A Model for Sensitivity Analysis of Aircraft Fleet Evolution Forecasting
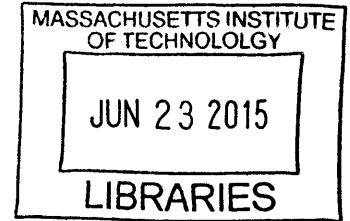
by

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ABSTRACT

As demand for the long range and high speed travel of commercial aviation continues to grow, the economic and environmental impacts of the industry are being scrutinized. One fleet performance metric that provides insight into these economic and environmental impacts is fuel burn. The total fuel burn of the commercial fleet is strongly influenced by fleet makeup, and therefore an understanding of how the fleet evolves over time provides insight into how these impacts will progress. In order to study trends in fleet evolution, a model has been developed with the focus of providing insight on the potential effects of different input sets and modeling assumptions on the predicted make-up of the future fleet. Using this model, test case analyses are performed on inputs and assumptions of interest, including aircraft retirement strategies, aircraft procurement strategies, demand forecasts and future aircraft performance. This study considers the sensitivity of fleet evolution and fleet-wide fuel burn performance to these inputs and assumptions of interest. An analysis of retirement strategies found that assigning newer aircraft to missions that required more fuel burn increased the fuel burn savings over a strategy which did not consider the fuel burn performance of aircraft when making replacement decisions. Furthermore, a study of procurement strategies showed that procuring more fuel efficient aircraft at higher rates than less efficient aircraft created fuel burn savings, but also that the entry into service date of an aircraft had a significant impact on the market share of that aircraft. A study of future aircraft design decisions showed that producing a more efficient aircraft may not lead to overall fuel burn savings if that aircraft takes longer to produce than a less efficient aircraft over a given timeframe. Finally, a study of the growth in passenger travel showed that increasing the amount of travel provided by the commercial fleet also increased the total fuel burn of the fleet, but that it is possible to provide the same amount of travel using many low capacity flights or fewer high capacity flights without affecting fleet wide fuel burn, depending on the fuel burn performance of the aircraft considered.

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Chapter 1: Introduction

1.1: Motivation

Commercial aviation is a driver of the global economy. As demand for the long range and high speed travel of commercial aviation continues to grow, the economic and environmental impacts of the industry are being scrutinized. In particular, multiple decision makers in the industry are interested in the emissions of CO2 caused by the commercial fleet, and multiple entities are involved in plans to reduce the effects of aviation on the environment, including climate and air quality impacts. At the same time, the high cost of fuel incentivizes airline operators to reduce fuel consumption as it is one of the main drivers of direct operating cost. For these reasons, strategies to reduce the fleet-wide fuel consumption of commercial aviation are valuable within the industry.

Current forecasts suggest that, without intervention, the rate of growth of commercial aviation will continue to outpace the rate of fuel efficiency improvements. This prediction suggests a continued increase in aviation-attributable emissions, at a time when other industries are taking steps to reduce their emissions impacts. Previous research by the International Civil Aviation Organization (ICAO), presented in Figure 1, shows that, though fleet-wide average aircraft efficiency has seen substantial benefits in recent years, total fuel consumption has continued to rise.
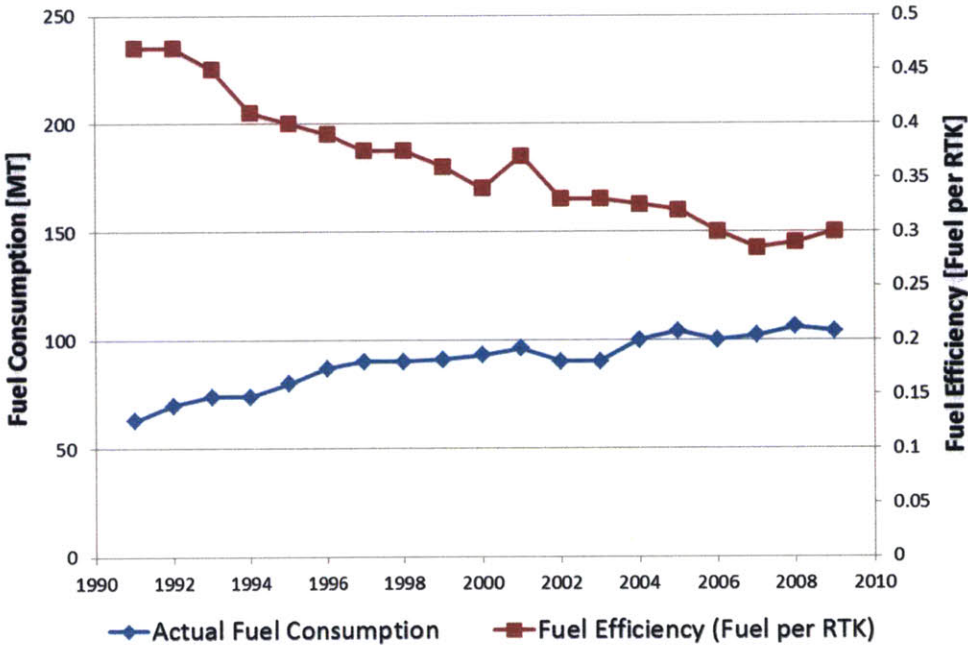
Figure 1: Total Fuel Consumption and Fleet Wide Fuel Efficiency per Year (ICAO, 2010)

As such, multiple entities have set emissions reduction goals for the aviation industry. The International Airline Industry Association (IATA) goal is to achieve carbon neutral growth by 2020 and a 50% reduction in net aviation CO2 emissions by 2050 relative to 2005 levels. (IATA, 2014) ICAO has also provided a clear goal, which aims for 2% annual fuel efficiency improvements through 2050. (ICAO, 2009)

The ICAO Committee on Aviation Environmental Protection (CAEP) has performed environmental trends assessments to determine the required advancements that must be made in the commercial fleet in order to reach carbon neutral growth requirements. Figure 2 shows that a mix of infrastructure, aircraft technology, alternative fuels, and market based measures must be used in tandem in order to meet carbon neutral growth goals.
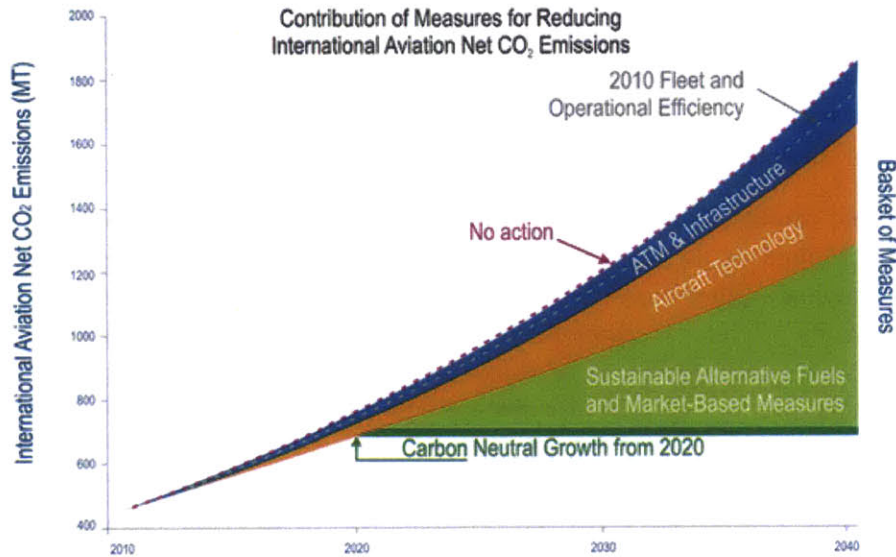
Figure 2: CAEP Predictions of Required Measures for Reducing Aviation Environmental Impacts to Meet Carbon Neutral Growth (CAEP, 2010)

Concurrently, airlines are focused on reducing the fuel consumption of their fleets in order to reduce the cost of fuel, the single largest contributor to operating costs. IATA estimates suggest that fuel costs make up roughly 30% of total operating costs. (IATA, 2015) Data collected by MIT's Airline Data Project shows, in Figure 3, that the fraction of fuel cost to total operating costs has risen over the past 2 decades, from roughly 10% in 1995 to 30% in 2013. (Airline Data Project, 2014) Furthermore, estimates of future jet fuel pricing suggest that the cost of fuel is expected to remain steady or rise in the coming years. (USEIA, 2015)
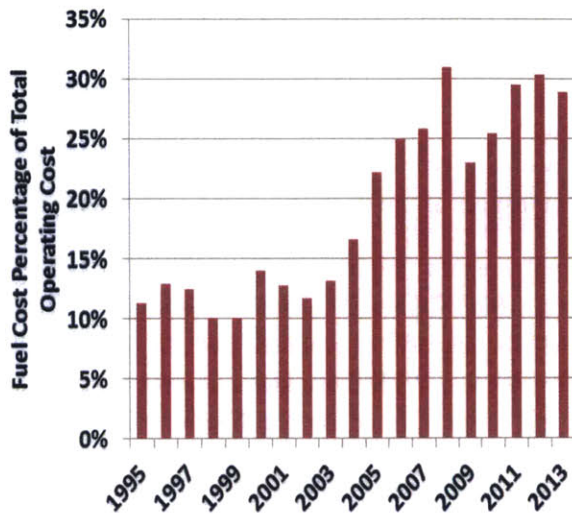
Figure 3: Percentage of Total Operating Cost Attributable to Fuel Cost (Airline Data Project 2014)
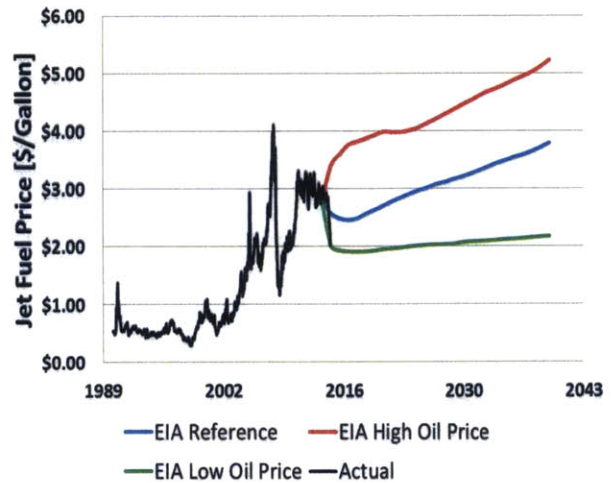
Figure 4: Jet Fuel Price Projection (USEIA, 2015)

Previous studies have shown three major fields within the industry that show potential for emissions and fuel consumption reductions: (1) Technological Improvements, (2) Operational Improvements, and (3) The use of alternative fuels. Operational improvements show promise for producing emissions savings in the short term, but emissions reductions would be modest. Introducing technological improvements could produce significant emissions reductions, but the benefits can only be expected in the long term due to the slow rate of turnover in the commercial fleet. (Kar, 2010) For these reasons, the makeup and growth of the commercial fleet have a significant impact on the fleet-wide performance of total fuel burn.

