets that are closely related to one another, such that the demand in the airline industry affects the demand for aircraft and therefore the aircraft market. It is no surprise then that aircraft manufacturers are keen on forecasting the demand for air travel (airline market) to be able to forecast the demand for their own market.

There are two major manufacturers of civilian aircraft that are dominant in the market, namely Airbus and Boeing. There are new manufacturers that are aiming to enter this market or have already done so, but have not found much popularity, such as COMAC with its C919 and the Sukhoi with the Superjet 100 respectively. There are also several manufacturers of regional aircraft, such as Bombardier and Embraer, some of which are also trying to enter the market by either creating new products that are expected to directly enter the market (as in the case of Bombardier’s CS series) or compete with the lower end (capacity-wise) of the civil aircraft in the market by altering their existing models to increase capacity.

The factors that affect the demand for air travel are passenger demand, regulatory and infrastructural changes, and the innovation of new services from existing business models. There is high correlation between Passenger demand, measured in Revenue Passenger Kilometers (RPK) or Revenue Passenger Miles (RPM) and Global Economic Growth, measured through the Gross Domestic Product (GDP). Additionally, consumer/personal income and consumer spending, employment, international trade, domestic investment and the age of the working population are reported as being major factors in passenger demand. Low air fares, higher standards of living, a growing middle class in large emerging markets and the growth of tourism are also significant factors in Airline business.

Aircraft manufacturers developed very effective tools to estimate the passenger demands not only by regions but also by airlines. Considering the fact that to establish such line for a new model requires huge investment and to change the production rate is not easy at all, they need these tools to estimate the number of aircraft to produce for each model in their assembly line. For example, Boeing now gears up its B787 Dreamliner program to 12 – 14 aircraft per month after the troubled introduction of the program 7-8 years ago with nearly $30 billion in total production and opportunity costs [1]. Similarly, Airbus introduced its A350 program to cope the changes in the wide body aircraft market.

In the single aisle (narrow body) aircraft market, a similar duopoly competition environment exists between Airbus' NEO program and Boeing's MAX program. The overall size of the commercial market becomes very obvious when considering the fact that the average yearly production rate for both manufacturers is in the ballpark figure of 1100-1200 aircraft. Therefore, the manufacturers really need not only good tools to predict the market demand (airlines requests for additional aircraft) but also good programs to convince airlines to phase out old aircraft and replace with the new models currently being manufactured.

Airlines, regardless of their business model, operate with very low profit margins. Ticket prices continue to decrease year by year and cockpit crew costs increase higher than inflation rates. Jet fuel prices fluctuate based on the crude oil prices. Then airlines do not have much room to maneuver rather than to control their maintenance costs and the other constituents of the operating costs. Maintenance costs as well as the operational efficiency do typically change with the age of the aircraft with more intensive events occurring at later stages of an aircraft's life cycle. Older aircraft are typically less fuel efficient than the new generation models due to advances in engine technology and aircraft design made over time. Coupled their higher maintenance costs, older aircraft will more likely be favored to be replaced if the fuel prices increase at the rates expected in the high price scenario.

Low Cost Carriers (LCCs) also force the legacy carriers to reconsider their position on keeping their aging fleet with increasing maintenance costs and decreasing operational efficiency. LCCs operate through the concept of cost minimization rather than revenue maximization and captures passengers in the short-haul market. The traditional "legacy" or "flag carriers", focusing on the long haul international destinations need short-haul market to feed the long haul. Thus, they have to encounter the efficiency of the LCC operations in any way.

Airlines use proper fleet planning, aircraft procuring-acquisition strategies and aircraft phase-out to meet the increasing demand while competing in a highly competitive low profit margin market environment. There are not that many articles on the subject of fleet expansion and/or replacement planning of aircraft because these decisions are mostly considered strategic and require very confidential data, and the analysis of such is therefore not often shared. A thorough review on the available work in the field will be made in the coming section. Furthermore, airlines' and manufacturers' strategies will be investigated, with special emphasis given on the Low Cost Airlines. Fleet replacement models and studies in other fields are also given to show the similarities in the models. In this thesis, the aim is to provide a mathematical tool to aid in the decision making process of fleet expansion and replacement.

1.1 Literature Review

Airlines need appropriate fleet replacement and acquisition strategies to be able to meet the increasing demand while competing in a low profit margin industry with a constantly changing competition environment due to the liberalization of the market. While there is a quite a few articles in the field of fleet assignment, which is usually used for meeting demand in flight scheduling and entails the assignment of aircraft to routes, the same is not true for fleet management, which encompasses the aircraft acquisition and aircraft phase out (replacement) decisions. There are several reasons for this lack of literature in the field, but two of most important ones are: i) these decisions are based on strategic plans and decisions, and; ii) they require very confidential data and analysis of which is usually even more confidential.

Literary works in the field of fleet assignment are numerous but can be divided based on their contributions. A common field of research is assigning aircraft to flights, typically under certain constraints or special conditions. The work by Hsu and Wen [2], who developed a model to determine the optimum flight frequencies using supply (flight availability)-demand (passenger demand) interactions for an airline network, is an example of such a study. The model they developed consisted of two sub-models that determine the passenger's flight choices (i.e. the demand) and a flight frequency determination model.

Another typical constraint considered is maintenance, which are hard constraints, especially in the civil passenger aviation business. Kozanidis [3] attempts to achieve maximum availability of aircraft in a fleet under maintenance requirement constraints. He further proposes two heuristic methods to solve large instances of the problem. The model developed, albeit with the heuristics for large scale problems, is not directly applicable for civil aircraft due to the more complex nature of aircraft maintenance scheduling requirements as well as the more rigid aviation authority regulations on maintenance intervals and events.

Some literary works even considered environmental constraints, such as looking to minimize the impact of aircraft selection on the environment or to determine the impact of the environment of an airline on fleet planning. An example of such a study is that by Rosskopf et al [4], who used a multi-objective optimization model to determine fleet plans that optimize the trade-off between environmentally friendly A/C to the cost factors of such aircraft.

A second example study [5] aims to study whether airport landing fees impact fleet planning decisions with regards to taking in higher capacity aircraft with lower service frequency to reduce landing fee costs. The study was conducted in a specific duopoly market environment and found that higher landing fees do infact have an effect on the choice of aircraft size, causing airlines to choose higher capacity aircraft with lower frequency service and additional incentives due to reducing airport congestion can further this decision. Of course, this study is limited in scope to landing fees and its effect on choice of aircraft size, but nevertheless shows that certain fees can have effect on the choice for aircraft size.

In the field of fleet management, which is the topic of this research, there are much fewer literary works for the reasons mentioned previously. After a thorough search of the available in the field, a sample of the literary works that are related to this thesis work have been reviewed below, as well as works that are directly on the field of fleet management.

The most directly related work is by Bazargan and Hartman [6], who developed an integer program to minimize total discounted purchasing, leasing, operating and maintenance costs, and presented results for the application of two US airlines with generally leasing options. They concluded that these solutions yield benefits from having newer aircraft with less diversity.

Table 1.1 presents the summary of the directly related works to this thesis, including their objective functions as well as their contributions to literature.

Table 1.1 Directly related work on the fleet replacement and acquisition

Ref No	Date	Author(s)	Title	Model and Methodology	Unknowns/Risks; Objective Function; and Contribution
6	2012	Bazargan, M., Hartman, J.	Aircraft replacement strategy: Model and Analysis	Binary integer linear programming model to determine the no of aircraft to buy, lease or sell to minimize total costs	Lease prices; Binary integer model to minimize costs associated with buying, leasing, operating and selling of A/C; Minimize the total discounted cost by identifying the number of aircraft to lease, buy and sell over a planning horizon
7	2011	Hsu, C., Li, H., Liu, S., Chao, C.	Aircraft replacement scheduling: A dynamic programming approach	Stochastic dynamic programming model and Grey topological models and Markov Chains used for stochastic data	Passenger traffic, demand; Optimize buying, leasing, or selling aircraft by minimizing the total cost during the period; Optimize airline decisions for buying, leasing, selling aircraft over time using Markov chains to estimate demand
8	2014	Ansaripoor, A., Oliveira, F., Liret, A.	A risk management system for sustainable fleet replacement	General decision support system using stochastic and conditional value at risk to account for uncertainty	Fuel price fluctuations, consumption, and mileage driven; Provides assistance in deciding replacement of vehicles for different technologies
9	2013	Mishra, S., Sharma, S., Khasnabis, S., Mathew, T.	Preserving an aging transit fleet: An optimal resource allocation perspective based on service life and constrained budget	Mixed integer mathematical model along with branch and bound algorithm to determine solution	Budget, policy constraints, demand; Minimize the net present cost of the fleet; Minimize the total net present cost of the fleet for all agencies over the planning period subject to budget, demand, rebuild, and non-negativity constraints

Table 1.1 (cont'd)

10	1997	Luxhoj, J., Williams, T., Shyur, H.	Comparison of regression and neural network models for prediction of inspection profiles for aging aircraft	Multiple regression models compared and analyzed with respect to multicollinearity to determine generalizability, and neural network models using grouped data and a two stage neural network model	Failure prediction; Probabilistic Neural Network in the first stage, back propagation neural network to predict the number of service difficulties; Probabilistic Neural Network in the first stage to determine the vector of age and class which is fed to a back propagation neural network to predict the number of service difficulties
11	2017	Wijka, O., Andersson, P.,Block, J. and Righard, T.	Phase-Out Maintenance Optimization for an Aircraft Fleet	Combination of matrix simulations and genetic algorithm	Faster method than the crude search and also locates the optimum more often than the steepest descent search
12	2009	Givoni, M., Rietveld, P.	Airline's choice of aircraft size - Explanations and implications	Regression analysis to explain airline aircraft size choice	Demand on existing routes, fuel prices not included; Regression analysis taking into account route, seat/flight, market size, airport characteristics, runways, hubs and slots; Find a relationship between the factors identified to determine the choice of aircraft size by airlines;
13	2012	Stasko, T., Gao, H.	Developing green fleet management strategies: Repair/retrofit /replacement decisions under environmental regulation	Dynamic programming model for making buy/sell/replace decisions	Fuel price volatility, regulations; Maximize the discounted future value of the fleet; Future value of fleet subject to dynamic value function estimates to be determined by model for optimum decisions on buy/sell/replace decisions

Another work directly related this thesis proposes a dynamic programming model employing Markov-chain and applied it over a case study in EVA airlines [7]. They use Markov-chains to estimate demand to then optimize airline decisions for buying, leasing, selling aircraft over time.

A stochastic mixed integer linear programming model was developed in [8] for vehicle fleet management problem with the uncertainties on the carbon prices, fuel prices, mileage driven, and fuel consumption. Replacement decisions are based on minimizing expected cost and risk simultaneously.

Vehicular fleet models have also been reviewed as there can be some applications to airline operations. The work in [9] was examined due to its application of fleet assignment on a vehicular fleet with constraints like budget and service life, which can be applied to airlines as well. The considerable cost of maintaining large fleets has generated interest in cost minimization strategies.

The Service Difficulty Reporting (SDR) system contains data related to the identification of abnormal, potentially unsafe conditions in aircraft and/or aircraft components/equipment. These indicators assist safety inspectors in diagnosing an airline's safety profile compared with others in the same peer class, and eventually resulting in replacement decisions. Both multiple regression and neural networks are used in [10] to create prediction models for the overall number of SDRs and for SDR cracking and corrosion cases. A work for cost-effective optimization of stop-maintenance strategies for a set of repairable items (rotables) in aircraft fleet might be extended for the aircraft itself. For a fleet of very capital-intensive systems, such as aircraft, the retirement process will often stretch over a decade or more, during which the operational fleet gradually contracts. This requires managing the operational resources for the remaining fleet at acceptable levels of cost, availability and risk. The combination of matrix simulations and genetic algorithm is shown to constitute a powerful method for solving this optimization problem in a fast manner [11].

Airlines usually tend to respond more by means of increasing frequencies than by increasing aircraft size when the demand grows. It seems that this choice is associated mainly with the benefits of high frequency service, the competitive environment in which airlines operate and the way airport capacity is allocated and priced. Regression analysis of over 500 routes in the US, Europe and Asia provides empirical evidence that the choice of aircraft size is mainly influenced by route characteristics (e.g. distance, level of demand and level of competition) and almost not at all by airport characteristics (e.g. number of runways and whether the airport is a hub or slot coordinated). The study by [12] argue that the choice of aircraft size depends on market size with an elasticity of 0.35 and aircraft size increases with distance, a natural result of the trade-off between cost of loading/unloading, and cost of flying. Two main market failures are lack of competition and congestion at airports with opposite impacts. The lack of competition allows carriers to reduce frequencies with larger aircraft and higher levels of congestion with lack of incentive to consider the use of larger aircraft eventually results in the aircraft size set at below optimal levels.

An approximate dynamic programming approach is presented in [13] for making vehicle purchase, resale, and retrofit decisions in a fleet setting with stochastic vehicle breakdowns. The model predicts the expected cost of compliance, the rules the fleet manager will use in deciding how to comply, and the regulation's impact on the value of vehicles in the fleet.

Lessors also face the same problem when redesigning their portfolio, adding more assets from manufacturers, from other lessors (novation), airlines (refinancing) or displacing some assets to other lessors or to part-out companies. From Avalon leasing company, Forsberg in [14] shed light to decision makers in the Aviation industry where 8000 aircraft were expected to be retired. This study must be renewed for the current aging fleet types, such as A340 family, B777 family as well as A320 and B737 classics and NG.

Flag carriers utilizing aircraft with different capacities, belonging to multiple families frequently face the problem of effectively matching supply and demand under uncertainty for short periods of time. A Demand Driven Swapping (DDS) approach is proposed in [15] to take advantage of the flexibilities in the system and dynamically swap aircraft as departures near and more accurate demand information is obtained. They analyze the effectiveness of different DDS strategies by testing them using data obtained from United Airlines.

The decision of lease versus purchase is discussed in [16] emphasizing the pitfalls of using discount factor or cost of financing for aircraft economic evaluation. They propose extension of adjusted present value and show that equity NPV demonstrates the overall returns of the project from a shareholder perspective.

Aircraft considered for purchase is usually new aircraft. Although some operators buy second-hand aircraft, this is region specific and also usually not preferred by LCCs. The purchase cost is taken as the most recent price offers from the manufacturer of the selected aircraft type by the LCC. Aircraft considered for lease are taken as being at a quarter of their typical operational age of 24 years i.e. 6 years of age [17]. The typical age is taken as the maximum age of aircraft allowed in the fleet as well.

Usually, researchers ignore the flexibility in terms of lease options. In practical application, any number of lease periods are possible as this depends on a number of factors such as the period of lease demanded by the airline, the lease period offered by the lessor, the demand in the market (both current and projected) for leased aircraft, conditions of the lease, etc. However, the most commonly seen periods are 8 and 12 years [18].

The fractional jet ownership models is discussed in [19] with strategic planning issues, such as, aircraft maintenance, crew swapping, demand increase and differentiation. Although, there are no fractional ownership practice in the commercial airline business, wet leasing or sub leasing practices may be re-studied under the joint ownership.

In the shipping industry shipping for dry bulk market, herd behavior is examined and provided evidence for that [20]. Obviously, knowing that herding exists in the capacity expansion or retirement decision may assist in shaping shipping strategies. A future study may be carried out to identify whether there is a similar practice in the aircraft leasing industry or in the slow introduction of Russian, Chinese and Japanese narrow body aircrafts.

1.2 Objective of the Thesis

In today's ever expanding airline transportation market, the competition between airlines has come to new levels. This has brought renewed importance to the problem of fleet planning and cost effectiveness. The global economic crisis, along with rising fuel prices, has increased the importance of good planning in the survival of an airline. It is a macro approach comprising of many forecasts, analysis and plans, such as details of the network, operating conditions, flight plans, maintenance plan, aircraft required, yield analysis and forecasts to name a few.

One important aspect in fleet planning is when to remove an aircraft from the fleet. This of course depends on several factors but in summary it is when the cost of operating the aircraft in the fleet is greater than the revenue it generates by flying any flight in the network or the cost of the next best alternative-leasing another aircraft. For airlines that are constantly growing, the problem of fleet planning and more so determining when to remove an aircraft from the fleet becomes increasingly complex. This complexity further increases with the number of destinations an airlines flies to, each destination with different operating parameters. The objective of this thesis is to develop an integer program that improves the one in current literature to minimize total purchasing, leasing, operating and maintenance costs, and apply it to different business models of a carrier in Turkey. With this model, practitioners can make strategic decisions for the fleet replacement and expansion scenarios based on quantitative techniques. For various financial options and interest rates, decisions could be made such that they are insensitive over high interest rates and high fuel prices.

1.3 Hypothesis

Maintenance costs as well as operational inefficiency typically increase with the age of the aircraft, with more intensive events occurring at later stages of an aircraft's life cycle. The new generation models, though with a higher purchase cost, have advanced engine technology and a high percentage composite mainframe resulting in lower maintenance costs and higher fuel efficiency. It is hypothesized that (1) older aircraft will more likely be favored to be replaced by the new generation of aircraft and (2) buying (purchasing) aircraft from manufacturer will be more likely be chosen over leasing from lessors at the beginning of the planning horizon or for a period of 10-12 year, whereas the opposite is more likely for midway towards the end of the horizon. Model developed here takes into account operational as well as financial costs so that various fuel costs and interest rates can be used to perform parametric studies.

1.4 Organization of the Remainder of the Thesis

A comprehensive analysis of the literature related to fleet management is presented in the rest of this chapter, after which the airline sector and aircraft manufacturer strategies as well as a brief overview of the aviation and airline business models are discussed in the next chapter. In Chapter 3, some of the constraints to be considered in fleet planning are analyzed and extension/replacement models are discussed. The proposed model is presented in the Chapter 4, followed by computational experiments and discussions in Chapter 5. Summary and future studies are given at the end.

1.5 Detailed Analysis of Directly Related Literature

The most directly related work to this thesis is by Bazargan and Hartman [6], and will be extensively analyzed in this section. As mentioned before, they had developed an integer program to minimize total discounted purchasing, leasing, operating and maintenance costs, and had concluded that these solutions yielded benefits from having newer aircraft with less diversity. While this is true for low cost carriers, in reality network carriers usually buy their aircraft from manufacturers and tend to diversify their fleet to service different segments of the passengers. So the model is limited in application to a specific type of LCC, one that does not use more than one type of aircraft.

Furthermore, although their results favored leasing, big low cost carriers also tend to order (purchase) from the manufacturer directly. One reason for the result obtained in their model may be the budget constraints in the model that combines and limits total short haul and long haul aircraft to be added to the fleet for a particular period. In practice, a certain percentage of aircraft price is paid in installments until the aircraft is produced and delivered to the airline. At this point, a leasing company or financer purchases the aircraft on behalf of the airline and leases the aircraft back to the airline. The airline is reimbursed the pre-paid installments from the manufacturer. The leasing term and the leasing rate are determined during the tender process. The budget constraint therefore unnecessarily limits the model to leasing.

Furthermore, in the model, there are no leased aircraft at the beginning of the planning period, whereas in reality, airlines will have leased aircraft with different termination periods at all times if it is an airline currently in operation.

Several key aspects practiced in reality are also omitted. Airlines almost always buy new aircraft from the manufacturer; whereas the model allows for the purchase of used aircraft, and hence, it unnecessarily introduces variables that will not take any value or occurrence in application. In practice, aircraft are leased from lessors at various ages and rarely, airlines sub-lease their aircraft to other airlines.

The model further assumes that all of the lessors ask for the same lease rent for the aircraft of same type and age. In reality, lease rates depend on financial and market position of lessors, the demand of aircraft by airlines, and the period of the lease, which can be varied depending on the needs of the airline. For example, a lessor with a large portfolio of aircraft could ask for a higher lease price for an aircraft that has a shorter lease period. More importantly, it is assumed that there are lease options where there are lags between signing of the lease and introduction of the aircraft into the fleet. This is not a widely available practice and thus introduces unnecessary and inapplicable solutions.

Finally, the model assumes that, at the same age, for the same type of aircraft, maintenance costs are the same. However, for leased aircraft, life limited parts (LLP) on the engines and landing gears, Airworthiness Directive (AD) requirements, component usage cycles, and so on will differ causing different maintenance intervals and costs. Additionally, some lessors require reserves monthly to guarantee that at the time of the maintenance, the lessor will have sum of money to pay the cost of the maintenance. Others opt what is called "end of lease compensation" in which the airline fixes and maintains the components and engines as required. For the LLP parts, whatever is not compensated by the maintenance program is paid back to the lessor through the formulas agreed at the beginning of the lease period.

Additionally, airlines may wet lease aircraft from other operators; an option not available in the model. In other words, for period when the airline has excess demand, they may opt to lease one or more aircraft from another operator for a 6 months or a year period on the ACMI (Aircraft, Crew, Maintenance and Insurance) basis. The owner of the aircraft (operator in this case) will bear the cost of lease rate, insurance, cockpit and cabin crew of the aircraft, and all the maintenance costs. In return, it will charge the airline a rate based on the operating hours. For example, for a guaranteed block hour of 300 hours per month, the lessor will ask the airline to pay 3000 USD per hour for the ACMI costs. If the airline uses 325 hours for a particular month, the operator will get 325*3000=975000 USD and if the airline uses the aircraft for example 215 hours then it will pay the minimum guaranteed sum of 300*3000=900000 USD. Beside this cost, the airline will pay all the remaining operating costs such as fuel, handling, catering, navigation, etc. This way of adding capacity to the fleet allows the airline to absorb fluctuating demand for short periods.

Another work directly related to fleet management proposes a dynamic programming model employing Markov-chain and applied it over a case study in EVA airlines [7]. The model may work for small - medium airlines that need to adjust their fleet against sever demand fluctuations in short periods. Additionally, larger network carriers may find it useful for the operational lease aircraft. Near the end lease periods, Airlines may opt to extend these leases. Here, effective models to capture the randomness of the demand can help to optimize the tradeoff between decreasing lease rate versus increasing airframe and engine maintenance costs. Besides these cases, ordering new aircraft in big number or disposing older types from fleet are airlines strategic decisions and usually based on the market position that the airline is aiming for.

In the current literature, there is no work that deals with the decisions pertaining to the acquisition of the wide-body new generation aircraft. There are more than 700 B787's and 150 A350 wide-body new generation aircraft currently being used and in this work. The operating costs of these aircraft are estimated through expert knowledge over different scenarios. Additionally, as in reality, there will be leased and owned aircraft in the beginning of the planning horizon so that the model can be re-applied every year on a rolling horizon basis to adopt to the changes over the years dynamically. Wet lease is also considered to accommodate sudden and unexpected increases in the demand. These flexibilities allow to exercise different fleet planning strategies as they change over the years.

1.6 Distribution of the Directly Related Methods in Literature

When looking at the literature, it is obvious that research with respect to fleet management models is concentrated on the assignment aspect and replacement is dealt with sparingly as deterministic part of the model, as discussed in Bazargan and Hartman [6]. The work of Hsu et al. [7] is an example where a dynamic fleet assignment model was used and replacement was considered with certain parameters.

Of the literature reviewed that are directed at airline fleet management, only five studies address fleet assignment/planning, of which only two are related to airline replacement models. Vehicular fleet models have also been reviewed as there can be some applications to airline operations. The paper by Mishra et al. [9] was examined due to its application of fleet assignment on a vehicular fleet with constraints like budget and service life, which can be applied to airlines as well.

Figure 1.1 below shows the solution methodologies of the models used in directly related literature that were mentioned in the Literature Review previously. As can be seen, among the limited works there is more concentration on dynamic and regression models. As the integer model proposed here allows sequential use of the fleet plans over the years on a rolling horizon basis, changes in demand data over the years can be handled dynamically.

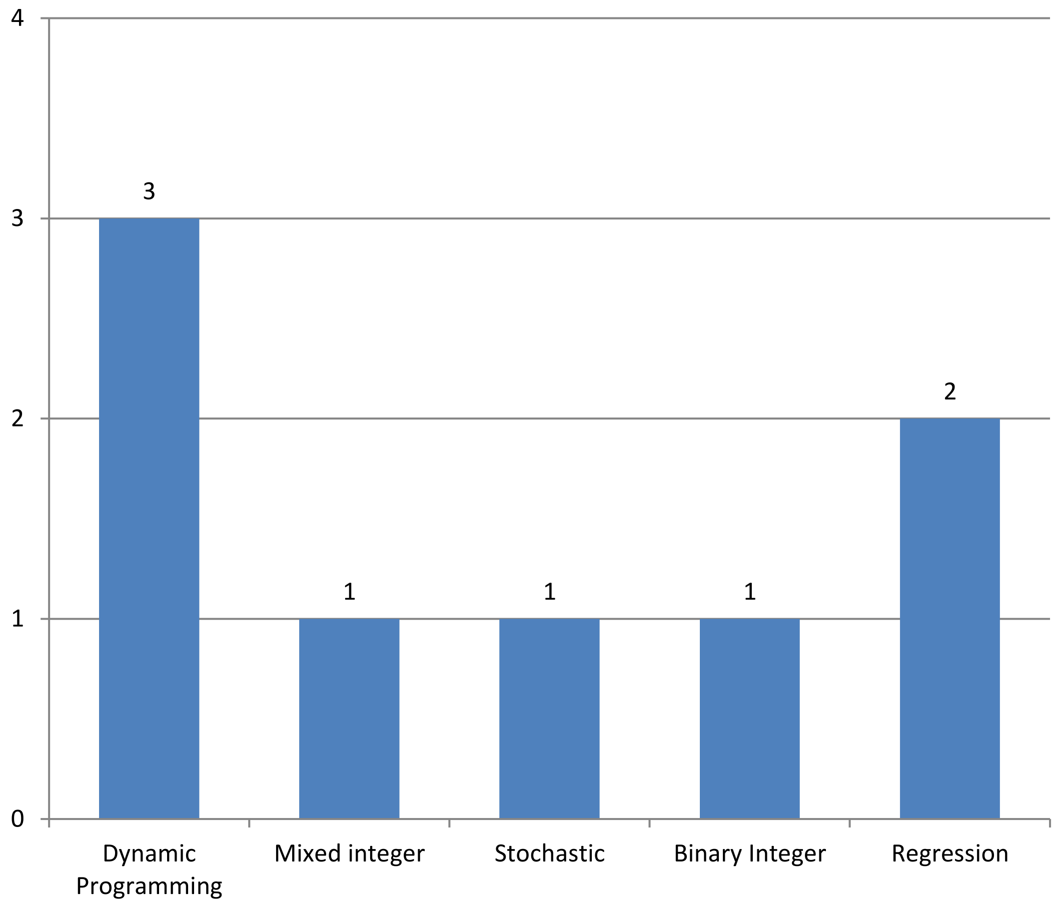

Figure 1.1 Solution methodologies of the models in works directly related to fleet assignment and replacement

CHAPTER 2

AN OVERVIEW OF THE AVIATION AND AIRLINE MARKETS

Airlines operate in a business with very low profit margins; the typical profit margin in the industry was expected to be around 4-5% in 2017 [21]. One of the major cost factors is fuel prices, which have increased steadily since the lows seen in 2015. Prices have already started to recover but in the short-term, prices are not expected to reach peak levels of the past [22] and the long-term forecasts for crude oil either favor a direct increase in price over time or offer two alternate scenarios [23]. Since fuel cost is one of the major constituents of an airline's (operating) costs, this price uncertainty reflects on the profitability expectancy and asset acquirement decisions to be taken. Depending on the type and age of aircraft, the fuel cost can range between 20-25% of the total operating expenses [21], though the average was slightly more than 17% worldwide [24].

The growing airline travel market, coupled with the low profit margins driving airlines towards cost savings and efficiency, all drive the demand for new aircraft. Both of the dominant manufacturers (Airbus and Boeing) expect more than 30,000 new deliveries in their 2017 forecasts, of which more than 55% are expected to be for growth and the remaining for replacement [22], [23]. The airline market and the aircraft market are two markets that are closely related to one another, such that the demand in the airline industry affects the demand for aircraft and therefore the aircraft market. It is no surprise then that aircraft manufacturers are keen on forecasting the demand for air travel (airline market) to be able to forecast the demand for their own market.

Besides, the two major manufacturers of civilian aircraft that are dominant in the market, namely Airbus and Boeing, new manufacturers are also aiming to enter this market or have already done so, but have not found much popularity, such as the COMAC C919 that is "aiming to make the first delivery in 2021 [25] and the Sukhoi

Superjet 100 respectively. There are also several manufacturers of regional aircraft, such as Bombardier and Embraer, some of which are also trying to enter the market by either creating new products that are expected to directly enter the market (as in the case of Bombardier’s C-series) or compete with the lower end (capacity-wise) of the civil aircraft in the market by altering their existing models to increase capacity.

Crew costs and maintenance costs are the other constituents of the operating costs of airlines. While crew costs do not typically change with the age of the aircraft, maintenance costs do as there are more intensive events occurring at later stages of an aircraft's life cycle. Older aircraft are typically less fuel efficient than the new generation models due to advances in engine technology and aircraft design made over time, with efficiencies of up to 15-20% expected for the A320neo and similar rates for the competitor Boeing 737 MAX [26]. Coupled with their higher maintenance costs, older aircraft will more likely be favored to be replaced if the fuel prices increase at the rates expected in the high price scenario.

2.1 Airline Passenger Market

The factors that affect the demand for air travel are passenger demand, regulatory and infrastructural changes, and the innovation of new services from existing business models [23]. Passenger demand is usually measured in Revenue Passenger Kilometers (RPK) or Revenue Passenger Miles (RPM). It is estimated that "air traffic (RPK) doubles every 15 years" [22] and "year-over-year passenger growth has averaged 6.2%" [23]. Global Economic Growth, usually measured through the Gross Domestic Product (GDP), is one of the key drivers of this demand but is not the only driver of passenger demand. Consumer/personal income and consumer spending, employment, international trade, domestic investment and the age of the working population are reported as being major drivers in forecasts as well as low air fares [22], higher standards of living, a growing middle class in large emerging markets and the growth of tourism [23].

Stronger economies in emerging markets have also contributed to the growth, with the domestic market in China alone expected to grow nearly 4 times in the next 20 years. The Middle East, Asia Pacific, Africa and Latin American Markets are expected to the major growth areas for the next 20 years in order of highest growth, with the mature European and US markets expecting growths of 3.4 and 2.4% respectively [22].

Another good example for such a market growth and airline is Turkish Aviation and Turkish Airlines, which has showed a remarkable growth trend with double digits for the last 13 years. Researchers in [27], [28] and [29] have examined the market position, advantages and strategies that brought Turkish Airlines from a local airline with 60 aircraft to a global brand with 330 aircraft today. A wide body aircraft fleet consisting of Airbus A330s and Boeing 777-300ERs makes up around 25-30% of the total fleet and a narrow body aircraft fleet that is evenly distributed between the Airbus A320 and Boeing 737 NGs comprises the rest. To maintain the cost efficiency in the ownership costs, Turkish Airlines has procured more than 300 aircraft from Airbus and Boeing for the last 6-7 years.

Positive regulatory changes also support the growth of the air travel industry. The most obvious example of this is in the case of the Trans-Atlantic Market. The Atlantic (including Europe and the Middle East) and Canada Markets are historically mature markets, with an expected average growth of 3% per year between 2017-2037 [30].This number is up from the 6.2% decline in growth experienced in the 2009 crisis and a more or less flat average 2% year on year growth experienced when evaluated in 2012 [31]. The market has grown steadily since then through bi-lateral agreements (such as the EU-US Open Skies), business model renewals, and the entry of Low Cost Carriers into the market. On a global scale, Open Skies Agreements worldwide have further allowed liberalization to extend beyond the borders of traditionally domestic markets [23]. Liberalization has also allowed for flights to previously restricted airspaces such as Cuba and Iran, allowing for growth opportunities.

The demand for US air passenger-services is studied by [32] with the short- and long-run effects of various determinants. They used the Johansen cointegration analysis and a vector error-correction (VEC) model. In the long-run, airfare, disposable income and NASDAQ are significant factors, explaining changes in air passenger-miles effects with population and airfare jointly.

Airlines operating different network of airports and different fleets have different passenger quantities and itineraries. Furthermore, the data is always confidential by most airlines due to its significant commercial implications, and thus, obtaining real data is difficult. This creates a barrier among researchers and limits potentially fruitful collaboration between research groups and practitioners. Thus, generating benchmark problems becomes a research topic [33]: It provides a framework and methodology for generating realistic airline demand data, controlled by scalable parameters. First they generate the flight network including passenger load on arcs, then calculate origin–destination (OD) pair demand, define passenger groups and finally allocate OD-pair demand to each passenger group. They produced 33 benchmark instances exhibiting a range of characteristics. In part II [34], they extend it by partitioning the demand in each market (OD pair) into market segments, each with its own utility function and set of preferences for alternative airline products. The resulting demand data will better reflect recent empirical research on passenger preference, and is expected to facilitate passenger choice modelling in flight schedule optimization.