1.2: Fleet Evolution

The commercial fleet is a complex system of systems, with each individual aircraft in the fleet having its own characteristics, including mission capabilities, performance, and flight assignments. As manufacturers introduce advanced designs, with greater performance capabilities than previous generations, those aircraft must make their way into the fleet through the process of fleet evolution. This process determines fleet makeup and is driven by economic activities including aircraft retirement rates, entry into service of new aircraft, aviation transport's market growth over time, as well as fleet assignment.

The commercial fleet is made up of aircraft that carry passengers along desired routes. These aircraft are operated by airlines. Each aircraft has mission capabilities that determine how far and with how much payload the aircraft can travel. The aircraft also has performance characteristics that determine how much fuel is burned on its missions. Finally, each aircraft has a limited service life determined by the cost to operate the aircraft. Many factors, including aircraft age, determine the cost to operate an aircraft, and this cost is used by airlines to determine when to retire and, if necessary, replace an aircraft. Separately, each aircraft has an assignment of missions that it flies, expending fuel to provide travel to a number of passengers.

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Demand for new aircraft is driven by two main characteristics: Aircraft retirements and demand growth for commercial air travel. In either case, airlines recognize the potential for additional flights that their current (or future) fleet cannot maintain, leading them to consider procuring new aircraft. Beyond determining that new aircraft must be procured, airlines must also determine what type of aircraft should be purchased. This decision is influenced by the expected mission requirements that the new aircraft will be taking on, and aircraft capabilities are an important aspect of the decision making process.

Once new aircraft enter the fleet, the final step of the fleet evolution is to create a fleet assignment, determining which aircraft will travel on which flights. As discussed above, this assignment is considered ahead of time when determining which aircraft to procure, but the actual process of assigning aircraft to missions must be performed by airlines. With these steps complete, the aircraft are ready to fly their assigned missions and analysis can be performed on the overall performance of the resulting air traffic network.

1.3: Fleet Evolution Impact on System Wide Fuel burn

A commercial aircraft expends fuel to carry payload over distance. If this payload/distance pairing is considered as a mission, and held constant as a requirement to be met by the commercial fleet, then the choice of aircraft directly determines the fuel burned on that mission. To take a more detailed view of this, consider the Breguet-Range Equation (Anderson, 1989):

$$R = \frac{V}{g}\frac{1}{SFC}\frac{L}{D}\ln(\frac{W_{initial}}{W_{final}})$$

Where R is the range of the mission. V is the aircraft velocity which is assumed to be prescribed for the mission. SFC is the aircraft's specific fuel consumption, a measure of the aircraft engine's fuel efficiency. Here, the gravitational constant is used to cancel out the thrust units in SFC. $\frac{L}{D}$ is the aircraft's lift over drag ratio, a measure of the aircraft's aerodynamic efficiency. $W_{initial}$ is the aircraft's takeoff weight, including the empty weight of the aircraft (i.e. the structural weight of the aircraft), the payload, and the fuel carried. Finally, W_{final} is the aircraft's landing weight, which still includes the aircraft empty weight and the payload, but excludes the fuel burned throughout the flight. From this equation, the aircraft fuel burn, or the weight of the fuel burned can be calculated as $W_{fuel} = W_{initial} - W_{final}$.

Rearranging to show the equation in terms of weight gives:

$$\frac{W_{initial}}{W_{final}} = e^{\frac{Rg}{V}SFC\frac{1}{\frac{L}{D}}}$$

Considering $W_{initial} = W_{final} + W_{fuel}$ and that $W_{final} = W_{payload} + W_{aircraft}$, the equation can again be re-written to give the total fuel burned in terms of the other values in the equation:

$$W_{fuel} = \frac{e^{\frac{Rg}{V}SFC\frac{1}{\frac{L}{D}}} - 1}{W_{payload} + W_{aircraft}}$$

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From this equation, the fuel burn can be determined to be affected by three terms defined by the mission: Range, speed, and payload, as well as 3 terms defined by the aircraft: lift over drag, SFC, and aircraft weight. Each of these terms is strongly affected by the aircraft's technology level, and increasing the thermodynamic, aerodynamic, and structural efficiency are major goals of manufacturers when performing upgrades or new designs.

For these reasons, effectively understanding the main factors which impact fleet evolution, and the sensitivity of fleet-wide fuel burn performance to these factors, is important. While it is relatively easy to calculate the fuel burn advantage of placing a single new aircraft on a mission that used to be flown by an older variant, understanding the larger scale implications and interdependencies of a new aircraft introduction can be far more complicated. This thesis will consider a model to provide insight on the potential effects of different input sets and modeling assumptions on the predicted make-up of the future fleet. This model will then be used to evaluate test cases of interest to the system.

1.4 The Importance of Forecasting on a Fleet Evolution Model

Forecasts of fleet evolution have real world implications. One example of the importance of fleet evolution forecasts is the way in which differences between Boeing and Airbus predictions of future demand for air traffic have led the two companies' fleet evolution predictions to vary. This variation between the two models led each company to produce different aircraft recently. These distinct predictions are visualized in Figure 5 and Figure 6. In particular, the Airbus Global Market forecast (GMF) has predicted an increase in high capacity flights between mega-cities, which contributed to the decision to produce the A380, whereas the Boeing Commercial Market Outlook (CMO) predicted an increase in long range flights, but no increase in capacity per flight, leading to the decision to produce the 787 and not a direct competitor to the A380. The manufacturer whose forecast is more accurate is likely to see better return on investment for these platforms in the coming years.
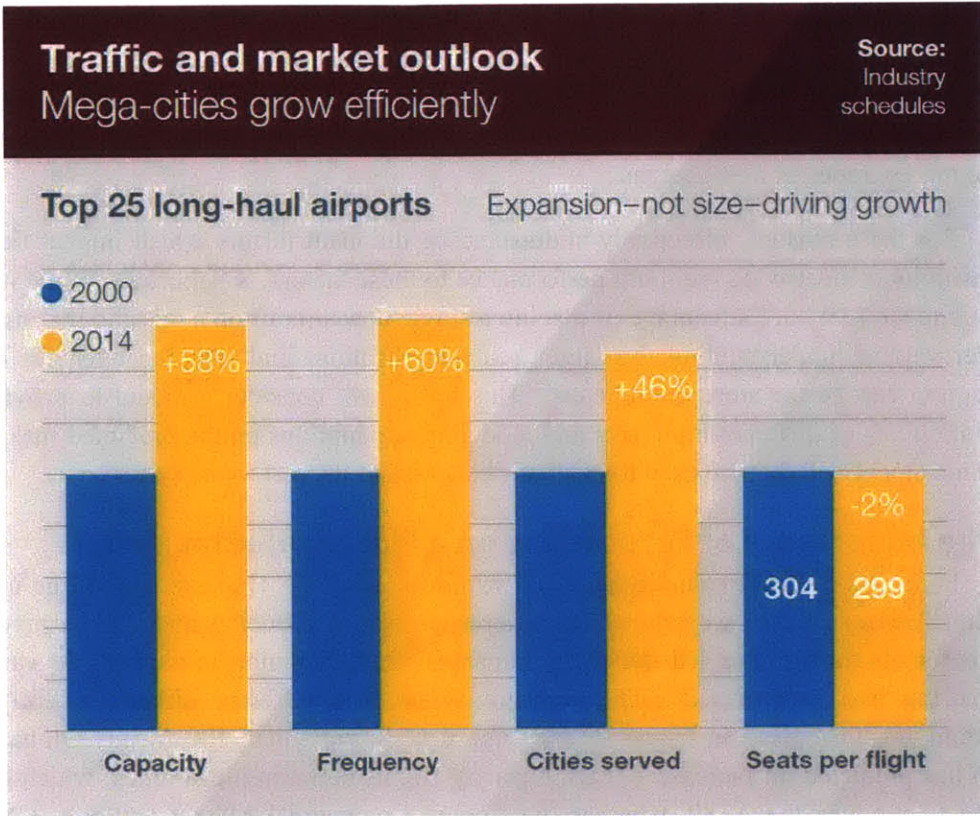
Figure 5: Boeing predicts growth in air travel will be driven by expansion, not aircraft size (Boeing CMO, 2014)

Figure 6: Airbus predicts growth in air travel will be driven by demand between mega-cities, requiring high capacity flights (Airbus GMF, 2014)

This example illustrates the importance of the demand forecasts to decision makers in commercial aviation. In this analysis, effort was taken to avoid choosing winners and losers through

forecasting assumptions, and to that end a compromise forecast was used. This will be discussed in further detail in the model inputs sections.

Chapter 2: Fleet Evolution Forecasting Model

This thesis presents a model for fleet evolution. This model is intended to be a first order tool for use in rapid fleet assessment strategies. The focus of this tool is to provide insight on the potential effects of different input sets and modeling assumptions on the predicted make-up of the future fleet. As discussed in Chapter 1, the main focus of this model will be fleet wide performance, with a focus on fuel burn. This chapter will begin with a model overview, followed by a discussion of simplifying assumptions used in the development of this model, then continue with a discussion of each main sub-routine within the model, and conclude with a discussion of the required inputs as well as the reasoning behind the input design.