For air passenger traffic demand in a hub-and-spoke network [35] developed an aggregate model considering service frequency, aircraft size, ticket price, flight distance, and number of spokes, hub airport capacity. Additionally, it also takes into account the influence of local passengers and social-economic and demographic conditions in the spoke and hub metropolitan areas. Results show that connecting passengers are more interested in increasing service frequency than in increasing aircraft size. Additionally, airlines' services in the first flight leg are more important to attract passengers than those in the second flight segment. Interestingly, 1% reduction of ticket price will bring about 0.9% more connecting passengers, and a 1% increase of airport acceptance rate can bring about 0.35% more connecting passengers.

2.2 Operations and Planning in Conventional-Network Airlines

Given a set of aircraft types, the optimal composition of the fleet (i.e., the number of aircrafts of each type to be the most profitable for the operation of an airline schedule) is determined by upper management levels involving many complex factors. A drastic change in passenger demand typically results in large scale reductions in flight schedules by canceling some routes or by announcing additional destinations or more frequent flights to existing destinations and eventually resulting in grounding some aircraft in the fleets or adding capacity by short dry-leased and or wet-leased aircrafts. The scenario aggregation–based approach in [36] takes explicitly taken into account stochastic nature of the passenger demand for dynamic allocation of the fleet's capacity. Results involving up to 2,000 flights and nine aircraft types show potentially robust fleet composition can be obtained with the increase of the load factors up to 2.6% and spill decrease up to 3.3%. Moreover, plane swapping can yield up to 1.7% higher load factors with 2.3% fewer turned-away passengers, in the bottom-line profits increase between 10.75% and 14.5%.

Econometrically, both the size of airlines and fleet mix decisions have significant impact on technical, allocative and, ultimately, cost efficiency. Key determinants of 58 passenger airlines' efficiency are evaluated in [37] by applying a two-stage Data Envelopment Analysis (DEA) approach, with partially bootstrapped random effects Tobit regressions in the second stage. It is shown that although stage length has an impact on an aircraft's unit cost, its impact at the airline level is limited to technical efficiency. Conversely, the age of fleets has no significant impact on technical efficiency but delivers, on average, a small positive effect on allocative and cost efficiency. The results over very young fleets with relatively high efficiency are not substantial.

Airlines usually tend to respond more by means of increasing frequencies than by increasing aircraft size when the demand grows. It seems that this choice is associated mainly with the benefits of high frequency service, the competitive environment in which airlines operate and the way airport capacity is allocated and priced. Regression analysis of over 500 routes in the US, Europe and Asia provides empirical evidence that the choice of aircraft size is mainly influenced by route characteristics (e.g. distance, level of demand and level of competition) and almost not at all by airport characteristics (e.g. number of runways and whether the airport is a hub or slot coordinated).

The choice of aircraft size obviously depends on market size such that aircraft size increases with distance, a natural result of the trade-off between cost of loading/unloading, and cost of flying. Two main market failures are lack of competition and congestion at airports with opposite impacts. The lack of competition allows carriers to reduce frequencies with larger aircraft and higher levels of congestion with lack of incentive to consider the use of larger aircraft eventually results in the aircraft size set at below optimal levels. Game-theoretic competition models are developed to determine both aircraft size and service frequency to maximize profit [38]. They use empirically derived cost function and market share model, which are calibrated through airlines' actual cost and market data.

It is impossible to determine a fully operative and optimal schedule which considers competitive effects, stochastic demand figures and uncertain operating conditions. Thus, airlines develop base schedules, much time in advance to the day of operations, ignoring all the related uncertainty. A mathematical model is proposed in order to update base schedules in terms of timetable and fleet assignments while considering stochastic demand figures and uncertain operating conditions [39]. Resulting large-scale problems are solved by accelerated Benders decomposition approach. Case studies involving the Spanish legacy airline, IBERIA show that significant reduction of miss-connected passengers can be achieved through this model.

Airlines experience periods of significant fluctuations in fuel costs and passenger demand during economic expansion, recession and recovery periods. Revenue management is universally used sophisticated pricing tools to cope with these fluctuations with likely passenger discontent. Alternatively, cost control is another option by hedging fuel costs and currency rates. Some airlines have increased profits substantially by hedging and others have experienced significant losses while some airlines have abandoned fuel hedging entirely. Adjusting capacity meanwhile seems a better option than the first two. In other words, aircraft size, load and the frequency of flights on a given origin-destination route can be adjusted simultaneously in response to three exogenous factors – passenger demand, fuel cost, and unemployment rate. A study of [40] for seven U.S. domestic carriers, including both low-cost and legacy airlines, over the 2003–2015 period shows that average aircraft size increased by more than 25% and average flight frequency decreased by almost 15% while, the average U.S. load factor climbed between about 15 and 20%.

The profitability change in the global airline industry is studied with a Bayesian approach for 53 airlines in the period 1983–2010 [41]. It is shown that variable costs are increasing at a decreasing rate, and that the average airlines benefits of almost constant returns to scale and increasing return to density. Overall an average 0.7 cost efficiency increasing from the 0.67 of 1983 to the 0.73 of 2010. Additionally, airline efficiency change increases almost constantly over time and productivity change is mainly driven by technical change, becoming positive from early 1990s.

Aircraft types are usually differentiated by fuel efficiency, maintenance costs and in less extent passenger’s preference in cabin configuration. Modular product architecture can be used for the modular organization of the product, product-service, and production system to virtually walk through the partially or fully manufactured aircraft. This approach can record the dynamic requirements of targeted customers and these changes can be carried out in the current version of the aircraft, and also incorporated into future versions [42].

Mergers and acquisitions (M&A) can be a very effective growth strategy in the competitive environments of many aviation markets when the home market experiences slower growth and growth outside is limited by Air Services Agreements. For example, Turkish Airlines cannot obtain additional frequencies in China and India for several decades. In some cases, airlines can be saved from financial default by the takeover of another airline, so even antitrust authorities sometimes agree to mergers although in almost all cases they result in less competition in some markets. Not all M&A are successful because of poor due diligence, clashing company cultures or union resistance. DEA models are applied over 66 airlines to determine efficient airline size; optimal airline size is between 34 and 52 bn ASK (available seat kilometer) capacity and that airlines with more than 200 bn ASK are definitely too large to operate efficiently [43].

2.3 Low Cost Models and Operations

Another prominent example of regulatory change that has promoted growth in the market is the entry of Low Cost Carriers (LCCs) into the market. "The LCC business model would not have flourished without relaxation of government-regulated airline ticket pricing and heavy new market entrant regulation" [23]. LCCs operate through the concept of cost minimization to maximize profitability. Most LCCs operate in the short-haul market, which is defined as "flights that are less than 5 hours" by IATA. Within the industry, however, short haul flights typically range less than 3 hours. Adopting different strategies to the traditional "legacy" or "flag carriers", LCCs have taken to take advantage of cost advantages on short haul flights, using short turnaround times, high utilization of crew and assets, service to lower cost airports and limited in-flight services and entertainment, higher density cabin, lower yield and higher volume and generating additional revenue from services traditionally offered by other airlines within the ticket price. Through these strategies, LCCs have contributed to the growth of the airline market significantly and have become an important method of transportation, accounting for as much as 50% in the South East Asian market and more than 30% and 35% in the North American and European markets respectively [23].

Some of the major airlines responded to the penetration of low-cost carriers (LCC) into the market by establishing ‘‘low-cost, no frills’’ divisions (airlines-within-airlines) or sub-models under the same AOC to seek a competitive advantage against LCCs [44]. These strategies are studied to determine when to retain hub-spoke network or shift to a mixed point-to-point network. Obviously these findings are important to determine what portion of the current fleet can be allocated to new LCC division. Low-cost airlines and conventional-network airlines have distinctly different strategies and network types, which make them able to compete with other airlines in specific markets [45]. Network airlines are relatively strong on long-haul markets, using their networks to keep costs per seat relatively low. Low-cost airlines, with scheduled long haul flights, need to tackle few issues: First, because seating density needs to be high to recover all cost, it may be necessary that larger aircraft are used. If such aircraft (and flight crew) cannot be leased, the single aircraft strategy is no longer applicable. Second, they have to revert to expensive and congested primary airports, if secondary airports cannot handle intercontinental flights. Lastly, a key advantage of low-cost networks, short turnaround times at airports, is more difficult to achieve on long-haul flights due to the necessary time for off-loading luggage, a large number of passengers that are to board the aircraft, aircraft servicing requirements, and cleaning of the cabin.

The airline industry operates in cyclical periods of survival, adaptation, recovery and innovation. For example, following September 11th, 2001, the airline industry was in survival mode with a number of bankruptcies, mergers and acquisitions occurring during this time. In the 2002–2003 period, airlines were forced to adapt to the changing environment and did so through cost reduction, whereby airlines reduced capacity, cut many inflight amenities, downsized management, outsourced non-critical operations and parked older aircraft to save on operating and maintenance expenses. From 2003 to 2005, it was a period of recovery and the airlines turned to focusing on revenue maximization. From 2005 onwards, airlines have continued to innovate and rethink the way they do business [46]. Both network and lowcost carriers have differentiated their business models to capitalize on emerging market trends. Many network carriers have long haul low cost models, such as Lufthansa’s Eurowings, Air Canada’s Rouge and Air France’s Joon.

The successful applications of the low-cost carrier model to long-haul flight operations are still controversial. It really requires through and systematical evaluation of profitability analysis for different operational scenarios and potential revenue sources. The results [47] suggest that it is possible for a network full service airline to establish regular low cost, long-haul operations for suitable trunk routes.

Overall, the findings about characteristics and viability of the long-haul low cost airline business model are still marginal. An attempt is made by clustering a sample of 37 transatlantic airlines in order to evaluate viability of model for cost differences between clusters. Average, 33% lower unit costs compared to legacy hub carriers were identified as a significant character of the long-haul LCC business [48]. In a sequel [49] revenue competitiveness of this model is evaluated with a new metric for bench-marking the revenue per equivalent flight capacity and a revenue model is developed by combining traffic, fare, load factor, and seat data. Not surprisingly, lower direct yields compensated by fewer low-yield connecting passengers and significantly more passengers per aircraft are found as key factors.

The efficiency of 33 Italian airports were studied with two additional factors noise and local air pollution between 2005 and 2008 [50]. First, a directional distance function (DDF) model is used to find airports' efficiency scores and then the factors affecting efficiency were studied. It is found that the fleet mix significantly affects technical/environmental efficiency of airports, public airports have higher efficiency scores and LCCs have no effect on airport efficiency. An empirical model of online airfares is developed to study the impact of the entry of a low-cost carrier (LCC) between the domestic airport-pairs of the largest aviation market in Brazil [51]. The results shows that LCC entry partially spoils the existing market segmentation schemes, forcing them to revise their distribution management strategy, simplify their fare structure and migrate from a non-monotonic to a weakly monotonic price curve.

The model presented in this thesis also allows low cost carriers to implement their fleet plans over the years not only for narrow-body uses of LCC's but also for LCC's that use wide body aircraft. Since LCC's operate with very low profit margins, they need to adopt to changes in the market more dynamically.

CHAPTER 3

FLEET PLANNING: EXPANSION AND REPLACEMENT

The purpose of this thesis is to determine an optimum replacement policy for different business models considering both ownership cost of aircraft and cost of operation, such as fuel, crew and maintenance. Airlines buy aircraft from manufacturers directly and usually in large quantities to increase the capacity for growth or maintain the capacity for replacement. Lessor firms buy aircraft from manufacturers usually as launch customers and enjoy highly reduced prices or buy aircraft to expand their assets regularly, which they lease to airlines.

Obviously, for an airline, buying aircraft from the manufacturers costs less in terms of the ownership cost and they finance this purchase through banks or lessers. As the aircraft is purchased from the manufacturer directly, the ownership cost is still less that directly leasing from lessers. However, manufacturers usually have very large backlogs with a usual production rate of about 100 aircraft per year. Considering that there are currently around 4620 wide body aircraft in the world, the fact that this number is expected to reach around 8590 aircraft, according to Boeing's estimates, indicates that the demand owning a new A/C from the new generation (NG) of aircraft is high.

Operation-wise, the operational cost of new generation A/C are around 15% less than current generation (CG) 2 engine aircraft. When you consider a Boeing 777 going from Istanbul to Los Angeles burning 100 tons of jet fuel one way, a 15% fuel efficiency on a one way trip means a fuel saving of $15,000 one way and $30,000 on a round trip. If this aircraft makes 20 trips per month, this results in a saving of $600,000 per month per aircraft.

Current lease rates average at around 1% of the purchase price of an aircraft; thus leasing an aircraft costs at least $1.6-1.7 million per month. There are also maintenance reserves paid to the lessors, which are nearly half of the lease rates and although this money is eventually used for the maintenance, there is a loss on the interest as this money is given to the lesser and cannot be used by the airline.

Keeping current aircraft in the fleet also has advantages to the airline. An aircraft purchased at around $160 million is depreciated in 15-20 years. Thus, the ownership cost of keeping this aircraft for the next 10-15 years is very little. However, the recurrent and non-recurrent maintenance costs in the bi-annual C Checks, 8-year heavy S checks and 4-year engine overhauls increase drastically as the aircraft gets older. Although these costs will also be present for new generation aircraft, the expectation is that both the maintenance costs and their increases will be lower.

Thus, the airline needs to determine when to replace an existing current generation aircraft with a new generation aircraft. The industrial practice will be discussed for different fleet planning models and any available fleet removal plans as well as for individual aspects of specific model, such as maintenance cost determination, operating cost determination, and non-routine maintenance prediction.

The methods employed by LCC (Low Cost Carriers) are discussed first here which use mostly narrow bodies from a same family type.

3.1 Short-term Use of Aircraft

Before introducing specific models, we will discuss some of the basic concepts which define the life cycles of narrow bodies in LCC airlines. Some airlines order a significant number of aircraft in order to negotiate and receive discounts due to the sheer volume of their orders. After a couple of years of operating the aircraft, the airline then sells the aircraft to another operator or conducts sale and leaseback of the aircraft with an aircraft lessor. Since the aircraft are still young, the salvage value in either approach is quite high.

This short term use approach has been adopted by a few operators with large fleets such as Ryanair, Spirit, easyJet, IndiGo Airlines and Lion Air. Obviously, a large fleet is a must for this strategy as it allows the operator market position to negotiate their ownership costs while keeping operating costs low due to the young age of aircraft. Another major requirement is a good source of finance. Most legacy and flag carriers do not employ this strategy.

3.2 Long-term Use of New Aircraft

This approach is what most legacy and flag carriers use: acquire new aircraft from the manufacturer and utilize them for as long as possible, whereafter they are retired and either salvaged (sold or scrapped) or returned to the lessor (in the case of a leased aircraft). Most LCC's do not employ this strategy, though there are exceptions. An example from the LCC market would most likely be Southwest, though there are some others that employ a mix of these two strategies to varying extents.

3.3 Importance of Financial Resources

Low-cost carriers that are subsidiaries of other major airlines or government owned or set up by large firms often have substantial finances available to purchase new aircraft. Thus, they have the flexibility of being able to place large firm orders and get discounts or to cover the lease rates while providing the collateral needed by the lessor.

The leading low-cost airlines with enough funds to cover the acquisition costs of newly built aircraft mostly are using their aircraft for a few years before selling them again given they originally got major discounts by the manufacturers. This allows them to operate at the lowest possible operating costs [52].

New aircraft have lower operating costs, provided the aircraft has a high average daily utilization and the airline/route has the demand to meet the capacity being provided. The market location is a crucial factor, however. In India and other Asian countries, a lot of LCCs are operating with brand-new aircraft with long average sector lengths. New market entries can only compete with the other carriers if they are using new aircraft as well. As a result, nearly all new and existing budget airlines have very young aircraft in this region. It is estimated that Ryanair is acquiring their Boeing B737-800 aircraft for half of the list price, meaning that the carrier is just paying around $42 million USD for a new airplane [52].

A 2005-built Boeing 737-800 has a value of $26 million USD today – a value loss of $16 million USD over eight years or $2 million USD per year. A carrier using the aircraft for the next couple of years has to cover a value loss of $10.5 million USD for seven years – a value loss of $1.5 million USD per year. In result, a carrier using a second-hand Boeing B737-800 has to pay three quarters of the cost Ryanair has for an aircraft that is eight years older with significantly higher maintenance and operational costs [52].

Also, leasing of second-hand planes does not reduce the costs of ownership. The annual average leasing costs of a 1998-built Boeing B737-800 is $2.3 million USD. Spirit is currently operating an all-leased fleet. In 2012 the airline paid almost $150 million USD for its fleet. In December the fleet consisted of 27 Airbus A319s (6.3 years average age), 16 Airbus A320s (1.4years average age) and 2 Airbus A321s (7.4 years average age). In total the airline paid between $3.5 and $4.0million USD per aircraft. All in all this is a real advantage for Ryanair and other low-cost carriers that have the possibility to follow their fleet strategy [52].