2.1: Model Overview

This model performs a step-by-step process iteratively in order to determine fleet evolution based on forecasting assumptions. The model has four main steps, which are performed consecutively in order to grow the fleet along one time-step. A workflow of the model is presented in Figure 7. The first step is to determine initial fleet makeup. Second, the model determines the mission set to be covered. By comparing these two intermediate outputs, the shortfall is defined and used to determine the number and types of procurements necessary. Finally a simplified fleet assignment model is used to complete the network for the current time-step, fuel burn performance per flight is calculated, and performance data is aggregated to facilitate fleet-wide evaluation.
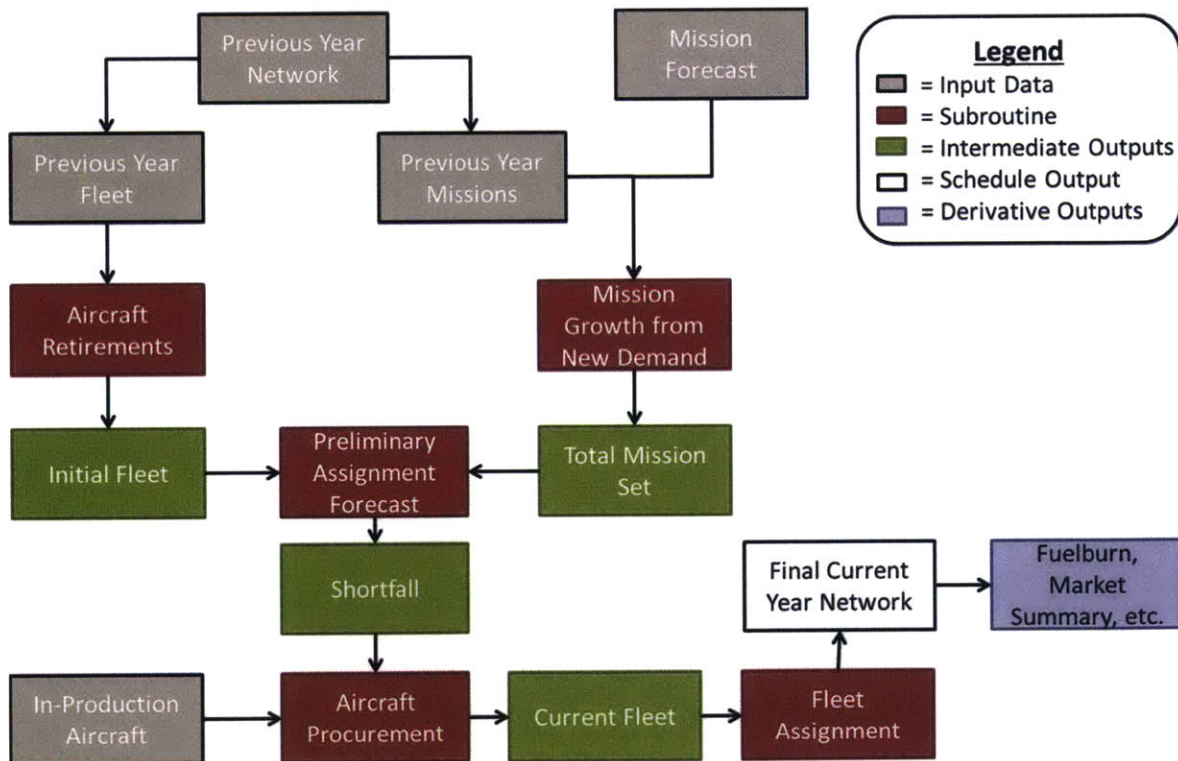
Figure 7: Fleet Evolution Forecasting Model Workflow

Determining the initial fleet makeup from the previous year's fleet requires performing a retirement calculation to determine which aircraft are removed and set for replacement. In parallel, the full mission set is calculated by considering the missions from the previous time-step and appending new missions due to growth. Once these two calculations are completed, a preliminary fleet assignment is used to determine the number of missions that will not be able to be covered by the current fleet, or flown by aircraft in the current fleet. This comparison provides the network shortfall, or the set of missions that require new aircraft to cover them.

Given the network shortfall, the next step in the process is to determine aircraft procurements. This is done using a competition model that determines which aircraft are procured to meet shortfall.

Once new aircraft have been procured, a final round of fleet assignment is performed in order to assign aircraft to missions. This produces a completed network, the full set of covered flights and the associated fleet, for the given time-step. Post-processing is performed to calculate the performance of each flight, and then the final network is passed off to the next time-step. This process is completed iteratively throughout the analysis timeframe.

2.2: Simplifying Assumptions

2.2.1: Timescale Discretization
This model considers fleet evolution on a yearly basis. In reality, fleet evolution is a continuous process, but to approximate this continuous process, the model assumes that fleet evolution decisions are made at discreet points in time, specifically on an annual basis. Furthermore, the model will consider fleet evolution on a year by year basis, as opposed to an approach that considers evolution as a distinct process from the baseline year to each subsequent year in the analysis. As an example to illustrate this point, if this model considers a fleet evolution scenario beginning from a 2010 network, which will be referred to as the baseline throughout this analysis, it will calculate the impacts of fleet evolution in 2011 based on the 2010 inputs, and will then calculate 2012 fleet evolution based on the 2011 calculations that have already been produced. The alternative approach, instead, would calculate the fleet evolution of each analysis year from the baseline year, such that impacts in 2012 would also be based on the 2010 inputs, and not consider the 2011 calculations.

The selected approach has certain drawbacks. In particular, the yearly evaluations cannot be parallelized as the calculation of yearly evolution becomes a serial process, and previous years must be completed before the next year can be considered. However, this year-by-year approach allows for a more nuanced look into the forecast produced by the model. It also opens up the possibility of studying more specific fleet entry scenarios. Specifically, this approach more accurately considers the effect that current technology aircraft have on the fleet for the foreseeable future.

For example, consider an aircraft available today, or a current technology aircraft, that is set to be replaced in 2025 with an updated redesign aircraft, an aircraft that is not currently in production and will have better efficiency performance than the current aircraft. In the year-by-year forecast, the current technology aircraft will enter the fleet regularly from the baseline year up until the update year of 2025, and these aircraft remain in the fleet until retiring from the fleet, while the updated redesign aircraft will begin entering the fleet as new demand for aircraft is recognized. Alternatively, in the analogous baseline-to-out-year direct model, the current technology aircraft would enter the fleet normally until the update

year. However, starting from the update year, the updated redesign would take over all demand, past and future; and the current technology aircraft would disappear as if they had never entered the fleet. The additional computation time required of this new model is considered a worthwhile tradeoff in order to provide more in depth analysis of entry and retirement trends.

2.2.2 Mission Definition

A flight is an aircraft carrying a number of passengers from an origin to a destination. This creates significant complexity and requires more precise forecasting than is reliably producible in a forecasting model. Instead, this model simplifies the problem by reducing each flight to a distance travelled carrying a specified payload. While this simplification reduces the resolution of the outputs, and the network produced is non-physical, the calculation of fleet-wide fuel burn is preserved, since the origin and destination of an aircraft have a negligible impact on a flight's total fuel burn.

Furthermore, while each flight in the network is unique, modeling every individual flight is computationally expensive and unnecessary for the scope of this model. Instead, missions are aggregated into mission bins defined by limits of flight ranges and payloads. The specific limits used for this analysis are presented in Figure 8. This figure shows bin limits for missions in both payload and range. Missions in each bin are estimated by an average payload and range for that bin. The limits chosen for seat classes are meant to roughly split the market into small and large regional jets, small and large narrow body aircraft, and three sizes of wide body aircraft.
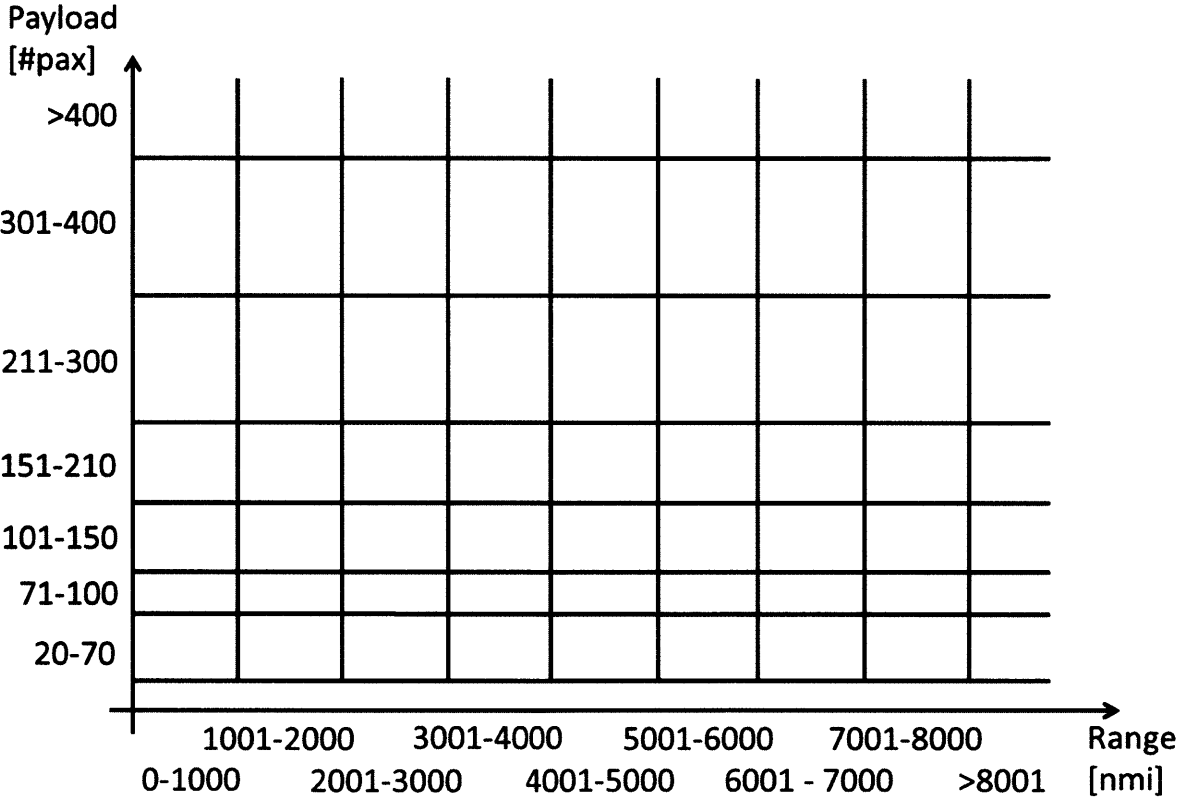
Figure 8: Mission Bin Definitions

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This assumption allows for two simplifications that reduce the complexity of the calculation. First, by reducing mission definitions into a payload and range, the user's requirement to produce a demand forecast, or an estimate of future demand for air travel, is simplified significantly. Rather than having to define each mission as a specified Origin-Destination (O-D) pair, the user must only define the number of flights in a given mission bin. This generalized definition of demand growth effectively matches the scope of the analysis with its focus on fuel burn rather than specific O-D pairs.

Secondly, fleet assignment and aircraft procurement can be simplified to determining whether an aircraft is able to perform the missions within a mission bin. This simplification allows the number of checks per time-step to be reduced from the number of aircraft multiplied by the number of missions, to only the number of aircraft multiplied by the number of mission bins.

2.2.3 Demand Growth

One of the main questions in a fleet evolution forecast is determining how much demand for fleet growth exists. Decision makers throughout commercial aviation, including airlines, manufacturers, and policy makers, agree that the industry is expected to continue growing, with increased demand for flights into the future.

This model uses a demand forecast based on number of available seat kilometers (ASKs) provided by the commercial fleet. As discussed above, the model breaks the available mission space into payload and range bins. The demand forecast is defined along the same parameters, defining a number of required ASKs in each mission bin in each year of the analysis. The number of ASKs and the mission bin definition together determine the number of new flights to be covered in each mission bin.

This increase in air traffic is essential to fleet evolution, as a major portion of new aircraft deliveries will be used to facilitate market growth. For example, Boeing's Current Market Outlook (CMO) predicts that 58% of new aircraft deliveries will be for growth between 2013 and 2033. Similarly, the Airbus Global Market Forecast (GMF) predicts 61% of new aircraft will be for growth between 2014 and 2033.
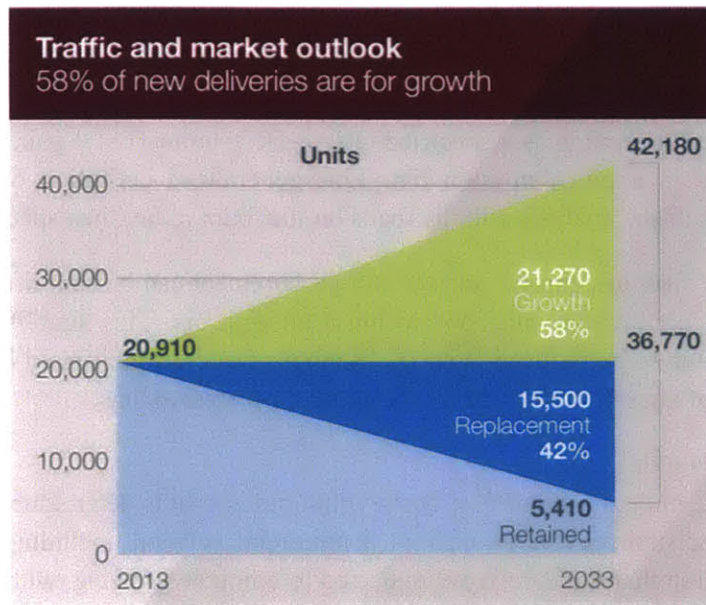
Figure 9: Boeing CMO fleet growth predictions (Boeing CMO, 2014)
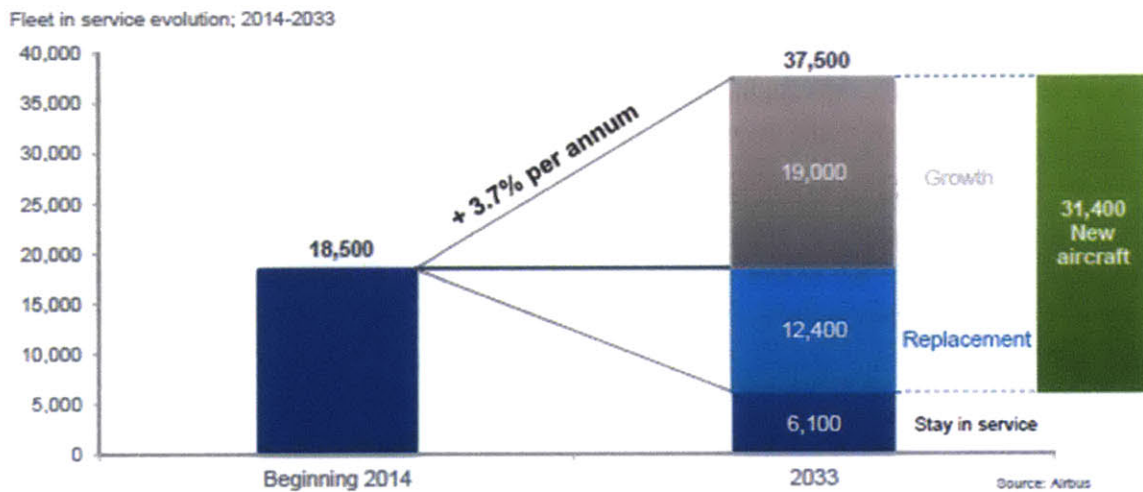
Figure 10: Airbus GMF fleet growth prediction (Airbus GMF, 2014)

As defined in this analysis, demand for new flights is always met by the commercial fleet. This implicitly assumes that the demand forecast includes consideration for what flights are offered by airlines, since a flight must be supplied by an airline as well as demanded by customers in order to be covered. Since the demand forecast includes considerations of what flights airlines will offer, feedback exists between the fleet evolution and demand forecast. This occurs because airlines will choose what flights to offer based, in part, on what aircraft are available in their fleet.

This feedback based interaction, however, goes beyond the scope of this analysis, and the results provided in this thesis are based on the assumption that the demand growth is static as input. This implicitly assumes that the demand forecast provided by the user has already settled into an equilibrium based on future aircraft technologies considered, also provided by the user. The analysis presented in

Chapters 3, 4, and 5 assumes static demand between different scenarios in order to provide targeted studies of the assumptions tested there. Chapter 6 will consider the impacts of altering the demand forecast on fleet evolution, but will still maintain that the forecast is static as input.

The demand forecast, therefore, is treated as an input, and aircraft procurement decisions are based on the demand growth provided by the user. Inputs will be discussed in further detail in the following section.

2.2.4 Retirement Curves

Along with demand growth, the other major factor of aircraft procurement needs from airlines is the retirement of old aircraft. Figure 9 and Figure 10 show that Boeing and Airbus models predict that 42% and 39% of new aircraft deliveries will be to replace retiring aircraft over the next 20 years. In order to model this process, this analysis uses retirement curves based on historical data in order to predict how quickly aircraft will exit the fleet.

Actual retirement decisions are made based on a series of criteria including capital, maintenance costs, and network needs. For this model however, retirement ratio assumptions provide an effective high level estimate of this process. Since the goal of this analysis is to consider large-scale fleet-wide impacts, using these retirement curves as a surrogate for retirement decisions is an effective tool.

Aircraft that enter the fleet during analysis are subject to the same retirement criteria as aircraft from the baseline fleet. If the analysis timeframe is long enough, these aircraft will also begin to retire from the fleet. The impact that this will have on the overall performance metrics considered will also be determined by the timeframe of the analysis.

2.2.5 Aircraft Competition

When considering which aircraft to procure or assign to a mission, the model first performs a simple analysis to determine which aircraft could be used to fly the mission. First, in order to be considered for a mission, the aircraft must be able to carry the specified number of passengers the specified range. Aircraft whose maximum range does not meet the mission range are excluded from the analysis. This assumption foregoes the possibility of breaking flights into multiple legs, assuming that the user will consider these options when defining the demand forecast. This does not, however, preclude aircraft with long range capabilities from flying on short range flights, as this usage is seen frequently in the real network on, for example, shuttle flights.

The second major question is what size aircraft should be considered for a mission. In order to answer this question aircraft matching against missions must be considered. Aircraft matching tests how closely an aircraft's design payload and range match the mission's payload and range. An aircraft cannot fly a mission that has a greater range or payload than the aircraft's maximum capabilities, but can fly a mission with lower requirements. However, flying a mission with lower payload and range than the design of the aircraft will incur an efficiency penalty. The decision of which aircraft are acceptable to cover which missions is based on the efficiency penalty incurred by flying less well matched aircraft on a mission versus better matched alternatives.

While both low range and low payload missions incur an efficiency penalty, a low payload mission incurs a greater penalty than a low range mission. This occurs because the structural weight

required to accommodate a larger design payload must still be carried on a low payload mission, whereas the fuel weight of a higher design range can be excluded for a long range flight by flying with only partially full fuel tanks. Furthermore, while a range penalty is incurred for longer range aircraft, these aircraft also provide airlines with greater network flexibility by providing more options for long range flights. For these reasons, long range aircraft are considered for short range flights, but high payload aircraft are not considered for low payload flights. In other words, mission load factors are restricted to only allow high load factor flights in order to avoid incurring large efficiency penalties.

By restricting aircraft to only fly missions with payloads near their design payload, the number of aircraft available to fulfill each mission is reduced. This allows a simplification of the aircraft competition model, but still leaves two competition considerations.
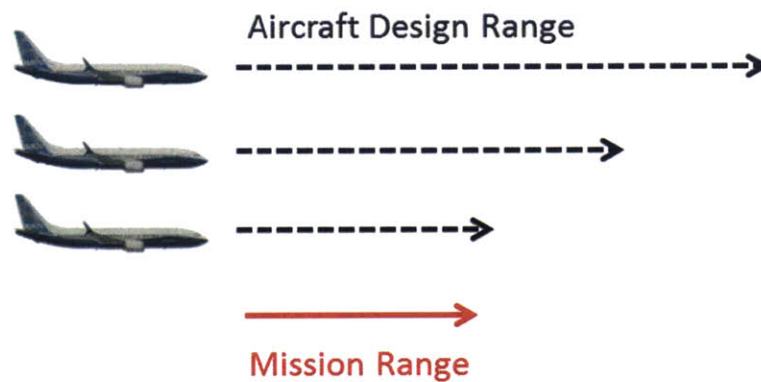
Figure 11: Competition for short range flights

The first of these competition considerations is shown in Figure 11. In this scenario, a short range route has been identified for a mission; however there are multiple aircraft with similar payload performances, but differing maximum ranges. Any aircraft whose maximum range is below the mission range is excluded from competition, but this may still leave multiple aircraft able to fly the mission. A competition surrogate that matches mission range to aircraft maximum design range does not effectively model reality, as airlines value fleet flexibility and are willing to incur a fuel burn performance penalty in order to maintain a fleet that has the ability to adjust to different mission requirements. As such, an effective competition model must allow long range aircraft to fly short range flights, but also not remove shorter range aircraft altogether. In order to meet this requirement, this model considers all of the aircraft that meet these criteria as equal competitors, and does not award or penalize aircraft based on their maximum design range's overshoot of the mission range.

Aircraft Design Range

Mission Range
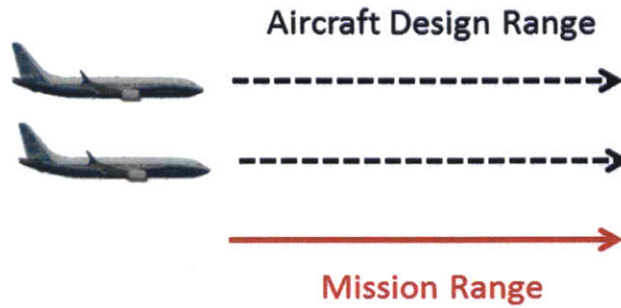
Figure 12: Competition Between Multiple Aircraft with Similar Mission Capabilities

Figure 12 depicts the second major form of competition between aircraft that must be accounted for. When two aircraft have similar mission capabilities in terms of both payload and range, there must be a way to determine which of these aircraft will be assigned to a given mission. Given that it is impossible to say that one aircraft is more suited than another to fly the mission, some other means of modeling competition must be considered.

In both of these cases, multiple aircraft can be seen as equally viable options for a given mission based on the mission requirements and aircraft capabilities. As discussed previously, this model considers missions within payload and range bins, so the competition model is used to distribute missions between all the aircraft available to handle the set of missions in each bin. In this way, the competition model can be considered to select a percentage of missions to go to each aircraft that meets the capability requirements. The specifics of how the model determines these percentages are discussed in detail in Section 2.3.