3.4 Operating Strategies

When multiple carriers are operating in the same market, it is very hard to survive with an aging fleet. Smaller LCCs focus on higher utilizations of aircraft, which mean higher operating costs. Bearing in mind the low profit margins of the airline market, if all other factors are equal, it will be very hard for a carrier with an aging fleet to fly in competition with airlines with new fleets due to their lower operating costs.

Larger LCCs and large legacy carriers, due to their use of large networks with connections through multiple hubs, often have lower fleet utilizations and thus using a younger fleet is not as efficient. Large legacy carriers often buy new aircraft and use them for a long time, often on longer routes where fuel costs compose a larger portion of operating costs. Although legacy carriers due place major aircraft orders with significant discounts from manufacturers, they generally do not plan to resell these after a couple of years to create additional revenue.

Nearly all major budget carriers are operating with new aircraft. Exceptions are selected leisure airlines and also Southwest, which in part is very akin to a legacy carrier as far as its fleet strategy is concerned.

3.5 Engine Factor

Another important factor to define the best life cycle of the aircraft is engine condition. There are two engine choices of the A320 families. For V2500 model engine their first big overhaul occur 10-12000 cycle and or 23000 hours on the average. LLC airlines usually perform 4000 hours per year with the ratio of 1:2. Thus, after 5.5 - 6 years their first overhaul requirement occur. Thus, to avoid 4-5 million dollars cost per engine it is better to sell the aircraft before the overhaul. Meanwhile, the engine must be in a condition that the new owner should be able to use the engine at least a year. Thus, just considering engine wise, the aircraft should be sold 4.5-5 years after usage.

Meanwhile, B737-800 aircraft uses CFM56-7B models engines which enter the first overhaul on the average 30-35000 hours and 16-18000 cycles. Again assuming that yearly 4000 hours with 1:2 rate performance, the first overhaul will appear after 7.5-8 years. Selling the aircraft with at least one year engine life time, the appropriate life cycle is 6.5-7 years.

Now let us consider the major airframe maintenance events, namely the C checks and S checks. For the A320 family of aircraft, costly checks are the structural and periodical cards which happen after 6 years. Combining this and the engine overhaul due date after C3 checks average 5.5 years (22500 FH) seems best replacement period. Additionally, the components become more costly after 4-5 years, 5.5 years again seems to be best period. Also in the interval between C3 and S1 checks, the period is small and this may affect the resale value of the aircraft adversely, performing C3 little early and selling the aircraft around 5 years may be better.

On the B737NG aircraft, structural checks and big cards start from 8-7.5 years, corresponding C4 checks. Thus, after C3 checks around 5.5 years, these models seem to be also more appropriate.

3.6 Ownership Cost

Aircraft values change with aircraft age, specification and physical condition of aircraft. Also, market availability and aircraft demand in a certain period affects aircraft market values. In addition to these factors, economical performance of competitors of specific type of aircraft has an impact on the aircraft market price.

When the aircraft specification, age and physical condition are assumed same, other impacts on the aircraft ownership cost can be determined. Due to this reason, Aircraft Value Reference (AVR) [53] is used to determine the impact of market demand and competition in economic performance on the aircraft market value as the aircraft which has same age and specification is chosen in this study.

Airbus and Boeing has several type of narrow body aircraft and most demanded models of both manufacturers are B737-800 for Boeing and A321-200 for Airbus. Because of this, these aircraft are chosen for the analysis. For 12 years old aircraft, decline in aircraft values in respect of new aircraft is examined from 14 AVRs catalogue ranging 2008 first half to 2014 second half. The result of this study is shown below figure.

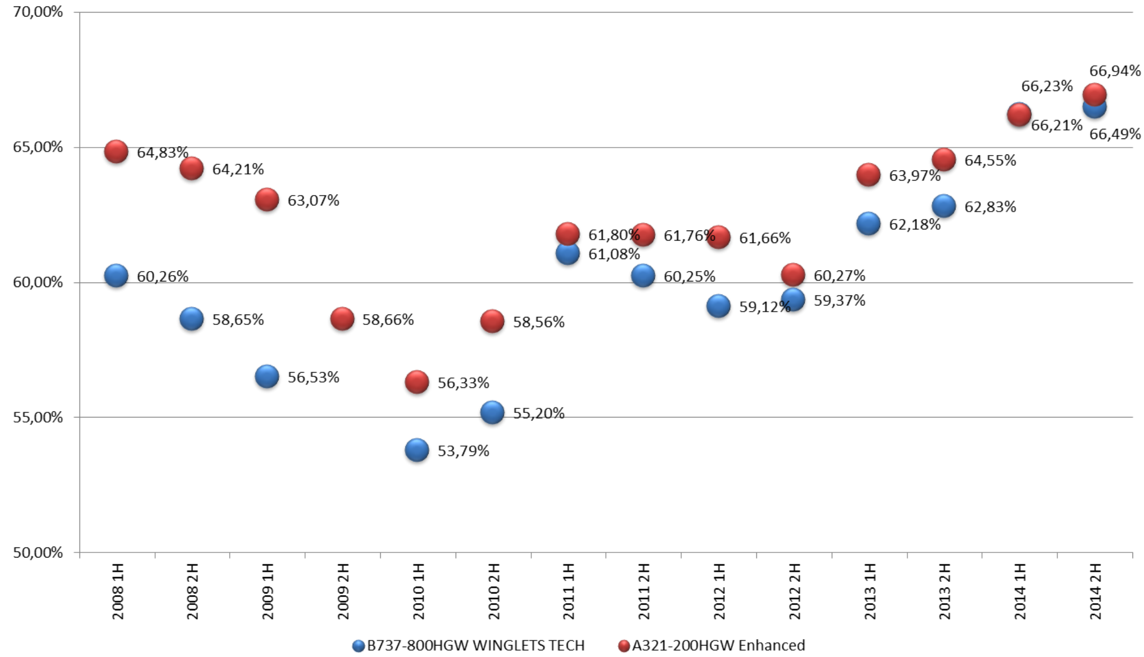

Figure 3.1 Decline in Aircraft Values after 12 Years

As shown in Figure 3.1, decline in aircraft values changes from year to year. In 2nd half of 2009 and 1st half of 2010, decline was very high level because economic crisis occurred in this period and it affects the aircraft demand. After 2010, decline in both type was close and in 2014 it was nearly same.

In addition to this data, Figures 3.2 and 3.3 below show the aircraft value decline in respect of age for different years and table shows aircraft values in respect of age. Both of these narrow-body aircraft types are highly popular in the market. However, it can be seen that the A321 has a higher depreciation rate than the B737-800. This is due to the fact that the A321 has a higher capacity seat capacity and thus limits the usage of the aircraft among LCC’s and airlines.

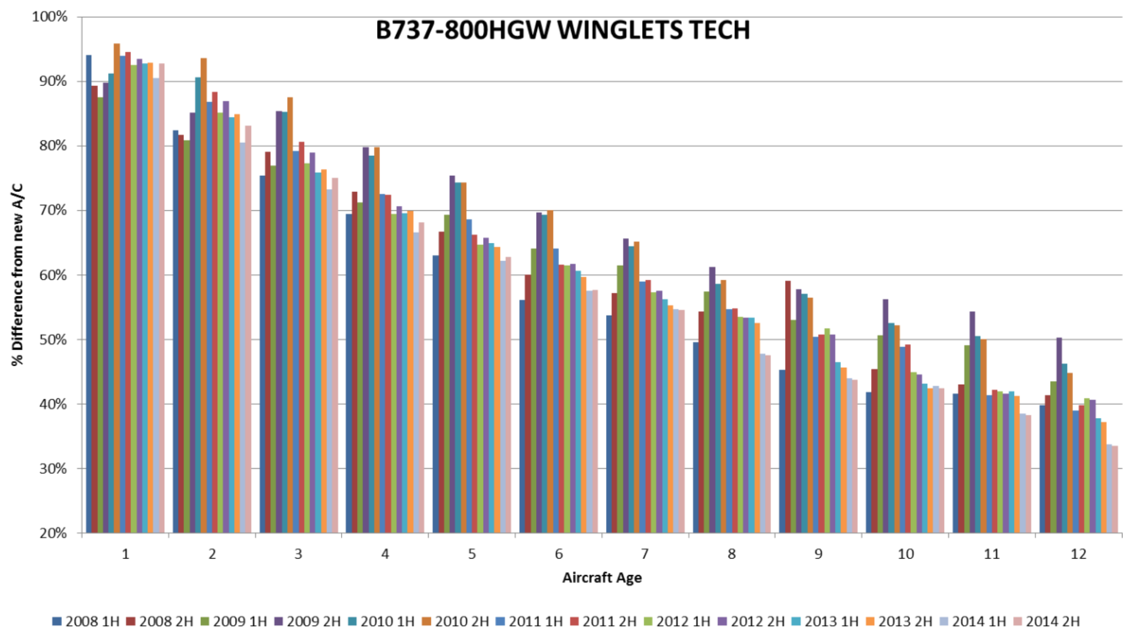

Figure 3.2 Aircraft Value Decline in Respect to Age for B737-800

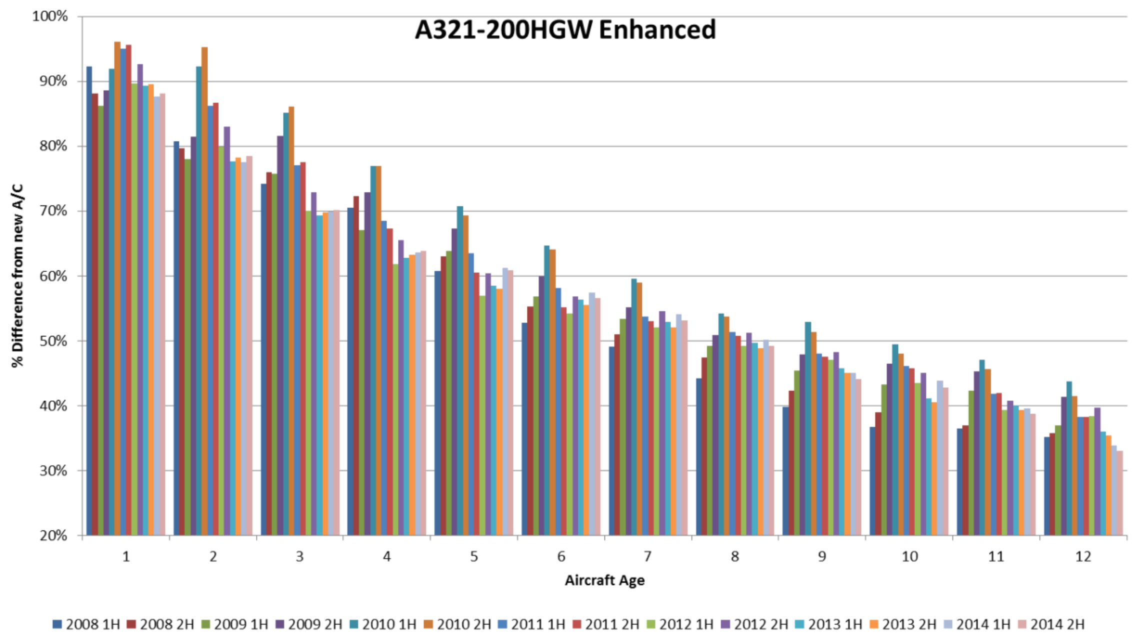

Figure 3.3 Aircraft Value Decline in Respect tof Age for A321-200

The tables below contain the estimated data for the value of B737-800 and A321-200 aircraft that forms the basis of Figures 3.1 and 3.2. The values presented in the tables are in million US dollars.

Table 3.1 Aircraft values for B737-800 aircraft

	B737-800HGW WINGLETS TECH VALUES (Million USD) OVER TIME												
	current	1	2	3	4	5	6	7	8	9	10	11	12
2008 1H	53.37	50.18	43.95	43.22	37.03	33.6	29.94	28.69	26.43	24.18	22.29	22.2	21.21
2008 2H	50.71	45.3	41.45	40.11	36.96	33.82	30.45	29.1	27.53	29.94	23.01	21.79	20.97
2009 1H	46.97	41.1	37.96	36.13	33.46	32.54	30.07	28.85	26.94	24.9	23.77	23.03	20.42
2009 2H	44.64	40.06	38.03	38.13	35.62	33.66	31.1	29.29	27.35	25.79	25.1	24.23	22.42
2010 1H	44.69	40.78	40.52	38.1	35.07	33.21	30.99	28.78	26.17	25.48	23.5	22.55	20.65
2010 2H	44.46	42.62	41.61	38.92	35.49	33.02	31.15	28.94	26.33	25.1	23.21	22.26	19.92
2011 1H	45.01	42.27	39.09	35.63	32.66	30.86	28.84	26.56	24.59	22.69	21.98	18.61	17.52
2011 2H	45.01	42.54	39.76	36.3	32.6	29.81	27.73	26.63	24.68	22.83	22.16	19.01	17.89
2012 1H	45.79	42.34	38.96	35.37	31.79	29.6	28.13	26.22	24.49	23.66	20.54	19.19	18.72
2012 2H	45.9	42.91	39.9	36.22	32.4	30.18	28.33	26.4	24.48	23.3	20.46	19.11	18.65
2013 1H	46.35	42.99	39.11	35.14	32.21	30.06	28.09	26.08	24.76	21.52	20.01	19.45	17.53
2013 2H	46.57	43.26	39.55	35.53	32.57	29.93	27.79	25.75	24.44	21.24	19.76	19.2	17.31
2014 1H	47.8	43.26	38.5	35.03	31.83	29.7	27.49	26.15	22.81	21.01	20.44	18.42	16.14
2014 2H	47.78	44.34	39.71	35.85	32.55	30	27.53	26.09	22.71	20.88	20.27	18.27	16.01

Table 3.2 Aircraft values for A321-200 aircraft

	A321-200HGW ENHANCED VALUES (Million USD) OVER TIME												
	current	1	2	3	4	5	6	7	8	9	10	11	12
2008 1H	55.1	50.87	44.5	40.85	38.83	33.5	29.09	27.03	24.33	21.96	20.22	20.12	19.38
2008 2H	52.53	46.29	41.85	39.92	37.97	33.08	29.05	26.8	24.89	22.24	20.49	19.38	18.8
2009 1H	47.04	40.58	36.68	35.65	31.53	30.02	26.73	25.09	23.14	21.35	20.35	19.88	17.37
2009 2H	45.02	39.88	36.67	36.74	32.81	30.29	26.98	24.82	22.89	21.54	20.94	20.37	18.61
2010 1H	45.98	42.28	42.42	39.17	35.36	32.5	29.73	27.36	24.94	24.32	22.72	21.63	20.08
2010 2H	45.73	43.95	43.56	39.37	35.17	31.68	29.3	26.97	24.58	23.47	21.97	20.89	18.95
2011 1H	46.23	43.93	39.87	35.64	31.65	29.34	26.88	24.81	23.75	22.19	21.34	19.34	17.66
2011 2H	46.57	44.5	40.38	36.13	31.36	28.18	25.67	24.7	23.66	22.15	21.32	19.52	17.81
2012 1H	47.05	42.16	37.58	32.97	29.1	26.8	25.48	24.5	23.14	22.15	20.46	18.48	18.04
2012 2H	47.07	43.61	39.09	34.31	30.86	28.44	26.72	25.7	24.11	22.73	21.2	19.16	18.7
2013 1H	47.57	42.51	36.93	32.95	29.86	27.84	26.8	25.14	23.62	21.78	19.58	19.02	17.14
2013 2H	48.07	43.02	37.58	33.53	30.38	27.9	26.7	25	23.48	21.66	19.46	18.91	17.04
2014 1H	49.07	42.99	38.06	34.28	31.19	30.05	28.16	26.55	24.62	22.07	21.49	19.4	16.58
2014 2H	49.45	43.56	38.82	34.70	31.56	30.09	27.97	26.28	24.337	21.78	21.178	19.126	16.35

3.7 Maintenance Cost

After the ownership costs, another important parameter for airline is maintenance cost of the fleet. Since almost all LLCs are using either A321 and or B737-800 aircraft, we will focus on these types. Each one has its own maintenance program and slightly differs from each other. Below table shows the maintenance intervals for both types.