2.2.6 Fleet Assignment

Once an airline has determined the routes it wants to service and has the fleet with which to service them, it must decide how to allocate aircraft to missions. This problem of defining a complex network to meet all the needs of the system is its own field of study, using advanced algorithms to determine which aircraft should fly which flights. Contemporary strategies for calculating such systems involve integer programming models that can be time intensive to run and are not suitable for this model, so simplifying assumptions are used in order to effectively predict fleet-wide performance without requiring significant runtimes.

As discussed previously, this model does not consider the specific O-D pair of each flight, but instead considers the network on a more aggregate level. Each flight is defined as an amount of payload being transported a certain range. While this simplifying assumption reduces the effective resolution of the problem, it retains the critical information of useful output per flight, in terms of seat-kilometers provided. This mission data can be used to determine which aircraft are suitable to fly the mission and also to determine the overall system-wide efficiency by considering the fuel burn expended per seat-kilometer provided.

A second simplifying assumption employed by this model on the fleet assignment problem involves the consideration of retained aircraft. In real world fleet assignment, the entire fleet is considered along with the entire desired network. This fleet includes both old and new aircraft and old and new

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missions. This model, however, assumes that aircraft that are retained from previous years will continue to service the same missions. As such, the missions considered when making procurement and assignment decisions include only missions that were previously flown by retiring aircraft or that meet new demand and were not previously flown.

2.2.7 Fuel Burn Use Estimation

As discussed in the introduction, fuel burn per flight is affected by a range of information about the flight. Using flight models to determine the fuel burn usage of each flight in the network is too costly and falls outside the scope of this analysis. For this reason, a simplification is used in fuel burn estimates.

As discussed in Chapter 1, according to the Breguet-Range Equation, fuel burn of a flight is dependent on three factors defined by the aircraft technology level: Lift over drag, specific fuel consumption, and aircraft weight. Furthermore, the mission specifications also contribute to overall fuel burn through payload, range, and flight speed. Assuming constant cruise flight speed and utilizing the assumption that airlines will not accept low load factor flights, the speed and payload can also be determined per aircraft type. Using these values, a fuel burn per kilometer value can be calculated as an estimate for fuel burn efficiency for the aircraft type. This fuel burn per kilometer value is used along with the total flight range in order to estimate the total fuel burn for each flight in the network, and these fuel burn values are summed to provide a fleet-wide fuel burn usage output.

This model works well for cruise flight, but misses on estimates for takeoff and landing. As such, the fuel burn value for each flight is augmented by a landing and takeoff (LTO) fuel burn value, also defined per aircraft type. Furthermore, while this data is available for currently produced aircraft, fuel burn per kilometer estimates for future aircraft are more difficult to predict. For these aircraft, fuel burn savings estimates against current aircraft are used to scale down the fuel burn per kilometer and LTO fuel burn values for those aircraft types.

2.2.8 Unified Network

The main users of the commercial fleet are the airlines that use aircraft to provide transportation services to customers. In real world fleet evolution, decisions by airlines that define airline strategy and goals have a strong influence on fleet evolution. Moreover, all orders for new aircraft, decisions about new routes to service, and determinations of when aircraft retirements and replacements should occur are made by airlines. These decisions are complex and economically motivated, weighing the costs and benefits of the significant spending necessary to acquire new aircraft. Furthermore, not all airlines are alike, and different airlines make different strategic decisions about the types of service to provide and therefore the choice of aircraft to procure. For all these reasons, airlines play an important role in fleet evolution.

For the sake of this analysis, however, competition between airlines will not be modeled. As discussed above, demand growth and retirement assumptions are used to model these aspects of airline decision making, and as such, this model effectively assumes how airlines will strategically plan growth and replacement. Since the decisions of which routes to serve and how often to serve them are left to the user to input, the strategic decisions of an airline are effectively accounted for before the computation begins. As such, this model does not provide logic for servicing decisions to be made, leaving those decisions up to the user through the input system.

One main effect of competition between different airlines is an increase in the frequency of flights due to different carriers providing the same flights in direct competition with one another. While this is not directly modeled, the effects of frequency shifts are included in the demand forecast and therefore are indirectly accounted for within the model. When determining the demand forecast, this frequency question is considered.

Another major influence that airlines have on fleet evolution is the decision of which aircraft to procure. Again this decision is complicated in the real world. Airlines must consider the efficiency benefits of new aircraft against their substantial sticker prices while also considering axillary effects such as manufacturer reliability and the customer experience that can be provided by these aircraft. As discussed above, the model decides between different aircraft with similar mission capabilities by using a set of assumptions for determining how to handle aircraft competition. Here again, an important aspect of the airline decision making process is handled in this model through a set of predefined assumptions and left to user inputs to determine how to address these issues.

A third major decision that airlines must make is how to allocate their fleets in order to meet the set of routes that they have chosen to service. Again, in the previous sections, the process for fleet assignment within this model has been discussed. While different airlines may have slightly different practices in determining fleet assignments, the general strategy is the same, and meeting the service routes is largely a matching exercise with aircraft capability. This model does not attempt to provide nuanced and separate rationale for making fleet assignment decisions, and instead uses a single, over-arching system to perform one fleet-wide assignment.

While the decisions of, and competition between, airlines have a significant impact on overall fleet evolution, it is beyond the scope of this thesis to consider the economic competition between airlines. Simplifying assumptions discussed in previous sections are utilized to account for the decisions that airlines in the real world must face. As such, this model effectively assumes that airlines act in accordance with the pre-defined input set provided by the user in order to predict fleet evolution without including logic for airline decision making.

2.3 Sub-Models

The fleet evolution model presented in this thesis is made up of a series of sub-models that work in tandem to provide a forecast for fleet evolution. As discussed previously, the model works on an annual timescale, so each of these models determines changes for one year, and the sub-models are looped upon for each year of the analysis.

2.3.1 Mission Shortfall Model

The first major step of the model is to determine which missions will need to be covered by new aircraft. This intermediate output is then provided to the competition model in order to determine what new procurements should be conducted. There are two main ways that missions are identified as requiring new aircraft coverage: aircraft retirements and new demand growth. Each of these will be discussed in detail here.

The first source of new missions is aircraft retirements. In order to determine which aircraft retire from the fleet, the model uses current fleet data along with retirement curves. In the first year of the analysis, the current fleet is defined by the baseline fleet input by the user, but in all years following the

first, the fleet output by the previous year's forecast is used as the input. The retirement curves are representative of historical data and used to predict how long aircraft of different types can be expected to remain in service. The retirement curves used for this analysis can be seen in Figure 13.
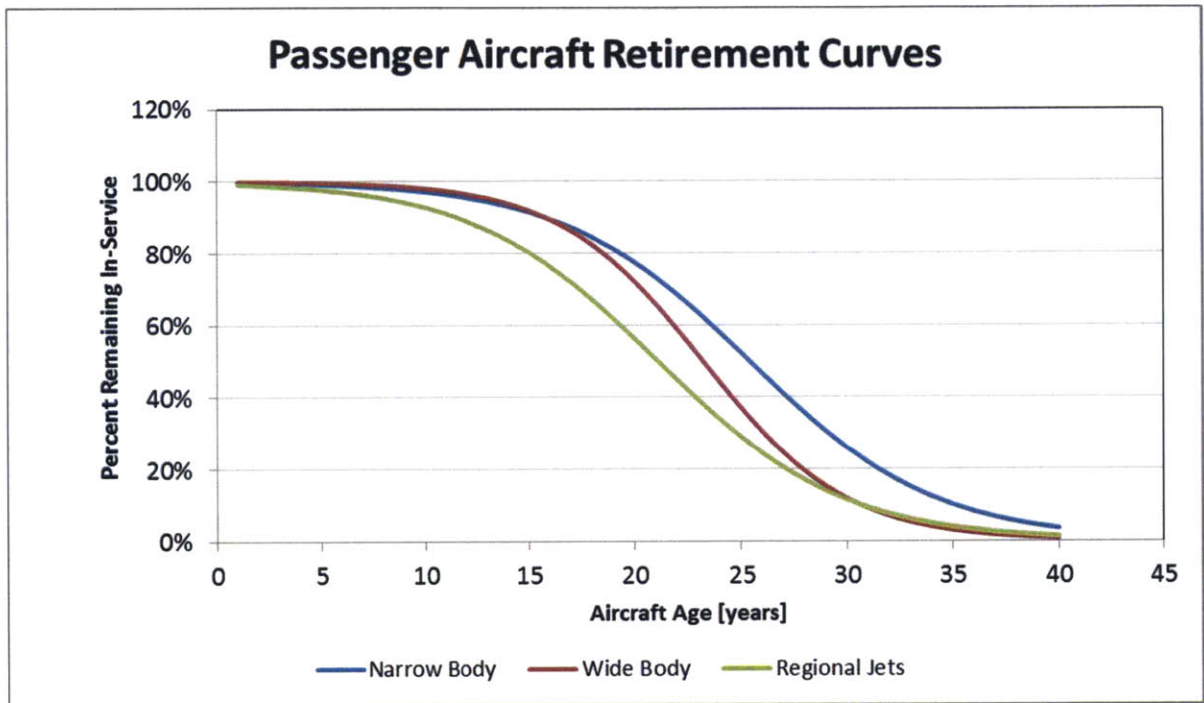
Figure 13: Retirement Curves

These retirement curves show the percentage of aircraft that remain in the fleet per number of years of service. Retirement curves are defined for a range of different aircraft classes, including regional jets as well as narrow and wide body passenger jets. This analysis focuses on narrow bodies, wide bodies, and regional jets, which can be seen to have service careers ranging roughly from 15 to 40 years. Each year of the analysis, the number of aircraft of each aircraft type to retire is determined based on the ages of the aircraft and the ratios provided in this chart. Using this ratio based system effectively predicts the retirement rates of aircraft as they enter the fleet.

In order to perform this calculation, each aircraft type is considered. For each aircraft type, all the aircraft of that model are grouped into different age bins by their entry into the fleet. For each of these bins, the appropriate number of new retirements is calculated based on the retirement curve for the current class of aircraft. The total number of retired aircraft is determined by summing for all the different ages of aircraft, and a final retirement number is output.

Once the number of retirements is calculated, the next step in the process is to determine which missions are left without an aircraft to service them. As discussed in the assumptions section, individual aircraft are not tracked in this model, but instead aircraft types are the focus of the calculation. Furthermore, since the model assumes that retained aircraft maintain their same flight schedule, the model requires determining which missions were previously flown by retiring aircraft. The model assumes that each aircraft within an aircraft type sees similar utilization by number of flights and therefore that the number of missions covered by a given aircraft type is equally split between all aircraft of that type.

Therefore, the percentage of aircraft retiring from the fleet is equivalent to the percentage of missions covered by that aircraft type which need new aircraft coverage.

Once the percentage of missions left uncovered is determined, the only remaining decision in this section is to choose the actual missions that are uncovered. The baseline system for making this decision is to randomly select which missions fall in each category, but Chapter 3 presents a study that tests the impact of this assumption by considering an alternative model in which new aircraft are assigned to the missions that take the greatest advantage of their increased fuel burn efficiency.

The second source of new missions is demand growth. Demand growth is fully defined by user inputs, which are required to define the amount of growth per mission bin for each year of the analysis. The model uses the expected volume of missions per seat class and range bin against the number of missions covered in the previous year to determine the number of new missions required. Chapter 6 considers the sensitivity of fleet evolution to different demand inputs. Other chapters assume constant demand.

By combining the missions defined in each of these two steps, the total shortfall for the initial fleet is calculated. This shortfall is passed into the next sub-model to inform the aircraft procurement decision.

2.3.2 Network Buildup Model

Once the total shortfall is computed and the set of missions that needs to be served by new aircraft is determined, the network buildup model takes over to determine new aircraft procurement. This model assumes that procurement decisions are made to serve a predefined set of routes determined to be valuable to the airline. The model does not consider the feedback loop between route definition and aircraft procurement opportunities since this intricacy goes beyond the scope of this thesis

This sub-model receives as inputs the set of missions to be served by new aircraft as well as the list of in-production aircraft available to be purchased. Given the assumptions discussed above, the fleet assignment logic must perform a matching process between the missions that must be served and the aircraft available to serve them. Keep in mind that a mission is defined as a set payload that must be carried a specified range. Given this definition, the matching process can be reduced to considering the design payload and range of aircraft available for procurement and determining for which aircraft the payload and range of the given mission match closely.

In order to illustrate this process, consider the missions in a single payload and range bin, as illustrated in Figure 14. The missions within this bin are for between 211 and 300 passengers and travel between 4001 and 5000 nautical miles. This mission bin is depicted in red in the figure.

In order to be considered to cover these missions, an aircraft must have a design maximum seating capacity and maximum range at least equivalent to these missions. Any aircraft with insufficient capabilities is excluded from covering these missions. This is depicted in the greyed out portion of the figure.

A second consideration is the efficiency penalty incurred by failing to match the aircraft's maximum design payload and range. As discussed above, this model will not consider low load factor missions, but will allow for long range aircraft to fly short range flights. Aircraft that would have low load

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factors if they covered this flight are depicted in yellow and aircraft that have acceptable mission capabilities to be considered for these missions are depicted in green. In total, any aircraft that has maximum mission capabilities in any of the red or green mission bins are considered available to cover these missions.
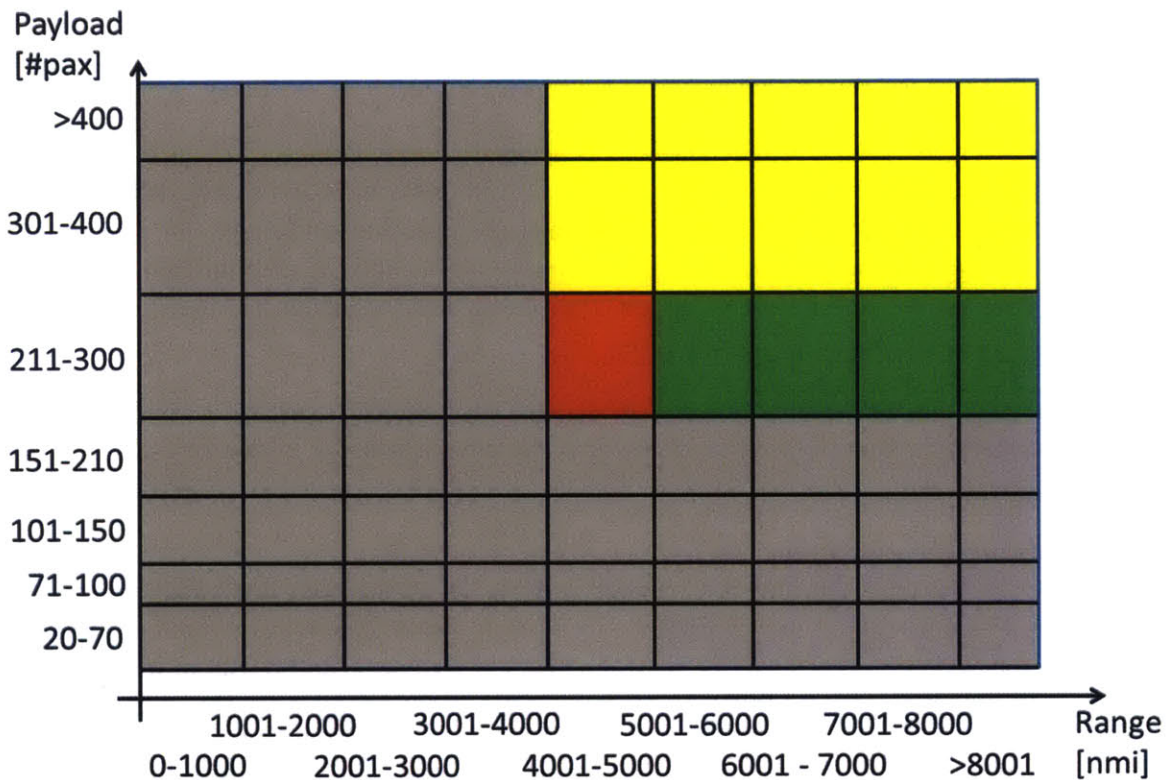
Figure 14: Visualization of Aircraft Available to Cover Example Missions

Since the focus of this model is to predict fleet-wide performance, the fuel burn performance aspect of competition will be considered while other areas of potential competition (such as pricing differences and passenger accommodations for example) will be neglected. This model considers two ways of assigning mission portions to different aircraft, referred to as a procurement strategy. The baseline procurement strategy is a simple equal market share assumption. Under this assumption, every aircraft that has been marked as eligible for a mission bin will be assigned an equal percentage of the missions in that bin. The second model uses aircraft fuel burn performance as a weighting parameter in order to preference more fuel efficient aircraft and provide a larger portion of missions to those aircraft. Chapter 4 will perform a sensitivity analysis of this procurement strategy assumption, and the details of the two models are discussed in detail there.

Once all aircraft procurements have been determined, the last stage of the network buildup process is fleet assignment. This model uses a simplified fleet assignment model, discussed in detail in the previous section, to determine which aircraft type will be used for each mission. Upon completing this step, the model will have produced a completed network, and can perform analysis on the total network to

determine fuel burn per flight, fleet makeup characteristics, fleet-wide fuel burn performance, and other data of interest.

2.4 Input Definitions

As with any forecasting model, this model for fleet evolution depends largely on model inputs to determine outputs. These inputs are particularly important in that they define the future scenario that the user is attempting to model. As such, focus has been placed on effectively defining the input set such that the user can communicate their modeling goals to the system. In order to achieve this, the inputs have been broken into three major sections. The first section defines the baseline fleet and is expected to be the most rigid as it will typically be based on past data. The remaining two sections define forecasting predictions for future commercial air travel demand and manufacturers product offerings. These two inputs allow for significant variability to allow for the testing of multiple different scenarios in order to achieve better understanding of the impacts of different potential trends in the future.

2.4.1 Base Year Data

The most basic form of input data is the base year data on which the fleet evolution forecast is performed. This includes two items, the initial fleet and the initial set of missions. A fleet and the missions it covers are considered a network, and the network is the only data that is passed from year to year in the main loop of the model. The model itself works on a yearly basis, and therefore the first year of the analysis only differs from later years in that the inputs are externally defined rather than created by the model during the previous year's analysis. While the network serves as a complete data set for each year of the analysis, this explanation will consider the fleet and the mission set separately.

First, consider the baseline fleet. This is made up of a set of aircraft. As discussed in the assumptions section, the model is not concerned with individual aircraft but instead considers the fleet from an aircraft type perspective. For each aircraft type the necessary data can be broken into three sections: mission capabilities, fuel burn performance, and age and quantity data. Mission capabilities define the payload and range capabilities of the aircraft, which are used to determine the missions that the aircraft can be used to cover. Fuel burn performance is used to calculate the overall fleet performance and is used to estimate how much fuel will be burned on each mission covered by this aircraft type. Finally age and quantity data is used for retirement calculations. The distinct ages of aircraft of this type in the fleet are enumerated alongside the number of aircraft of each age of this type in the fleet. This information, along with retirement curves, is used to determine how frequently aircraft of this type exit the fleet.

Along with the aircraft that make up the baseline fleet, the missions and aircraft assignments are necessary to complete the network definition. A mission is defined as a distance travelled along with a payload carried. When paired with an aircraft assignment, the two together define a full flight. Using the mission definition and the aircraft fuel burn performance, overall fuel burn for the flight can be calculated. Furthermore, this pairing of data will be used to determine when a mission needs a new aircraft to cover it based on retirement.

Not all aircraft in the baseline fleet will be included as in-production aircraft. This occurs when an aircraft type goes out of production based on manufacturers' decisions, but aircraft of that type remain in service. This generally has no impact on the model, since there is no need to link the two aircraft sets, but there is a concern when the performance data required for the model to run is not available for the

aircraft. In these cases, the user can use actual flight fuel burn data to determine the fuel burn cost of each mission covered by this aircraft type, instead of calculating an estimate based on aircraft performance data. As long as one of these two pieces of data is available, the model can run unperturbed.

For the analysis in this thesis, base year data is defined by 2010 flight data.

2.4.2 Demand Forecast

The demand forecast defines how many new flights are expected to be flown in each year of the analysis. Since this model does not consider flights on an individual basis, the format of the demand forecast is expected to follow the mission binning setup used in the rest of the model. Therefore, the demand forecast is defined as the number of new flights expected in each bin, delineated by both seat count and flight range.

This forecast has a significant impact on the overall fuel burn of the fleet, since changes to the amount of passenger travel output will necessarily cause changes in the amount of fuel expended. While aircraft technology also has a significant impact on fleet-wide fuel burn usage, it is clear that, for constant technology, greater volume of service requires greater fuel burn to provide. This, however, is expected to not have a significant impact on the fuel burn per passenger travel performance metric. The sensitivity of fleet-wide fuel burn performance to changes in the demand forecast is studied in Chapter 6.

2.4.3 In-Production Aircraft

The second major forecasting input for the model is the question of what aircraft will be considered for procurement throughout the analysis. Each aircraft included in this dataset must have the necessary aircraft type information detailed above, which includes aircraft capabilities in both range and payload as well as fuel burn performance of the aircraft. Also required is information about when the aircraft will be available for procurement, in particular when the first and last year of production should be, or the in-production and out-of-production year respectively. By using this information, the model can simulate aircraft replacements with newer models boasting technology and efficiency improvements. In order to do this, two similar aircraft are included in the potential procurement dataset, with one having lower efficiency performance and earlier in- and out-of-production years, and the other having better efficiency and later in- and out-of-production years.