Table 3.3 Maintenance intervals for B737-800 aircraft

B737-800	
maintenance	interval
A check	1000 FH
B check	4000 cycle
C check	7500 FH (or 730 days) whichever comes first
S check	8-10-12 years

Table 3.4 Maintenance intervals for A321-200 aircraft

A321-200	
maintenance	interval
A check	750 FH (or 120 days) whichever comes first
B check	6000 FH (or 600 days) whichever comes first
C check	7500 FH (or 730 days) whichever comes first
S check	6 years

The maintenance cost depends on the environment that the aircraft are used, i.e., harsh and hot country takeoffs will deteriorate the engines more. Average 1,000 USD can be assumed for B737-800s and around 1,100 USD for A321-200s. Also a fair industry assumption for 12 year total maintenance cost is 40 MUSD for B737-800 and 50 MUSD for A321-200.

Thus, the airline needs to determine when to replace an existing current generation aircraft with a new generation aircraft. The industrial practice will be discussed for different fleet planning models and any available fleet removal plans as well as for individual aspects of specific model, such as maintenance cost and operating cost determination.

3.8 Aircraft Financing

A very important strategic decision is how to finance aircrafts purchased from manufacturer. After signing deals with the manufacturers such as Boeing or Airbus, certain percentage of the list price of aircraft is deposited into manufacturers account. Until the actual delivery of the aircraft, airlines continue to pay certain percentages in a fixed intervals. These are called Pre Delivery Payments (PDP) and they depend on the purchased contract terms, varying between 10-30 % of the list price of the aircraft.

Way before the delivery of the aircraft, airlines open tenders for financing this aircraft to be delivered from manufacturer. Usually, funds such as investor funds, pension funds or banks are interested to finance this aircraft. At the delivery, they pay the actual delivery price of the aircraft to the manufacturer and lease this aircraft back to airline for 10-12 year period. At the delivery manufacturer pay back all the PDP collected for this aircraft to airline, usually without any interest payment. Lease amount per month is the result of the tender. At the end of the lease period airline keep the aircraft and it becomes airlines asset. This type of leasing is called finance lease.

Strategically, airlines may prefer not to keep the aircraft at the end of the lease term. Usually, lessors are interested in this type of lease. All the above steps are also applicable here except at the end of the period, lessor takes back the aircraft and it becomes its asset. This type of leasing is called operational lease. Here the issue is the delivery conditions of the aircraft. Since the lessor will lease the aircraft to some other airline, they would like the aircraft is in marketable condition such that the airline puts the aircraft into service without much maintenance.

Contrary to the expectation, operational leases are not cheaper than financial leases. However, airlines may opt for an operational lease if they anticipate that the residual value of the aircraft is not worth keeping it in its asset book. Extensive amount of work has been done for aircraft leasing decision such as [54], [55], [57], and [57]. Recently, Chen et al in [58] proposed a mathematical model to make decisions about lease and loan terms. What percentage of the aircraft price is paid by airline and how the rest is financed are key decisions at the delivery of the aircraft. If the Airline has good credit and the aircraft is highly preferred one in the market, such as NEO, MAX, B787, A350, the asset could be fully financed such that Airline does not have to share any portion of the purchase price and whole amount is financed. Meanwhile, LCCs usually refrain from high MRO investments such that they do not keep the aircraft in their book long time to avoid heavy maintenance costs. Thus, they prefer operating leases for 8 years until the first heavy check. This way they also optimize the cabin configuration costs. In [58] extensive study has been done for different airline characteristics and different leasing options.

CHAPTER 4

PROPOSED MODEL

Using the integer linear model developed by [6], a new model is designed to address the issues that are sometimes over simplified and sometimes unnecessarily complicated the problem. Brief explanation of the existing model is as follows: The objective function minimizes the total cost over the planning horizon taking into account the total purchasing, leasing, operation and maintenance costs, revenue from selling off of owned aircraft, and the savings from keeping an existing aircraft type in the fleet (spare part availability, crew training, hangars, etc.). Constraints for meeting demand each year, maintaining balance on the number of new and old aircraft that are both purchased and leased, cost of keeping an aircraft of a type in the fleet, limiting the number of salvaged aircraft to the total in the fleet, budget limits, aircraft purchase or lease limits, and integer and binary status are also present in the model.

4.1 Critiques of the Existing Model

MBH [6] ignores several key aspects practiced in reality, which makes the results of it impractical to be used directly. They are as follows:

1) Purchase: airlines almost always buy new aircraft from the manufacturer; the model allows for the purchase of used aircraft which is not realistic because of lack of availability. Thus the model unnecessarily introduces variables that will not take any value or which cannot be applied by the airline.

2) Lease: Aircraft are leased from lessors most of the time at various ages at most one year before introduction into the fleet. This model assumes that there is a differing lag period between the initiation of the lease and introduction of the aircraft into the fleet. However, in reality the maximum lag period between the

signing of a lease and introduction into the fleet is one year under the most extreme circumstances. This is an unnecessary variable in the model.

3) Budget: One of the critical assumptions of the model is the budget constraints, which unnecessarily combines and limits total short haul and long haul aircraft to be added to the fleet for a particular period j. In reality, none of the airlines purchase an aircraft in cash and pay in a lump sum. The usual practice is that a certain percentage of aircraft price is paid in installments until the aircraft is produced and delivered to the airline. At this point, a leasing company or financer, which is determined before the delivery of the aircraft, purchases the aircraft on behalf of the airline and leases it back. The airline is then reimbursed the pre-paid installments from the manufacturer. The leasing term and the leasing rate is determined during the tender process. However, the credibility of the airline usually defines the lease rate. Lease terms are usually 12 years for wide body aircraft and at the end of the lease period, the aircraft becomes the property of the airline. For narrow body aircraft, lessors may tend to propose what is called operational lease for shorter periods such as 6-8 years and at the end of the lease period, the aircraft is re-delivered to the lessor. In summary, the budget assumption of this model unnecessarily combines the decisions for short haul and long haul aircraft.

4) Initial Fleet: MBH [6] assumes that there are no leased aircraft at the beginning of the planning period. In reality airlines will have leased aircraft with different termination period at all times.

5) Wet Lease: Additionally, airlines may wet lease aircraft from other operator. In other words, for period when the airline has excess demand, they may opt to lease one or two aircraft from another operator for a 6 months or a year period on the ACMI (Aircraft, Crew, Maintenance and Insurance) basis. This model ignores this option. The owner of the aircraft (operator in this case) will be bear the cost of lease rate, insurance, cockpit and cabin crew of the aircraft, and all the maintenance cost and in return it will charge the airline a rate based on the operating hours. For example, for a guaranteed block hour of 300 hours per month, it will ask the airline to pay 3000 USD per hour for the ACMI costs. If the airline uses 325 hours for a particular month, the operator will get 325*3000=975.000 USD and if the airline uses the aircraft for example 215

hours then it will pay the minimum guaranteed sum of 300*3000=900.000 USD. Beside this cost airline will pay all the remaining operating costs such as fuel, handling, catering, navigation etc.

Considering all the points discussed above, a model is developed and applied to different business case models.

4.2 Parameters and Decision Variables

To address the issues set forth regarding the existing model, the following mathematical model has been developed.

Parameters:

A Maximum allowable aircraft age

F Number of Fleet Types

T Length of planning horizon

$T2$ Final planning period, T+1 year

mS Minimum allowable salvage age

Lp_o Number of operational lease period for operational lease alternative *o*

La_o Aircraft age for operational lease alternative *o*

D_{ft} Demand of aircraft type *f* in period *t*

LC_{fo} Lease cost of leased aircraft type *f* with operational lease alternative *o*

BC_f Acquisition cost of owned aircraft type *f*

WC_f Annual cost of wet leased aircraft type *f*

SC_{fa} Salvage cost of owned aircraft type *f* with age *a*

OC_{fa} Operating cost of aircraft type *f* with age *a*

$I0_{ft}$ Number of initial aircraft type *f* which will exit at *t*

Index:

f for aircraft type where $(f = 1,...,F)$

a for age of aircraft where $(a = 0,...,A)$,

t for planning period where $(t = 0,...,T)$, 0 is the current year

Decision Variables:

B_{fat} Number of owned aircraft *f* with age *a* in period *t*

NB_{ft} Number of aircraft *f* acquired in period *t*

RB_{fat} Number of owned aircraft *f* with age *a* sold in period *t*

L_{fat} Number of operational leased aircraft *f* with age *a* in period *t*

NL_{fot} Number of aircraft *f* leased in period *t* with option o

W_{ft} Number of wet leased aircraft *f* in period *t*

If the aircraft is sold/parted out, there will be a positive cash flow into the model and thus will be taken out of the cost function. Furthermore, at the end of the planning horizon (T), at time T2, any remaining lease periods will continue on to the next planning horizon and can be taken out of the current model as a positive cash flow (since the airline will not be making lease payments for the remaining lease beyond time T).

4.3 Proposed Model

Binary linear mathematical model is given below with a brief explanation of objective function and constraints.

$$\mathrm{Min} \sum_{f \in F} \sum_{t=1}^{T} BC_f NB_{ft} + \sum_{a \in A} OC_{fa}(B_{fat} + L_{fat}) + \sum_{o \in O} Lp_o LC_{fo} NL_{fot} + WC_f W_{ft} - \sum_{a \in A} SC_{fa} RB_{fat}$$

$$- \sum_{o \in O} \max(0,\ t + Lp_o - T2) LC_{fo} NL_{fot} \qquad (4.1)$$

Subject to:

$$B_{fa1} = 0 \qquad \forall f \in F,\ a = 2....A \qquad (4.2)$$

$$B_{f1t} = NB_{ft} \qquad \forall f \in F,\ t = 1....T \qquad (4.3)$$

$$B_{fat} - B_{fa-1t-1} + RB_{fat} = 0 \qquad \forall f \in F,\ a = 2..A, t = 2....T2 \qquad (4.4)$$

$$L_{fat} - \sum_{o \in O} \sum_{t2 \in 1...T: t-Lp_o < t2 \le t, a = La_o + \max(0, t-t2)} NL_{fot2} = 0 \qquad \forall f \in F,\ a = 1...A, t = 1....T \qquad (4.5)$$

$$\sum_{a \in A} B_{fat} + L_{fat} + W_{ft} + \sum_{t2 \in 1...T: t2 \ge t} I0_{ft2} \ge D_{ft} \qquad \forall f \in F,\ t = 1....T \qquad (4.6)$$

$$RB_{fat} = 0 \qquad \forall f \in F,\ a = 1....mS, t = 1....T \qquad (4.7)$$

$$RB_{fa1} = 0 \qquad \forall f \in F,\ a = 1....A \qquad (4.8)$$

$$RB_{f1T2} = 0 \qquad \forall f \in F \qquad (4.9)$$

$$RB_{fat} \le B_{fa-1t-1} \qquad \forall f \in F,\ a = 2....A, t = 2....T \qquad (4.10)$$

$$B_{faT2} = 0 \qquad \forall f \in F, \;\; a = 1....A \qquad (4.11)$$

$$B_{fat}, L_{fat}, NB_{ft}, NL_{fot}, RB_{fat}, W_{ft} \in Z^{+} \qquad (4.12)$$

The objective function (4.1) can be summarized as the minimum of the total purchase cost + total operational cost of leased and owned aircraft + total lease cost + total wet lease cost – Revenue from sold aircraft (salvage) – payback from lease aircraft at the end of the horizon.

Some of the constraints to note are:

Eq (4.2) No purchased aircraft enters at the beginning;

Eq (4.3) Purchased aircraft comes 1 year after order;

Eq (4.4) Owned aircraft is made of purchased last year minus the number sold this year;

Eq (4.5) Leased aircraft this year at age a is sum of leased A/C in previous years until age a;

Eq (4.6) All aircraft in fleet must meet the demand.

The rest of the equations are for initial conditions and integer requirements of the variables.

4.4 Testing the Model

We assume two types of narrow body aircraft Boeing B737-800 and Embraer E-190 with the following industrial data for testing the model:

Monthly Lease Rates:

For B737-800: $275K for 6 year, $255K for 8 year and $205K for 12 year old

For E-190: $168K for 6 year, $145K for 8 year and $91K for 12 year old

Purchase Price: $46M for B737-800 and $29M for E-190

Wet Lease Cost (per operational hour): $2,545 for B737-800 and $2,100 for E-190

Salvage Cost: Around 3% depreciation for Boeing, 4-5% for Embraer, Blue book prices for estimates are used and presented in Table 4.1.

Initial Conditions:

- *T*=24, *T2*=25 (end of horizon)
- *A*=24 (max age), mS=12 (consider salvage after 12 years)

- F={B737-800,E190}
- Lp_o=6 years lease term fixed for all aircraft from lessor
- La_o=6, 8, 12 (age of aircraft considered for lease)
- BC_f= purchase price ($46M B737-800, $29M E190)
- WC_f= ACMI yearly cost ($17.9M B737-800; $18.6M E190)
- LC_{fo}= lease cost B737-800 $3.3M (6 year old), 3.06M 8 yr, 2.46M 12 yr; E190 2.017M 6 yr, 1.738M 8yr, 1.096M 12 yr
- OC_{fa}=$9.81M for years 1-7, $10.9M for years 8-12, $11.99M 13-16, $13.18M 17-20, $14.508M 21-24 for B737-800; $8.731M for years 1-7, $9.7M for years 8-12, $10.67M 13-16, $11.738M 17-20, $12.918M 21-24 for E190
- IO_{ft}= No of leased aircraft to leave in period t from type f
  - B737-800: 2 in 2,5,9; 1 in 3,4; 6 in 6 and 8; E190: none
- B_{fat}= No of owned aircraft age a type f in period t
- RB_{fat}= No of aircraft to be sold from B737-800 and for E190

The salvage values of two types of aircraft (B737-800 and E 190) which are used in the model, are provided in Table 4.1 below.

Table 4.1 Salvage cost (USD) from type f at age a

Age	B737-800	E 190
1	45601000	30086000
2	42041000	26680000
3	38971000	24099000
4	36344000	22158000
5	34516000	21634000
6	33752000	20851000
7	30234000	19798000
8	28628000	18171000
9	28352000	17933000
10	26196000	16542000
11	23636000	14494000
12	21619000	13209000

Table 4.1 (cont'd) Salvage cost (USD) from type f at age a

13	19744000	11985000
14	17147000	10330000
15	15105000	9426000
16	13200000	8430000
17	12009000	7849000
18	10993000	7134000
19	9433000	6734000
20	9165000	6502000
21	9000000	6404179
22	8900000	6108853
23	8700000	5841699
24	8600000	5597806

Demand:

Table 4.2 presents the number of aircraft needed from each type at each period that is usually obtained from Network and Production Planning Department of an airline based on passenger demand on various routes. Demand increase is estimated by using previous years progress data as well as market demand increase data. As can be seen, B737-800 from 25 aircraft from period 1 to 135 aircraft in period 24 whereas E190 has a much lower demand and demand increase over the planning horizon.

Table 4.2 Demand (number of aircraft) from type f at period t

Period	**B737-800**	**E 190**
1	25	3
2	30	3
3	35	3
4	35	5
5	40	5
6	45	5
7	50	5
8	55	5
9	60	6
10	65	6

Table 4.2 (cont'd) Demand (number of aircraft) from type f at period t

11	70	6
12	75	6
13	80	6
14	85	6
15	90	6
16	95	6
17	100	8
18	105	8
19	110	8
20	115	8
21	120	8
22	125	8
23	130	8
24	135	8

Problem Size:

Variables:

- B_{fat}, L_{fat}, RB_{fat}: 2x24x25 = 1200 (3600 total)
- NB_{ft}, W_{ft}: 2x24= 48 (96 total)
- NL_{fot}: 2x3x24 = 144

Total No of Variables = 3840

Constraints:

- Eq (4.2): 2x23 =46
- Eq (4.3): 2x24=48
- Eq (4.4): 2x23x24=1104
- Eq (4.5): 2x24x24=1152
- Eq (4.6): 2x24=48
- Eq (4.7): 2x12x24=576
- Eq (4.8): 2x24=48
- Eq (4.9): 2

- Eq (4.10): 2x23x23 = 1058
- Eq (4.11): 2x24 = 48

Total No of Constraints = 4130

Solution:

Running the model with the sample data using CPLEX with IBM-ilog as the interface provided the following results in an optimum solution. The details of the aircraft purchased in the optimum solution are presented in Table 4.3 below.

Table 4.3 Number of purchased aircraft from type f at period t.

Period	**B737-800**	**E 190**
1	0	3
2	0	0
3	7	0
4	0	2
5	6	0
6	7	0
7	16	0
8	10	0
9	11	1
10	8	0
11	10	0
12	0	0
13	0	3
14	0	0
15	0	0
16	0	2
17	0	2
18	0	0
19	0	0
20	0	0
21	0	1
22	0	0
23	0	0
24	0	0

Besides these purchases, the model also leases aircraft but only from the B737-800 type. The lease periods and other data are provided in Table 4.4 below. As can be seen in the table, the model favors leasing 6 year old aircraft for the lease period duration as opposed to the others due to the lower operating cost associated with the other aircraft. Furthermore, the model favors buying the E190 to meet demand and then selling when no longer needed due to the higher lease rates and better salvage value of aircraft at earlier stages of this aircraft's life cycle.

Furthermore, it is interesting to note that the model does not wet lease any aircraft. This is most likely due to the high cost of wet lease as opposed to leasing.

Table 4.4 Number of leased aircraft from type f at period t

Period	**B737-800**		**E 190**	
	NL	Na	NL	Na
1	0	6	0	-
2	0	6	0	-
3	7	6	0	-
4	0	6	0	-
5	6	6	0	-
6	7	6	0	-
7	16	6	0	-
8	10	6	0	-
9	11	6	0	-
10	8	6	0	-
11	10	6	0	-
12	0	6	0	-
13	0	6	0	-
14	0	6	0	-
15	0	6	0	-
16	0	6	0	-
17	0	6	0	-

Table 4.4 (cont'd) Number of leased aircraft from type f at period t

18	0	6	0	-
19	0	6	0	-
20	0	6	0	-
21	0	6	0	-
22	0	6	0	-
23	0	6	0	-
24	0	6	0	-

CHAPTER 5

APPLICATIONS TO DIFFERENT BUSINESS MODELS

The integer linear model developed is a generic and very adaptive one that can be applied to different scenarios and business models. In this section, we will take on different airline business models, such as single type narrow body usage as in the case of many low cost carriers and wide-body new generation aircraft selection for a network full service carrier. In the case of the LCC, by keeping some of the simplifications such as single type aircraft and no wet lease option, an approach that is typical of most Low Cost Carrier operations to reduce costs through fleet standardization (mostly maintenance costs but also affects parts supply and purchase costs) is achieved. We then introduce wet lease to see if there is any difference in the optimum result. Finally, we apply the model to the problem of selecting wide-body aircraft of a network carrier to see if new generation aircraft will be preferred over existing models as hypothesized in this thesis.

5.1 Application in the LCC Environment

In the case of the LCC in question, only one type of aircraft was used in the fleet. This is in accordance with what is expected as is typical in this business segment. The model is to consider two options for delivery: buy (purchase) or lease (operational). It is known that the cost function will be comprised of the either the purchase (BC) cost or the lease cost (LC) and the operational (OC_a) costs for operating the aircraft. For the purposes of this model, OC is taken as a total of costs including the fuel, crew and maintenance costs of operating the aircraft for 1 year. These data are easily accessible from the LCC's operational records.

If the aircraft is sold/parted out, there will be a positive cash flow into the model and thus will be taken out of the cost function. Furthermore, at the end of the planning horizon (T), at time T2, any remaining lease periods will continue on to the next planning horizon and can be taken out of the current model as a positive cash flow (since the airline will not be making lease payments for the remaining lease beyond time T).

5.2 Assumptions for LCC Model

Aircraft considered for purchase can be only a new aircraft. Although some operators buy second-hand aircrafts, this is region specific and also usually not preferred by LCCs. The purchase cost (BC) is taken as the most recent price offers from the manufacturer of the selected aircraft type by the LCC. This is the same assumption as in the previous model.

Aircraft considered for lease are taken as being at a quarter of their typical operational age of 24 years (Jiang [17]), i.e. 6 years of age. We also consider an aircraft at 8 years of age as well as an aircraft that is at the maximum age of aircraft allowed in the fleet (A).

Operational lease periods (LP) is taken as 6 years and the age of aircraft considered for lease (La) is 6, 8 and 12 year old aircraft; typically lease periods for newer aircraft are 8 or 12 years [18]. The lease cost (LCa) is a function of aircraft age and is available through analyzing past data of the lease offerings to the LCC.

As the LCC is currently in operation, there will be aircraft currently in their fleet and also aircraft incoming from previous commitments and lease agreements made. The time these will leave the fleet are represented by IO_{T2} as before. The values of IO_{T2} are also the same as before.

Demand (Dt) is forecasted over the planning horizon by the LCC’s network planning and scheduling department's activities and is assumed to be an accurate forecast (as when compared to the industry estimates of the manufacturers as well as air transport associations).

Salvage is considered only after half of the serviceable life of the aircraft has been accomplished (mS=12). The salvage/sale cost is provided by the LCC and is available through past data on aircraft sales accomplished.

Figure 5.1 is the graph of operational cost vs salvage cost over the life of the aircraft. As is expected, as the aircraft ages, the salvage value decreases while operational cost increases.

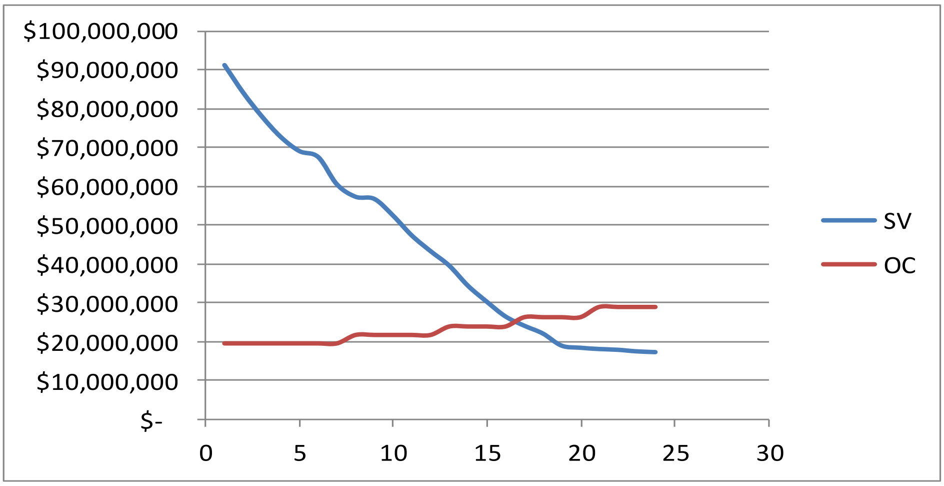

Figure 5.1 Salvage Value vs Operating Cost over the planning horizon

5.3 Adaptations in the Mathematical Model for LCC's

The most noticeable changes are the exclusion of the wet lease option and a single fleet type considered. Using the above, the below model to represent the fleet management problem was developed.

$$\mathrm{Min}\sum_{t=1}^{T} BC\ NB_t + \sum_{a\in A} OC_a (B_{at} + L_{at}) + \sum_{o\in O} Lp_o LC_o NL_{ot} - \sum_{a\in A} SC_a RB_{at}$$

$$-\sum_{o\in O} \max(0, t + Lp_o - T2) LC_o NL_{ot} \qquad (5.1)$$

Subject to :

$$B_{a1} = 0 \qquad a = 2....A \qquad (5.2)$$

$$B_{1t} = NB_t \qquad t = 1....T \qquad (5.3)$$

$$B_{at} - B_{a-1t-1} + RB_{at} = 0 \qquad a = 2..A, t = 2....T2 \qquad (5.4)$$

$$L_{at} - \sum_{o\in O} \sum_{t2\in 1...T: t\text{-}Lp_o < t2 \le t, a = La_o + \max(0, t-t2)} NL_{ot2} = 0 \qquad a = 1...A, t = 1....T \qquad (5.5)$$

$$\sum_{a\in A} B_{at} + L_{at} \sum_{t2\in 1...T: t2\ge t} I0_{t2} \ge D_t \qquad t = 1....T \qquad (5.6)$$

$$RB_{at} = 0 \qquad a = 1....mS, t = 1....T \qquad (5.7)$$

$$RB_{a1} = 0 \qquad a = 1....A \qquad (5.8)$$

$$RB_{1T2} = 0 \qquad \forall f \in F \qquad (5.9)$$

$$RB_{at} \le B_{a-1t-1} \qquad a = 2....A, t = 2....T \qquad (5.10)$$

$$B_{faT2} = 0 \qquad a = 1....A \qquad (5.11)$$

$$B_{at}, L_{at}, NB_t, NL_{ot}, RB_{at}, W_t \in Z^+ \qquad (5.12)$$

The constraints are the same as before but with a single A/C type and no wet lease. They can be summarized as follows:

- Purchased aircraft comes 1 year after order;
- No purchased aircraft enters at the beginning of the horizon;
- Owned aircraft this year is made of purchased last year minus the number sold this year;
- Leased aircraft this year at age a is sum of leased A/C in previous years until age a;
- All aircraft in fleet (purchased, leased or what is on hand) must meet the demand;
- No sale of aircraft in the initial year;
- No sale of aircraft until minimum salvage age mS.

5.4 Solutions for LCC Model

IBM-ilog Studio IDE 12.7.1 software with CPLEX optimization engine was used to program the model. The demand data is the same as that in Table 4.2 for the B737-800 type. Additionally, there are 20 aircraft at the beginning. These aircraft will leave the fleet as follows: 2 in period 2, 5, 9; 1 in periods 3 and 4; and 6 in period 6 and 8. Running the model yielded an optimum result with a cost of $22,975,960,000 over the 24 year planning horizon. The model required the acquisition (purchase) of 75 aircraft and lease of 176 aircraft. Table 5.1 shows the number of aircraft purchased and leased throughout the planning horizon.

From the table, it is obvious that the model favors buying over leasing at the beginning of the horizon whereas the opposite is true midway towards the end of the horizon. However, the appearance of a single aircraft being leased in the fifth period is interesting. It can be inferred that the model attempts to employ purchased aircraft to meet a certain portion of long term demand, and lease options to meet the remaining demand that occurs particularly towards the end of the horizon due to the projected growth in the market. In fact, there is not a single aircraft purchase past period eleven, which is the last period where an aircraft was purchased. Furthermore, the large number of leases towards the end of the planning horizon are interesting; at this point, the aircraft purchased during the initial stages are sold and to meet the demand, a large number of aircraft are purchased to meet the demand.

Table 5.1 Aircraft Purchased and Leased over the planning horizon

t	NP	NL	*T*	NP	NL
1	0	5	13	0	5
2	0	5	14	0	5
3	7	0	15	0	5
4	0	1	16	0	5
5	6	0	17	0	5
6	7	0	18	0	5
7	16	0	19	0	10
8	10	0	20	0	10
9	11	0	21	0	16
10	8	0	22	0	17
11	10	0	23	0	62
12	0	0	24	0	20

It is important to note that all aircraft leased are from option 1: an aircraft of age 6 for a 6 period lease. Older aircraft are most likely not favored (8 and 12 years old) due to their higher operating costs. We can infer then that the lower lease cost does not outweigh the higher operating cost and that the difference in operating cost is significant.

Table 5.2 below shows the age of salvaged aircraft and the period of the planning horizon they were salvaged in. The aircraft sold are highlighted for ease of view. We should note that the model reacts well to the salvage function, and actually makes use of purchased aircraft as much as possible. This is mostly seen at the beginning of the planning horizon. Furthermore, the model does not purchase any aircraft past a certain point, most likely due to the fact that the salvage of such aircraft would either need to occur before the minimum salvage age requirement.

The only aircraft that are close to mS are those sold due to the end of the planning horizon (T=24 and 25). This indicates that the purchasing and lease cost of other aircraft outweighed the cost of operating these aircrafts throughout their usable life.

Table 5.2 Salvage occurrence over the planning horizon

		Period T				
		21	22	23	24	25
Age a	1	0	0	0	0	0
	2	0	0	0	0	0
	3	0	0	0	0	0
	4	0	0	0	0	0
	5	0	0	0	0	0
	6	0	0	0	0	0
	7	0	0	0	0	0
	8	0	0	0	0	0
	9	0	0	0	0	0
	10	0	0	0	0	0
	11	0	0	0	0	0
	12	0	0	0	0	0
	13	0	0	0	0	0
	14	0	0	8	10	0
	15	0	0	11	0	0
	16	0	0	10	0	0
	17	6	7	16	0	0
	18	0	0	0	0	0
	19	0	0	0	0	0
	20	0	0	0	0	0
	21	0	0	7	0	0
	22	0	0	0	0	0
	23	0	0	0	0	0
	24	0	0	0	0	0

Furthermore, the large number of leases, especially towards the end of the planning horizon, are most likely the result of allowing the remaining lease payments to be deducted at the end of the lease period from the cost of lease. However, the lease is not being terminated and as the operation of the LCC will continue beyond the planning horizon, coupled with the fact that demand for air travel is expected to healthily and steadily grow in the region that the LCC is currently operating in, this situation is not really an issue.

In fact, it would be interesting to see how the model reacts to having so many leased aircraft at the beginning of the next planning horizon. A dynamic modeling approach may be used to use the results of the initial planning horizon as the inputs (initialization conditions) of the next.

Furthermore, operational leases are not the only type of lease available in the market. Of particular note is the "wet lease", where an aircraft is available with its crew ready to fly, typically for shorter lease durations (3-4 years). The disadvantage of this type of lease particularly for LCC operations is that the cabin is typically not in the LCC standard (high density cabin) and thus, lowers the volume of passengers per flight and the short lease duration does not allow for cost effective modification of the cabin. However, if and when the model is applied for a traditional operator, the wet lease option can easily be incorporated into the model.

Although it is typical for many LCCs to use a single fleet type for cost reduction purposes, using different aircraft for different flights as applicable strengthens the bargaining power of airlines. Therefore, traditional airlines typically have a mix of fleet types. This is also due to the fact that traditional airlines fly long-haul flights as well as short-haul flights, so a single fleet type alone does not meet the demand or cost-minimization requirements. Hence, when considering traditional carriers, additional fleet types will need to be considered.

This application ignores the flexibility in terms of lease options. In practical application, any number of lease periods are possible as this depends on a number of factors such as the period of lease demanded by the airline, the lease period offered by the lessor, the demand in the market (both current and projected) for leased aircraft, conditions of the lease, etc. However, the most commonly seen periods, besides that taken in the model, are 8 and 12 years.

Since the case study was performed with a LCC and the model designed for the specific needs and situation of the LCC, certain restrictions were placed on the lease options. Lease age was one of these restrictions in the model; a 6 year old aircraft is not difficult to find in the lease market and is at a good trade-off point for operational cost vs lease cost. Furthermore, with a lease period of 6 years, the redelivery occurs at the 12 year maintenance check, allowing the heaviest maintenance check to coincide with the redelivery check (which is typically requested by the lessors). However, though it is quite possible to find a 6 year old A/C in the market, an 8 and 12 year old A/C is as, if not more, common due to the fact that these aircraft may be coming out of a lease from an operator that leased the A/C when brand new. The model should therefore be expanded to allow for 8 and 12 year old aircraft to be leased; this will also allow the model to be more flexible so that it can be applied in the case of a regular operator. Therefore, more data are needed to be collected on past availability of different lease options and the current market prices for such options today (as well as current availability).

5.5 Relaxing Lease Restrictions

As mentioned previously, lease periods have an effect on the lease prices. So far, we have only considered lease period options of 6, 8 and 12 years for 6 year old aircraft due to their practical application and commonality as seen in use [13 and 14]. However, in application, any number of lease options for a given age of aircraft should be available for lease.

Using the market values of the leases from industry experts, the lease rates for varying aircraft age (1-12) and lease periods (2-12) were collected. In the model, this is represented by the indices “o” and in this case 132 lease options are available. The full list of lease options can be found in Table A.1 presented in Appendix A.

The rest of the model is the same as mentioned in sections 5.2 and 5.3 in terms of constraints and parameters.

Running this model, we achieve an optimal solution with a cost of $21,714,938,200. Compared to the results in section 5.4, this difference is obviously significant. Table 5.3 below shows the number of aircraft leased, lease option (lo) that the aircraft is leased from and the number purchased over the planning horizon.

Table 5.3 Aircraft Purchased and Leased over the planning horizon

t	NP	NL	*lo*	*T*	NP	NL	*lo*
1	0	5	28	13	0	5	39
2	0	5	28	14	0	5	28
3	0	7	28	15	0	5	28
4	1	0		16	0	5	28
5	11	0		17	0	6	121
6	12	0		18	0	26	121
7	18	0		19	0	27	122
8	5	0		20	0	28	123
9	11	0		21	0	10	124
10	7	0		22	0	16	125
11	5	0		23	0	12	126
12	0	5	61	24	0	10	127

5.6 Comparison with Current Practice

In order to validate the model presented in this thesis and to compare the performance of the solutions provided by the model to the fleet plan and cost thereof in real life, the fleet data of a an airline are obtained for the last 15 years from their annual reports, information which is publicly available. As for the remaining 9 years, the purchase patterns in the last 10 years were repeated to meet demand.