Again, this amount of control over the fleet evolution forecast is significant. The most basic way to see this is by considering if an entire aircraft type were ignored. Consider again the A380 and 787 discussion from Chapter 1. If one of those aircraft were not available to be purchased, the entire question of which aircraft would be a better investment for the manufacturer would be moot. Furthermore, when defining future aircraft that will enter the fleet, the fuel burn benefits to claim based on predicted performance of next generation aircraft must be considered. These decisions have impacts on the overall fleet-wide fuel burn metrics considered as outputs to the model.

This analysis does not attempt to predict economic competition between manufacturers, and as such, for the tests in this thesis, the aircraft in each mission bin will be reduced to one per technology level. This means that no two aircraft will have both similar mission capabilities and fuel burn performance. This simplification is taken loosely from the Purdue FLEET model (Tetzloff and Crossley, 2012), and is used because it closely fits the scope of the analysis, with a targeted focus on fleet wide fuel burn. The aircraft used in the baseline analysis can be seen in Table 1. Aircraft in the current technology

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column are used in the opening years of the analysis before eventually going out of production if a newer aircraft is available to replace them. In the analyses presented in the coming chapters, future technology aircraft will be added to this baseline list with more efficient fuel burn performance and later entry into service dates. The choice of aircraft to include will be based off the particular analysis being performed and details for this aircraft will be provided. Fuel burn data is based off BADA 3 (EuroControl, 2013) data for current technology aircraft, and will be scaled based on percentage fuel burn savings assumptions for future aircraft.

Table 1: Representative Aircraft Used in Each Seat Class

Seat Class	Number of Seats	Aircraft Based Off	Fuel Burn per Kilometer	Fuel Burn per LTO
1	20-70 seats	Embraer 145	1.57	212.35
2	71-100 seats	Bombardier CRJ1000	2.28	324.70
3	100-150 seats	Boeing 737-700	3.31	547.79
4	151-210 seats	Airbus A320-200	3.68	633.94
5	211-300 seats	Airbus A330-300	8.07	1454.01
6	301-400 seats	Boeing 777-300ER	9.26	2010.07
7	>400 seats	Airbus A380-800	17.58	3663.43

Furthermore, Chapter 5 considers the effects of different aircraft introduction strategies and tests the significance of this input set by considering the effects of providing different aircraft types to the fleet evolution model.

2.5 Model Usage

The following chapters will consider sensitivity analyses regarding inputs and assumptions of interest. Each analysis run through this model will require certain alterations to the baseline inputs and assumptions. Each analysis will utilize a specific set of assumed future aircraft defined to meet the needs of that analysis. Chapter 3 will consider modifications to retirement and replacement strategies for aircraft exiting the fleet. Chapter 4 will consider different models of new aircraft procurement, asking how significantly fleet wide fuel burn is affected by procurement strategies that focus more heavily on fuel burn performance. Chapter 5 will consider the impact of different future aircraft sets by studying two different aircraft development routes and the fleet impacts of the resulting aircraft. Finally, Chapter 6 will study the importance of the demand forecast on fleet wide fuel burn.

Chapter 3: Retirement Strategy Sensitivity Testing

As aircraft retire from the fleet they will need to be replaced by new aircraft. The process of replacement not only requires determining which aircraft retire and which aircraft are procured, but must also determine which flights will be flown by older aircraft remaining in the fleet from previous years and which will be flown by newly procured aircraft. The model must determine which flights will be covered by new aircraft, with more advanced technologies and therefore greater fuel burn savings, and which will be covered by older, less efficient aircraft.

For this analysis, two models for aircraft retirement and replacement will be considered. The first model, referred to as the random retirement model, will randomly assign old and new aircraft to flights. This assumption models a replacement system that does not consider fuel burn performance in retirement decisions.

Conversely, the second model, referred to as the fuel burn efficiency retirement model, attempts to place new aircraft on flights that are more fuel burn intensive, thus maximizing the fuel burn savings of more efficient aircraft. Aircraft fuel burn performance is calculated based on a fuel burn per range value in this model, and therefore longer flights provide more potential for fuel burn saving. By retiring older aircraft from long range flights before short range flights, this model can simulate an aircraft retirement strategy that preferences placing new, more efficient aircraft on the most beneficial missions available.

3.1 Model Specifications

The retirement strategy analysis focuses on a specific model assumption, and so baseline inputs and assumptions will be used in most cases for inputs other than the retirement model. This section will focus on the future aircraft set as well as the specifics of the retirement assumptions

3.1.1 Future Aircraft Set

The focus of the retirement strategy model is replacement of older aircraft, not the manner of introduction of new aircraft, and therefore a simplified future aircraft set is appropriate. In particular, a single future aircraft will be assigned for each seat class, and these aircraft will all enter into production simultaneously 10 years after the beginning of the analysis, in 2020. The aircraft in each seat class will be 10% more efficient than the current technology aircraft in that seat class. This scenario allows the model to predict the effects of updates to technology levels. This data is presented in Table 2

Table 2: Retirement Assumption Test In-Production Fleet

Technology Level	In-Production Year	Out-of-Production Year	Fuel Burn Performance
Current Technology Aircraft	Pre- 2010	2023	Baseline Values
Future Technology Aircraft	2020	Post- 2040	10% Fuel burn Efficiency Improvement

3.1.2 Retirement Strategy

As aircraft retire from the fleet based on their age and retirement curves described in the previous chapter, they will need to be replaced by new aircraft. The model assumes aircraft that remain in the fleet

retain their flights, or continue to cover the same missions as the previous year. Therefore, the model for retirement strategy answers the question of which missions will be marked as flown by retiring aircraft. This determines which flights will be flown by new aircraft and which will continue to be flown by older aircraft.

The rate of retirements and the process of aircraft replacement are not altered in this analysis. Instead, the logic for determining which missions will be left uncovered, or in need of a new aircraft to fly them, will be altered for this model.

Two cases for retirement strategies, introduced above, will be considered. In the random retirement case, uncovered missions are assigned randomly, and new aircraft will be equally likely to take over any mission from a retiring aircraft type. In contrast, the fuel burn efficiency based retirement case ranks missions by range and assigns new aircraft types to the longest range missions first.

3.2 Retirement Strategy Analysis Results

In order to understand how the retirement assumption affects fleet evolution, this analysis will study two main sets of results. First, the types of missions covered by different technology levels will be tested. This analysis will show that different retirement assumptions change the range distributions of flights covered by the baseline fleet, current technology aircraft, and future technology aircraft. Second, fleet wide fuel burn impacts of this assumption will be presented and discussed.

3.2.1 Baseline Fleet Mission Coverage

The impacts of this modified assumption can be studied by comparing the mission coverage of aircraft in the baseline fleet over time under the random retirement assumption versus under the fuel burn efficiency based retirement assumptions. In order to study the impacts of these assumptions, one representative seat class will be chosen. Since aircraft in the lowest seat classes do not take on long range missions, the results are less pronounced, and so a higher seat class with a wider mission envelope for ranges is more appropriate. For this study, seat class 5 (small wide body aircraft) will be considered.

Figure 15 depicts the range distribution of flights covered by baseline aircraft in different years of the analysis under the random retirement assumption, while Figure 16 shows the same data but for the fuel burn efficiency based retirement assumptions.

In both figures the 2010 distribution of flights is identical. Over time, these flights will be reduced due to retirements of the baseline aircraft. The retirement strategy assumption determines which range flights are retired first. All flights that are retired by baseline aircraft will be taken over by new, more efficient aircraft.
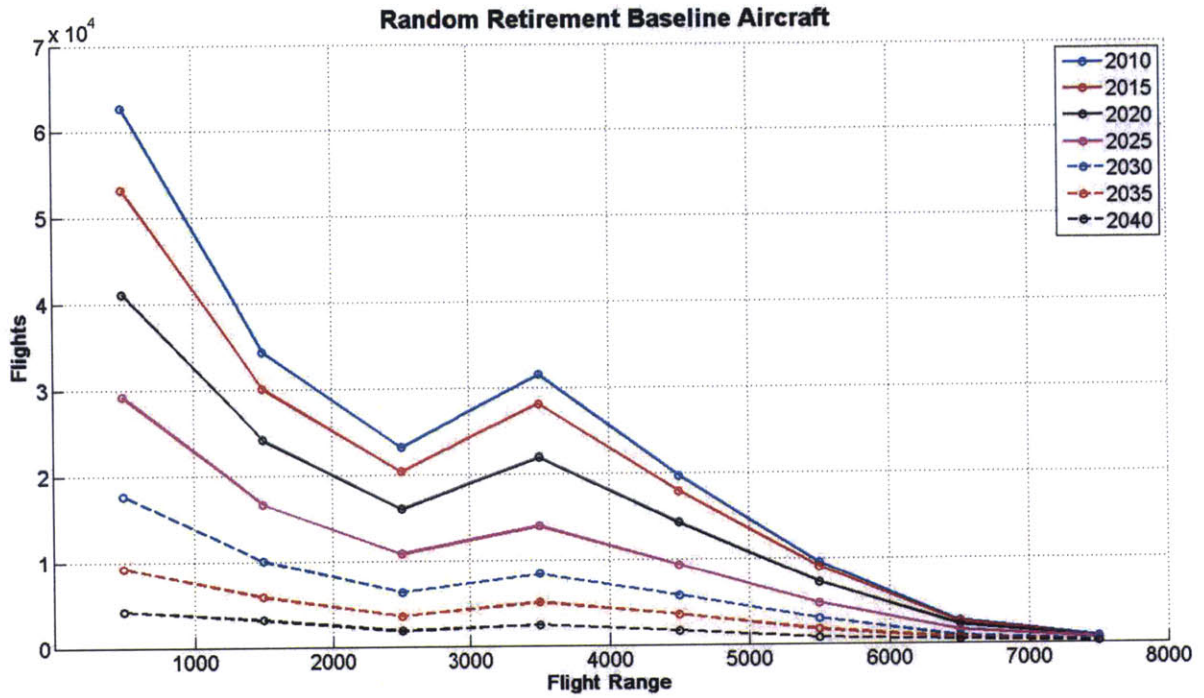
Figure 15: Baseline Aircraft Operations Ranges Under Random Retirement
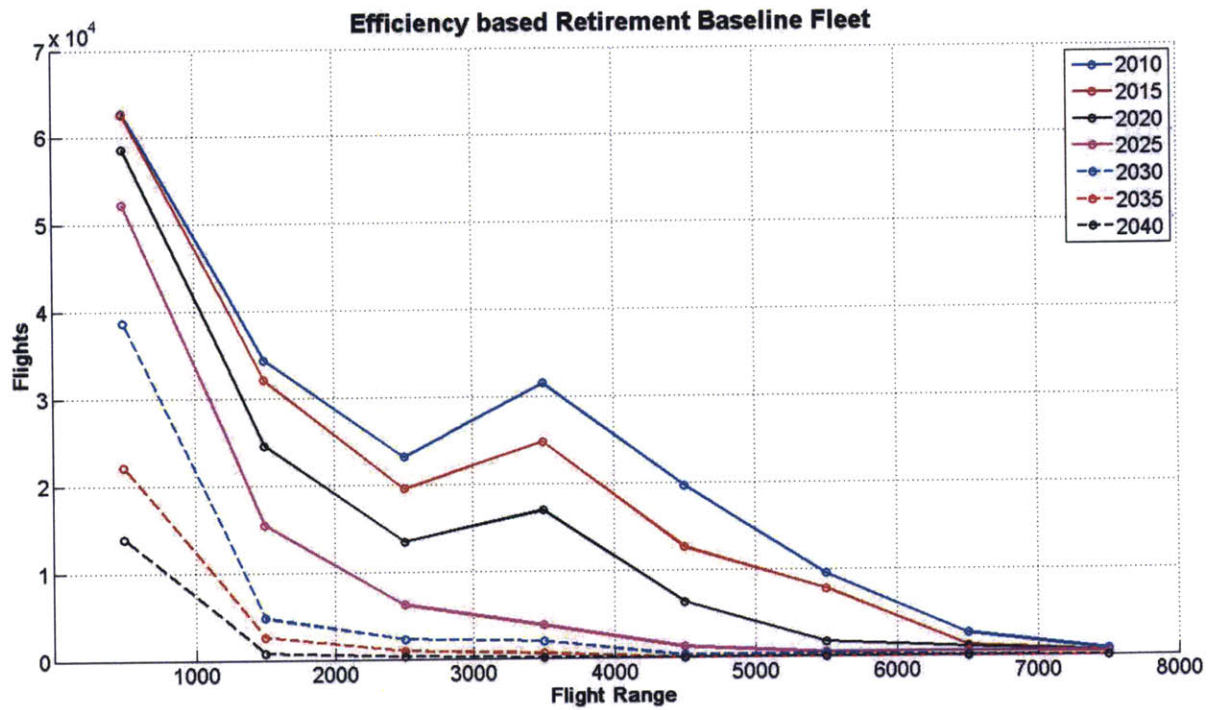
Figure 16: Baseline Aircraft Operations Ranges Under Efficiency Based Retirement