Table 5.4 displays the fleet composition obtained. The cost of the fleet composition in real application was compared to that produced by the model given the same data. The model produced a fleet plan with a cost that was significantly lower than that of the actual, despite acquiring (either through purchasing or leasing) more aircraft over the planning horizon.

Table 5.4 Actual fleet data including past data and future demand predictions

Period	B737-800				E 190			
	P	No	Lp	La	P	No	Lp	La
1						0		
2	1	1	4	4		0		
3	4	12	4	4		0		
4	8	3	4	4		0		
5	1					0		
6	12	1	4	4		0		
7	5					0		
8	3	2	6	1		0		
9	5	6	6	1		3		
10	6	12	6	1		0		
11	6					0		
12	14					2		
13						0		
14		7	6	1		0		
15	10					0		
16	15					0		
17	10					0		
18	10					0		
19	15					0		
20	10					0		
21	10					0		
22	15					0		
23	15					0		
24	10					0		

The difference being significant is indicative of the validity of the model and that the model can improve over the actual real life fleet assignment. Having been validated, the moel can be implemented to the final phase of the thesis.

5.7 Application with Wide Body Aircraft

For a full service network carrier, there are number of different aircraft types. However, there are narrow bodies, such as Airbus series of A320 families with NEO options or Boeing Series of B737 NGs with new generations MAX options. There are also airlines using Embraer series of Bombardier series with less numbers. For wide body aircrafts, here are A330 or new generation A350 families from Airbus and B777 and B787 families from Boeing.

There are also ultra wide body aircrafts A380 and B747-8 with less numbers. In any case, narrow body and wide body aircraft usages are used for specifically short and long distances such that their fleet planning are done separately. Obviously, narrow body aircrafts are used to feed the long range wide body aircrafts in hub and spoke network models. Network planning and consequently, fleet planning are not the subject of this work. We will assume that these are done such that demand as the number of seat for each period is determined earlier.

5.7.1 Data Collection and Preparation

In this part of the thesis, we will consider an existing wide body fleet composed of one type of aircraft. A local carrier has A330-200, A330-300, and B777-300 ERs in its fleet. Alternatively, a new generation wide body aircraft will be considered for the existing fleet. For the real case study, this aircraft is either B787 family or A350 family. Thus, the study will make the tradeoff between leasing or buying from existing type, or buying or leasing from a New Generation type with more efficient fuel consumption.

Below table is developed for A330-200, A330-300, B777-300ER, B787-9, A350-900 aircraft for a destination over 8500 km with Block Hour of 10.1 hours. All the five aircraft is expected to make this trip approximately in similar flying hours. Ownership cost is determined by the monthly the lease cost of the aircraft. Whether it is operational or financial lease they are usually 1 % of the purchase price of the aircraft. However, here industrial expert estimates are used to determine exact ownership costs. Maintenance costs are developed from the manufacturer catalogs.

For this flight, usually 3 pilots and 11-12 cabin attendants are used each way. They sleep one night and the other crew takes back the return flight. In any case, crew cannot fly more than 1000 hours per year, thus 21-24 pilots is need for a year operation for this trip. The other costs are defined from industry standard data for such distance.

Three different fuel prices are used to estimate the fuel costs. 600, 700 and 800 USD per tones are used for jet fuels corresponding to 60, 70 and 80 USD per barrel. The aircraft types are disguised for confidentiality purposes, and indicated here with A/C1…A/C5. Table 5.5 presents one way trip costs for all five different wide body aircraft in terms of USD. From now on we will confine the study for only two of these aircraft, namely A/C3 and A/C4.

This table is prepared by using the available data in literature and industry, such as [14], [18], [53], [59], [14], IATA, Boeing and Airbus sites. Ownership, Maintenance, Crew and Insurance costs are summed to distinguish from wet and dry lease options. Ownership cost is also called Aircraft cost. The first row presents total of Aircraft, Crew, Maintenance and Insurance costs per trip. The second row is the sum of Catering, Handling, Landing and Airport Charges, Gate, Air traffic Corridor, other variable costs and indirect costs.

Table 5.5 Cost breakdowns for 5 different wide body aircraft over 8500 km distance for one way trip

	A/C 1	A/C 2	A/C 3	A/C 4	A/C 5
A.C.M.I	37,700	40,100	56,000	43,750	47,500
All Other Costs without Fuel	39,500	41,300	46,200	42,100	44,000
Total Cost without Fuel	77,200	81,400	102,200	85,850	91,500
Fuel Cost (600 USD/Ton)	38,000	39,500	51,200	39,400	42,200
Total Trip Cost (600 USD/Ton)	**115,200**	**120,900**	**153,400**	**125,250**	**133,700**
Fuel Cost (700 USD/Ton)	44,350	46,100	59,750	45,950	49,250
Total Trip Cost (700 USD/Ton)	**121,550**	**127,500**	**161,950**	**131,800**	**140,750**
Fuel Cost (800 USD/Ton)	50,700	52,650	68,300	52,500	56,250
Total Trip Cost (800 USD/Ton)	**127,900**	**134,050**	**170,500**	**138,350**	**147,750**

For the leased and owned aircraft almost all the above cost items are identical. Only ownership cost differs. In the leased aircraft, monthly leases will be paid to the lessor and owned aircraft case purchase price is paid in the beginning. Although none of the airlines pay this amount from their bank accounts rather they finance it over the years, the issue is finance cost of this amount and is not subject to this thesis and does not affect the analysis at all.

Table 5.6 is prepared for two types of aircraft that under consideration. One of them is the back bone of the existing fleet and there are 32 of them in the fleet. The other is the new generation aircraft with more efficient engine resulting in less fuel consumption. However the existing one is with 350 seat total and the alternative one is with 300 seat total. Additionally, existing has big maintenance check at every 4 years while the new requires this at every 6 years.

Table 5.6 Operating cost per year (x1000USD) for two different wide body aircraft over 3 different fuel price

	Fuel 600 USD/ton		**Fuel 700 USD/ton**		**Fuel 800 USD/ton**	
Year	**A/C1**	**A/C2**	**A/C1**	**A/C2**	**A/C1**	**A/C2**
1	92725.33	75790.06	98957.34	80581.78	105188.62	85373.5
2	92725.33	75790.06	98957.34	80581.78	105188.62	85373.5
3	92725.33	75790.06	98957.34	80581.78	105188.62	85373.5
4	92725.33	75790.06	98957.34	80581.78	105188.62	85373.5
5	95725.33	75790.06	101957.34	80581.78	108188.62	85373.5
6	92725.33	75790.06	98957.34	80581.78	105188.62	85373.5
7	92725.33	79790.06	98957.34	84581.78	105188.62	89373.5
8	92725.33	75790.06	98957.34	80581.78	105188.62	85373.5
9	98725.33	75790.06	104957.34	80581.78	111188.62	85373.5
10	92725.33	75790.06	98957.34	80581.78	105188.62	85373.5
11	92725.33	75790.06	98957.34	80581.78	105188.62	85373.5
12	92725.33	75790.06	98957.34	80581.78	105188.62	85373.5
13	101725.33	83790.06	107957.34	88581.78	114188.62	93373.5
14	92725.33	75790.06	98957.34	80581.78	105188.62	85373.5
15	92725.33	75790.06	98957.34	80581.78	105188.62	85373.5
16	92725.33	75790.06	98957.34	80581.78	105188.62	85373.5
17	104725.33	75790.06	110957.34	80581.78	117188.62	85373.5
18	92725.33	75790.06	98957.34	80581.78	105188.62	85373.5
19	92725.33	87790.06	98957.34	92581.78	105188.62	97373.5
20	92725.33	75790.06	98957.34	80581.78	105188.62	85373.5
21	107725.33	75790.06	113957.34	80581.78	120188.62	85373.5
22	92725.33	75790.06	98957.34	80581.78	105188.62	85373.5
23	92725.33	75790.06	98957.34	80581.78	105188.62	85373.5
24	92725.33	75790.06	98957.34	80581.78	105188.62	85373.5

The engines are maintained by the engine manufacturer by what is called Power by the Hour program. Airline pays every month sum amount based on the total flight hours during this month such that all maintenance required of the subject engine is overhauled by the manufacturer whenever needed. This is a uniform payment over the period. Going back to Table 5.6, the numbers indicate total operating costs of leased or purchased aircraft over 24 year period. For example, operating A/C1 costs 92.725.330

USD per year while maintenance costs increases this value at years 5, 9, 13, 17, 21. Similarly, A/C2 costs 75.790.060 USD per year while maintenance costs increases this value at years 7, 13, 19.

Purchase price of A/C1 is assumed to be 165 M USD and that of A/C2 is 150 M USD by using the average AVR values. Wet lease is a temporary solution for capacity addition for the airlines. Airlines sometime ask carriers to bring their aircraft and operate on their behalf. In this case the crew, maintenance and insurance is covered by the wet lease operator. That is the reason this operation is also called Aircraft Crew Maintenance and Insurance (ACMI) operation. All other costs including fuel are paid by the airline. Since carrier includes higher profit rate, this operation usually costs higher and airline does not prefer wet lease operation. Table 5.7 provides yearly wet lease costs for both aircraft types. Since wet lease operators uniformly distribute the maintenance costs, the annual wet lease operation costs is basically ACMI rate per block hour multiplied by the number of block hour per year. To find the total costs this value is added by the other costs such as fuel, catering and all other costs as given in Table 5.6.

Table 5.7 Wet lease cost per year (x1000USD) for two different wide body aircraft over 3 different fuel price

	Fuel 600 USD/ton		**Fuel 700 USD/ton**		**Fuel 800 USD/ton**	
Year	**A/C1**	**A/C2**	**A/C1**	**A/C2**	**A/C1**	**A/C2**
Fuel other Costs per trip	97412	81494	105948	88058	114485	94622
ACMI Cost per trip	65650	75100	65650	75100	65650	75100
Total Costs per year	119035.3	111101.6	125266.5	115893.3	131498.6	120685.1

Salvage value is the market price of the aircraft. Obviously it depends on the market conditions, aircraft conditions and other factors. However, industry uses AVR value analysis [53] to determine the value of their assets. Here the values are based on the age of the aircraft and aircraft conditions are categorized by three classes, high, average and low. Table 5.8 presents the average values for both aircraft at different ages basing 2018. Every year these numbers are reevaluated and published accordingly.

Lease costs of the aircrafts are the monthly leases paid to the owner of the aircraft. Leasing companies called lessor purchase aircraft from manufacturer in large numbers and lease them to airlines. Usually wide body aircraft are leased for 12 years or longer. Occasionally, they lease for shorter periods such as 8 or 10 years with higher lease rates.

This is basically, they lease aircraft just after the delivery from manufacturer and would like to get back their aircraft fresh from all heavy checks and overhauls. Since the big checks with large bills start from 6 years and onwards, they want their assets amortized and free of big maintenance costs.

Table 5.8 Salvage value (Million USD) for two different wide body aircraft

End Year	A/C 1	A/C 2
1	156.60	143.19
2	143.47	134.83
3	132.33	125.89
4	127.57	109.79
5	115.66	97.66
6	106.84	94.21
7	104.70	84.17
8	96.08	77.33
9	89.99	69.96
10	81.61	63.97
11	76.10	56.99
12	68.59	51.94
13	59.01	46.97
14	53.13	43.27
15	48.83	39.30
16	44.35	36.35
17	40.92	35.20
18	39.62	33.23
19	37.20	31.37
20	35.06	30.76
21	33.16	30.26
22	32.00	30.00
23	31.00	29.80
24	30.00	29.5

Bankrupted airlines return the aircraft to its lessor much earlier than the end of the lease period. Similarly, sometimes lessors seize their asset if the airline is in default. Thus, lessors sometimes find themselves in a position to lease for shorter periods with much higher lease rates. Table 5.9 below and Table 5.10 on the next page are prepared by using the expert knowledge in the industry for yearly lease costs of both aircraft types for different age and for different lease periods.

Table 5.9 Yearly lease costs (Million USD) for A/C1 for different age of the aircraft for different lease periods

	Total Lease Periods										
Age	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
1	24	22.70	21.40	20.10	18.79	18.06	17.33	16.59	15.86	15.13	14.40
2	24	22.30	20.60	18.90	17.22	16.75	16.28	15.82	15.35	14.89	14.40
3	24	21.98	19.95	17.93	15.88	15.63	15.39	15.14	14.89	14.65	14.40
4	18	17.33	16.65	15.98	15.31	15.16	15.01	14.85	14.70	14.55	14.40
5	18	16.97	15.94	14.91	13.88	13.37	12.85	12.34	11.83	11.31	10.80
6	18	16.71	15.41	14.12	12.82	12.48	12.15	11.81	11.47	11.14	10.80
7	15	14.39	13.78	13.17	12.56	12.27	11.98	11.68	11.39	11.10	10.80
8	15	14.13	13.27	12.40	11.53	11.41	11.29	11.16	11.04	10.92	10.80
9	15	13.95	12.90	11.85	10.80	10.33	9.87	9.40	8.93	8.47	8.00
10	12	11.45	10.90	10.35	9.79	9.49	9.19	8.89	8.59	8.29	8.00
11	12	11.28	10.57	9.85	9.13	8.94	8.76	8.57	8.38	8.19	8.00
12	12	11.06	10.12	9.17	8.23	8.19	8.15	8.12	8.08	8.04	8.00

The data in both of these tables will be used in the model as the lease cost data for the two aircraft models in the lease options determination and selection. The periods will form the lease period parameter while the age will form the lease age parameter.

Finally, we require the demand for the wide body aircraft, which is given in terms of the number of available seat over 24 years period. The current number of A/C1 aircraft is known for the airline under study, basically it is 32. The seat count for this aircraft is 350 seats, whereas that of A/C2 is 300 seats.

The airline has had around 10% yearly growth for the past 10 years and thus this growth rate can be used as the assumed projected growth rate. Furthermore, it can also be assumed that this pace will continue for the coming 5 years and will continue with less rate for the following years.

Table 5.11 presents the demand for the number of seats over 24 years based on what was mentioned previously. This data will be used in the model in the demand constraint for the selection of the optimal aircraft to meet the demand.

Table 5.10 Yearly lease costs (Million USD) for A/C2 for different age of the aircraft for different lease periods

	Total Lease Periods										
Age	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
1	22.20	21.10	20.00	18.90	17.18	16.32	15.46	14.59	13.73	12.87	12.00
2	22.20	20.85	19.50	18.15	16.18	15.48	14.79	14.09	13.39	12.70	12.00
3	22.20	20.43	18.66	16.89	15.11	14.59	14.07	13.55	13.03	12.52	12.00
4	15.60	14.99	14.39	13.78	13.17	12.98	12.78	12.59	12.39	12.20	12.00
5	15.60	14.63	13.66	12.69	11.72	11.37	11.01	10.66	10.31	9.95	9.60
6	15.60	14.53	13.45	12.38	11.31	11.02	10.74	10.45	10.17	9.88	9.60
7	12.00	11.52	11.05	10.57	10.10	10.02	9.93	9.85	9.77	9.68	9.60
8	12.00	11.32	10.64	9.96	9.28	8.93	8.59	8.24	7.89	7.55	7.20
9	12.00	11.10	10.20	9.30	9.00	8.70	8.40	8.10	7.80	7.50	7.20
10	9.60	9.38	9.15	8.93	8.70	8.45	8.20	7.95	7.70	7.45	7.20
11	9.60	9.30	9.00	8.70	8.40	8.20	8.00	7.80	7.60	7.40	7.20
12	9.60	9.20	8.80	8.40	8.00	7.87	7.73	7.60	7.47	7.34	7.20

Table 5.11 Wide body demand (number of seat per day) at period t

Year	Demand	Year	Demand	Year	Demand
1	11200	9	22400	17	32200
2	12250	10	23800	18	33250
3	13650	11	25200	19	33950
4	15050	12	26600	20	34650
5	16450	13	28000	21	35350
6	18200	14	29050	22	35700
7	19600	15	30100	23	35700
8	21000	16	31150	24	36050

5.7.2 Formulation

The formulation of the model is exactly the same as in Section 4.3, with the exception of Equation 4.6, which is modified to accommodate the new demand form.

$$Cap_f * \left(\sum_{a \in A} (B_{fat} + L_{fat}) + W_{ft} + \sum_{t2 \in 1..T : t2 \geq t} IO_{ft} \right) \geq D_t \quad (5.13)$$

All other equations remain the same and there is no change to the model parameters, decision variables or constraints.

5.7.3 Computational Results

The model is run with the following purchase price $165M for the A/C 1 and $150 M for the A/C 2 types. There are 30 aircraft already in the fleet of aircraft type A/C 1 and 3 of which are operational leases and leave at the end of period 2. Additionally, we have 8 aircraft at age 2, 7 at age 4, 6 aircraft at age 5 and 6 each, all of which will leave the fleet at the age of 12 from aircraft type A/C 1. (Without loss of generality these numbers are made up to exercise the futures of the model.) Operational cost of these aircraft are not considered as they are already in the fleet and should not be considered in the objective function of the model. The seat count for the existing aircraft is 350 seats per aircraft/. Aircraft type A/C 2 is a new generation aircraft with lower operating costs but with 300 seat count and there is not any in the fleet.

The optimal solution results in total 151,469,062,840 USD and summarized in Table 5.12. We note that model does not buy any aircraft from type 1 and 49 aircraft from type 2 over the first 8 years. Similarly, it leases 15 aircraft from type 1 and it leases 156 aircraft from type 2. Interestingly, it leases two different lease types in period 18: 1 aircraft of age 10 for a period of 3, and 2 aircraft of age 10 for 2 years.

Since, there are no owned aircraft from Type 1, it does not salvage any from this type and it salvages 2 at period 23 and 47 at period 24 from type 2. Looking at the results, it can be seen that in period 10, there are 8 aircraft from type 1 in the fleet that are to exit at the end of period 10 and 2 from the 2 year lease that was made in period 8. There are also 49 A/C from type 2 and 21 total leased aircraft from type 2 in this period. The total number of seats offered then are: 10*350 + 70*300 = 24500 seats. The demand in this period was 23800 seats, hence the demand has been met. In period 11, all A/C from type 1 have left the fleet, and an additional 14 aircraft have been leased from type 2. The total seats available is 84*300=25200, which is exactly what the demand is for this period.

5.7.4 Parametric Studies

Now, we confine the model to a single fleet type to conduct parametric studies. We keep the focus here on the trade-off between purchasing and leasing options. The seat count is assumed to be 350 and the demand values in Table 5.11 are converted to the number of A/C1 aircraft needed at period t and given in Table 5.13. There are 30 aircraft already in the fleet of this same aircraft type, 3 of which are operational leases and leave at the end of period 2.

Table 5.12 Optimal Fleet Replacement Policy for both A/C 1 and A/C 2 types over 24 year periods

	A/C 1				**A/C 2**			
Year	**Number of Purchased**	**Number of Leased**	**Age**	**Period**	**Number of Purchased**	**Number of Leased**	**Age**	**Period**
1	0	0			3	0		
2	0	0			3	0		
3	0	0			8	0		
4	0	0			5	0		
5	0	1	10	2	2	0		
6	0	0			7	0		
7	0	0			13	0		
8	0	2	10	2	8	0		
9	0	0			0	14	8	11
10	0	0			0	7	8	11
11	0	0			0	14	8	11
12	0	0			0	5	8	11
13	0	2	10	2	0	2	8	11
14	0	2	10	2	0	0		
15	0	0			0	7	8	12
16	0	0			0	0		
17	0	2	10	3	0	1	10	3
18	0	1+2	10	3,2	0	0		
19	0	2	10	2	0	0		
20	0	0			0	22	8	12
21	0	0			0	13	9	12
22	0	0			0	15	8	12
23	0	0			0	7	8	12
24	0	1	10	12	0	49	9	12

As before, we keep the assumption that all the leased aircraft can be returned at the end of the planning period without any penalty. This is a realistic assumption because at certain intervals, fleet replacement model will be solved again for another 24 years or longer period. Thus, the aircrafts leased for longer period near the end of the planning period will not be returned, rather they will be kept for the extended planning horizon.

We assume that there are 3 leased aircraft to leave at the end of period 3, i.e., $\mathbf{IO_1 = 3}$ and there are 6 aircrafts purchased 6 and 5 years ago and 7 aircraft purchased 4 years and 8 aircraft purchased 2 years ago. All will be sold at the end of their 12 year in service in the fleet. In other words, $\mathbf{B_{6,1} = 6}$, $\mathbf{B_{5,1} = 6}$, $\mathbf{B_{4,1} = 7}$, $\mathbf{B_{2,1} = 8}$. Finally, we assume that Internal Rate of Return (IRR) is 0, i.e., there is no escalation factor due to inflation.

Table 5.13 Demand for A/C1 at period t

Year	Demand	Year	Demand	Year	Demand
1	32	9	64	17	92
2	35	10	68	18	95
3	39	11	72	19	97
4	43	12	76	20	99
5	47	13	80	21	101
6	52	14	83	22	102
7	56	15	86	23	102
8	60	16	89	24	103

The program is run with this instance and the result is given in Table 5.14. Total cost of this solution is $1.5828E^{11}$ with the revenue of selling all owned aircraft at the end 24^{th} period.

We note that model buys only in the first10 periods, namely it purchases 2, 3, 7, 4 and 4 and so on in periods, 1…10. Then in period 11, it starts to lease enough aircraft to meet the demand and continues until the end. For example, it leases 11 aircraft at age 10 for 11 year lease period in the beginning of period 11 and so on.

Obviously, it benefits the low lease rates for longer leasing periods and thus it leases 44 aircraft at age 12 for 12 years lease period even we are at the beginning of period 24. This is understandable if we will extend the planning horizon on a rolling horizon bases and we will keep the A/C 1 type aircraft in the fleet longer. System salvages 3 aircraft at the period 22, 17 aircraft at the period 23 and 41 aircraft at the end of period 24.

Table 5.14 Optimal Fleet Replacement Policy for A/C 1 type over 24 year periods

Year	Demand	Number of Purchased	Number Leased	Age	Period
1	32	2	0		
2	35	3	0		
3	39	7	0		
4	43	4	0		
5	47	4	0		
6	52	5	0		
7	56	10	0		
8	60	10	0		
9	64	12	0		
10	68	4	0		
11	72	0	11	10	11
12	76	0	4	10	11
13	80	0	4	12	9
14	83	0	3	10	12
15	86	0	3	10	3
16	89	0	3	11	6
17	92	0	3	12	5
18	95	0	6	10	12
19	97	0	2	10	12
20	99	0	2	11	12
21	101	0	2	9	12
22	102	0	27	10	12
23	102	0	21	11	12
24	103	0	44	12	12

Thus, in this part of the analysis, it is assumed that A/C 1 type aircraft will be phased out from fleet at the end of planning horizon 24. This is also a very practical assumption because of the introduction of the new aircraft types with better fuel and maintenance efficiencies. Therefore, the last part of the cost function in the model, i.e., revenue coming from early the termination of the leased aircraft, is omitted. In other words, it will be like penalty of paying the lease rates for the remaining lease period when the planning period is over.

Table 5.15 presents the results that the model produced when run under these conditions. The total cost of this optimum solution was $159.32 billion.

Table 5.15 Optimal Fleet Replacement Policy for A/C 1 type when leased aircraft can't be returned without Penalty at the end of planning period

Year	**Demand**	**Number of Purchased**	**Number Leased**	**Age**	**Period**
1	32	2	0		
2	35	3	0		
3	39	7	0		
4	43	4	0		
5	47	4	0		
6	52	5	0		
7	56	10	0		
8	60	10	0		
9	64	12	0		
10	68	4	0		
11	72	0	11	10	3
12	76	0	4	10	2
13	80	0	4	9	2
14	83	0	18	10	11
15	86	0	3	11	10
16	89	0	3	12	9
17	92	0	3	12	8
18	95	0	3	10	7
19	97	0	2	11	6
20	99	0	2	12	5
21	101	0	2	11	2
22	102	0	9	10	3
23	102	0	55	11	2
24	103	0	3	12	2

The number of the purchased aircraft in the optimum solution remains the same as before, i.e., a total 61 aircraft is purchased at different periods. Also as before, starting from period 11, the system only leased aircraft on a dry lease basis. Interestingly, there were no wet leased aircraft as before. Also, we note that there is only 3 leased aircraft at the period 24. As expected, near the ending period, all aircraft are leased for shorter periods with higher lease rates. For instance, at period 23, 55 aircraft is leased at age 11 for only 2 years.

One last comment on these results is about salvaging policy of aircraft: All purchased aircraft are kept for longer than 12 years and 8 of them are sold at the end of 22nd and 53 at the end of 23rd period.

Next, we wanted to analyze the effect of Internal Rate of Return (IRR) rates over the tradeoff between purchase and lease options. As IRR increases the costs of lessors, who buy the aircraft and lease them to airlines, increasing the IRR results in higher lease rates, which in turn increases the lease rates.

After running the program for 15 different IRR rates, the results were collected and are presented in Table 5.16 and Figure 5.2.

Table 5.16 Optimum solutions over different IRR rates

IRR %	**Number of Purchased**	**Sold at Last Periods**
0 - 4	61	8, 53, 0
5 - 15	72	8, 53, 11

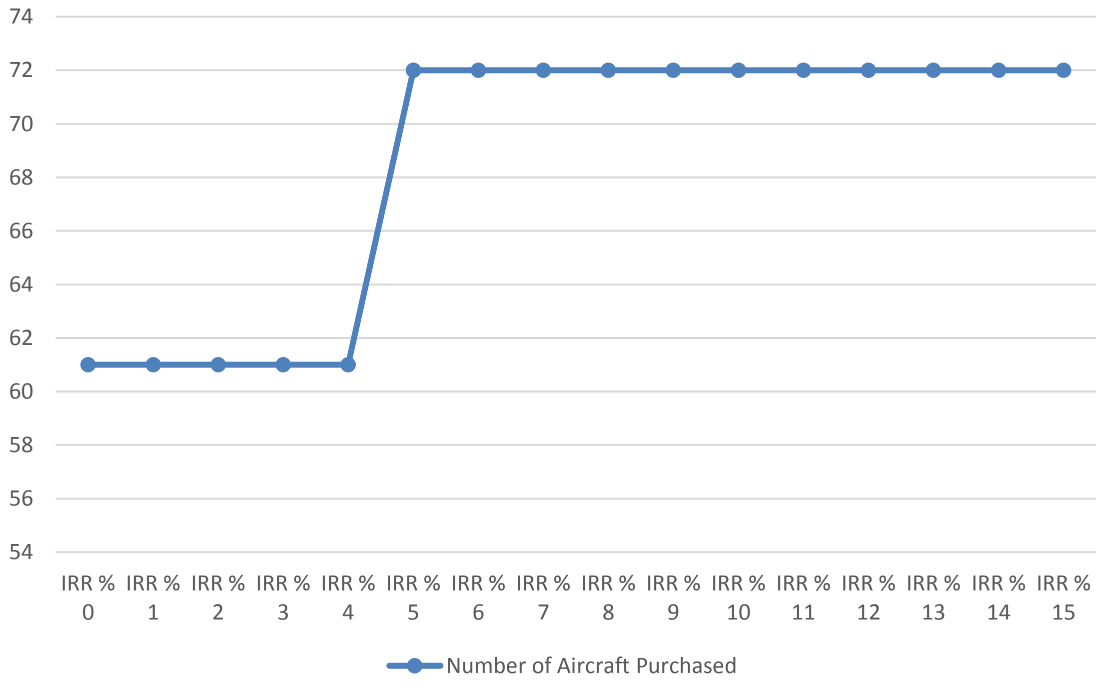

Figure 5.2 Sensitivity of the number of purchased aircraft against IRR rates

It should be noted that the salvaging practice is not affected, i.e., aircraft are kept in the fleet 20 years are longer and sold at 22^{nd}, 23^{rd} and 24^{th} periods. Furthermore, and contrary to the expectation, higher IRR rates did not result in more purchased aircraft in the model overall.

CHAPTER 6

SUMMARY AND FUTURE STUDIES

This thesis deals with very important decisions in the airline industry: fleet replacement and expansion policies. There is a dearth of published work on this topic because these decisions are based on strategic policies and sensitive data. Two directly related works have been extensively reviewed and their shortcomings are discussed with ideas to overcome their drawbacks. An integer mathematical model is presented and solved by using ILOG solver for different business models. The model presented here has several features to contribute to the literature:

- Buying is done only from manufacturer, as in reality, fresh at zero age.
- Different lease rates are available for different lease periods and different ages of aircraft. Specifically, near the end of planning period, short term lease periods must be chosen if the option is to lease rather than to purchase.
- Model allows that there are leased aircraft at the beginning of the planning period and their redelivery periods are given.
- Wet lease option (paying Aircraft, Crew, Maintenance and Insurance (ACMI) rates to an aircraft operator for short term basis) is allowed in the model.
- We differentiate the maintenance costs of lease and purchased aircraft over years.

For some other minor additions, the developed model is used to see how it differentiates between alternative narrow body options. Secondly, model is used for a LCC (Low Cost Carriers) business model with fleet from the same family type. Extensive amount of discussion is made for wide body aircraft operations and cost parameters are determined for different fuel prices. Since current fuel rate is around 50 USD per barrel, we use the related operational costs. Sensitivity analysis is made for IRR rates from 0% to 15%. As hypothesized, we have found that the new generation models with higher operational efficiency are preferred over existing aircraft types. Secondly, buying (purchasing) aircraft from manufacturer are more likely option over leasing from lessors at the beginning of the planning horizon or for a period of 10-12 year whereas the opposite is more likely for midway towards the end of the horizon.

There are certain improvements/extensions that can be made to the model for more accurate representation of reality.

Demand: First of all, demand for aircraft types can be forecasted using stochastic concepts. There are 3 levels of demand for each type during the year: low, medium and high. These result in spoil costs (excess capacity/empty seat) and spill costs (under capacity, lost passengers). Spoil cost- flying seat empty can be easily estimated for each type and Spill cost- passenger lost due to unavailable seat can be set as highest seat fare. Obviously, the spill cost is much more than the spoil cost. From past data, we can summarize that during the low season (7 months of the year), 60% low, 30% medium and 10% high demand conditions exist whereas during the high season, the high demand is around 75% and medium demand level is 25%. Thus, we can add to the objective function the total expected spoil and spill costs, accordingly.

Various Aircraft Types: To make the model to suit the needs of a legacy carrier, the model will need to take into account both narrow and wide body aircraft types. Demand will need to be categorized for domestic and international narrow and wide body routes. This way, model will not only make the fleet replacement and or expansion decision but also will make the fleet planning of the airline.

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APPENDIX-A

LEASE OPTIONS TABLE

The table A.1 below shows the lease options (lo) and their corresponding lease age and lease periods.

Table A.1 Lease Option and the corresponding aircraft age and lease period

lo	a	p	lo	a	p	lo	a	p
1	1	2	**34**	10	4	**59**	11	6
2	2	2	**30**	6	4	**60**	12	6
3	3	2	**31**	7	4	**61**	1	7
4	4	2	**32**	8	4	**62**	2	7
5	5	2	**33**	9	4	**63**	3	7
6	6	2	**35**	11	4	**64**	4	7
7	7	2	**36**	12	4	**65**	5	7
8	8	2	**37**	1	5	**66**	6	7
9	9	2	**38**	2	5	**67**	7	7
10	10	2	**39**	3	5	**68**	8	7
11	11	2	**40**	4	5	**69**	9	7
12	12	2	**41**	5	5	**70**	10	7
13	1	3	**42**	6	5	**71**	11	7
14	2	3	**43**	7	5	**72**	12	7
15	3	3	**44**	8	5	**73**	1	8
16	4	3	**45**	9	5	**74**	2	8
17	5	3	**46**	10	5	**75**	3	8
18	6	3	**47**	11	5	**76**	4	8
19	7	3	**48**	12	5	**77**	5	8
20	8	3	**49**	1	6	**78**	6	8
21	9	3	**50**	2	6	**79**	7	8
22	10	3	**51**	3	6	**80**	8	8
23	11	3	**52**	4	6	**81**	9	8
24	12	3	**53**	5	6	**82**	10	8
25	1	4	**54**	6	6	**83**	11	8
26	2	4	**55**	7	6	**84**	12	8
27	3	4	**56**	8	6	**85**	1	9
28	4	4	**57**	9	6	**86**	2	9
29	5	4	**58**	10	6	**87**	3	9

Table A.1 (cont'd) Lease Option and the corresponding aircraft age and lease period

lo	a	p	lo	a	p	lo	a	p
92	8	9	**106**	10	10	**120**	12	11
93	9	9	**107**	11	10	**121**	1	12
94	10	9	**108**	12	10	**122**	2	12
95	11	9	**109**	1	11	**123**	3	12
96	12	9	**110**	2	11	**124**	4	12
97	1	10	**111**	3	11	**125**	5	12
98	2	10	**112**	4	11	**126**	6	12
99	3	10	**113**	5	11	**127**	7	12
100	4	10	**114**	6	11	**128**	8	12
101	5	10	**115**	7	11	**129**	9	12
102	6	10	**116**	8	11	**130**	10	12
103	7	10	**117**	9	11	**131**	11	12
104	8	10	**118**	10	11	**132**	12	12
105	9	10	**119**	11	11			

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