The random retirement model shows a proportional decrease in the number of flights covered at all ranges. In contrast, the efficiency based retirement plot shows more significant reductions for long range flights, and by the end of the analysis there are only a significant number of short range flights, with no long range flights covered by baseline aircraft.

Since the baseline aircraft are the least technologically advanced and therefore least fuel burn efficient aircraft, reducing the number of long range flights of these aircraft reduces their fuel burn impact.

3.2.2 Current Technology Aircraft Mission Coverage

The analysis performed here runs for a total of 30 years, from 2010 to 2040. In that timeframe, a significant portion of aircraft that enter the fleet in the first years of the analysis will retire by the conclusion of the analysis. For this reason, studying the mission coverage of these aircraft can also provide insight on the impacts of the modified retirement strategy system.
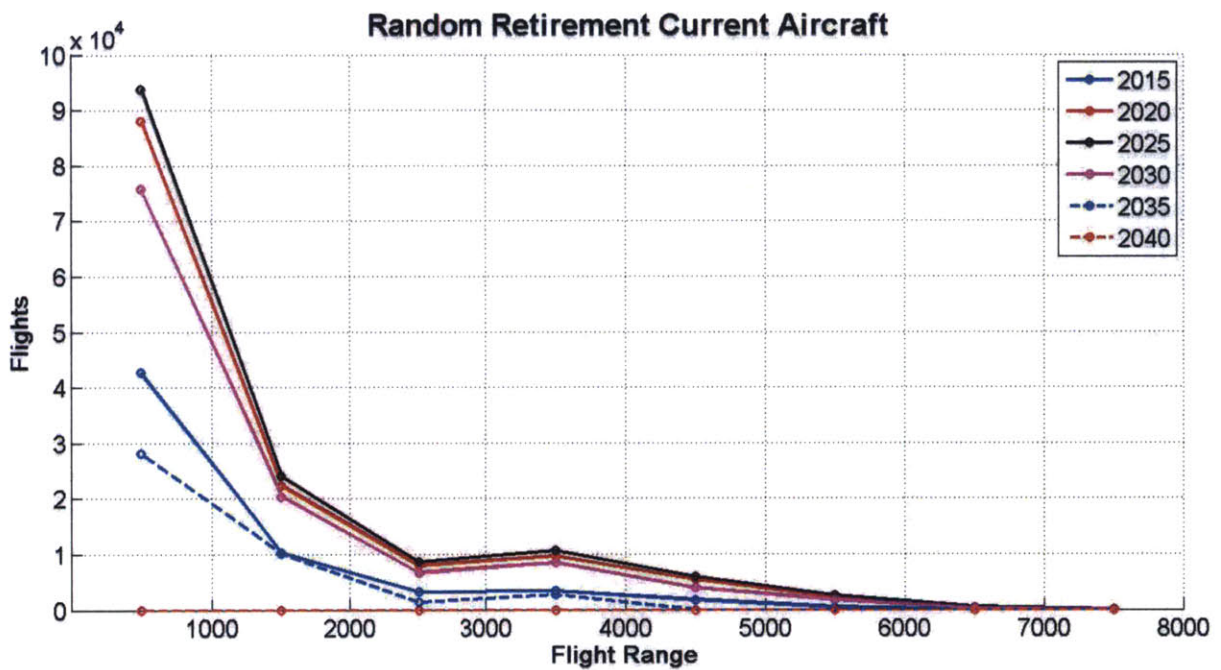
Figure 17: Current Technology Aircraft Operation Ranges Under Random Retirement
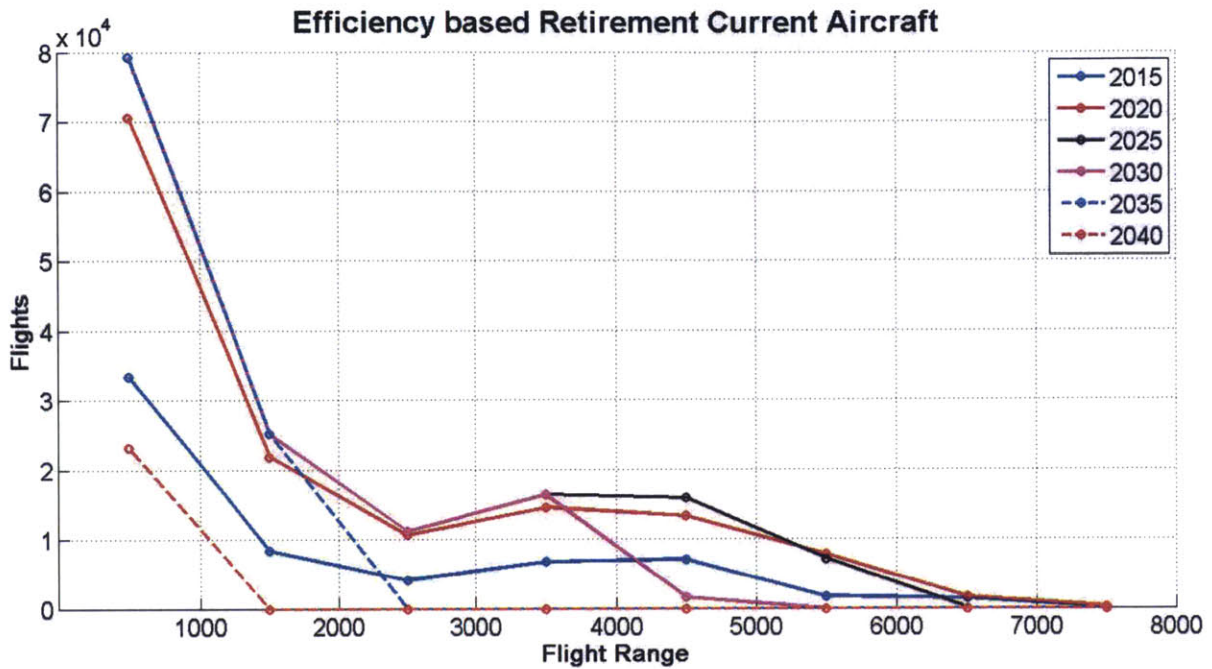
Figure 18: Current Technology Aircraft Operation Ranges Under Fuel Burn Efficiency Based Retirement

Figure 17 shows the total number of operations flown in each range bin at different times in the analysis for the random retirement strategy assumption. Similarly, Figure 18 shows the same data for the fuel burn efficiency based retirement strategy assumption.

Unlike the baseline operations, the flights covered by current aircraft are not monotonically decreasing since new aircraft enter the analysis through aircraft procurement. It can be seen that in the first years of the analysis there are far fewer flights than in some of the later years. However, this aircraft also goes out of production and therefore will decrease in number of flights starting after 2023.

The first point of interest in these figures is the difference in the entrance of this aircraft into the fleet. It can be seen by comparing the values in 2015 of the two plots that early on in the analysis, the efficiency based retirement model has the new, more efficient aircraft cover more long range flights and less short range flights than the random retirement model. As the analysis continues, this trend is also seen to continue through 2025, where a lower number of short range flights are covered in exchange for a larger number of long range flights covered.

Also of interest is the fact that this aircraft does go out of production during the analysis and a newer aircraft becomes available after it. In the later years of the analysis, specifically after 2023, this aircraft is no longer available for procurement and therefore no longer takes on new flights, but instead only retires, giving up flights to the newer more efficient aircraft that replaced it. Similarly to the baseline aircraft, it can be seen that, from 2025-2040, the random retirement model has a proportional decrease in the number of flights covered by this aircraft across all ranges, while the fuel burn efficiency based retirement model preferences giving up longer range flights before short range flights. Specifically, it can be seen in 2030 that the number of flights over 5000 nautical miles is reduced to zero, and in 2035 no

flights over 3000 nautical miles are covered. This reduction in long range flights, but maintenance of short range flights simulates a system in which aircraft of these types are assigned to the shortest range missions available in order to minimize the fuel burn penalty received by utilizing these aircraft instead of a newer more efficient aircraft.

3.3.3 Future Technology Aircraft Mission Coverage

The final technology level aircraft are the most efficient aircraft to be used in this analysis. Unlike the aircraft considered previously, these aircraft provide better fuel burn performance than any other, and therefore assigning these aircraft to long range flights over short range flights provides the greatest fuel burn savings possible.

Unlike the previous plots, the number of missions covered by aircraft in this technology level will continuously rise from the time of first delivery until the end of the analysis. Figure 19 depicts the number of flights covered by future technology aircraft throughout the analysis under the random retirement strategy. Figure 20 shows the number of flights covered by future technology aircraft under the fuel burn efficiency based retirement strategy.
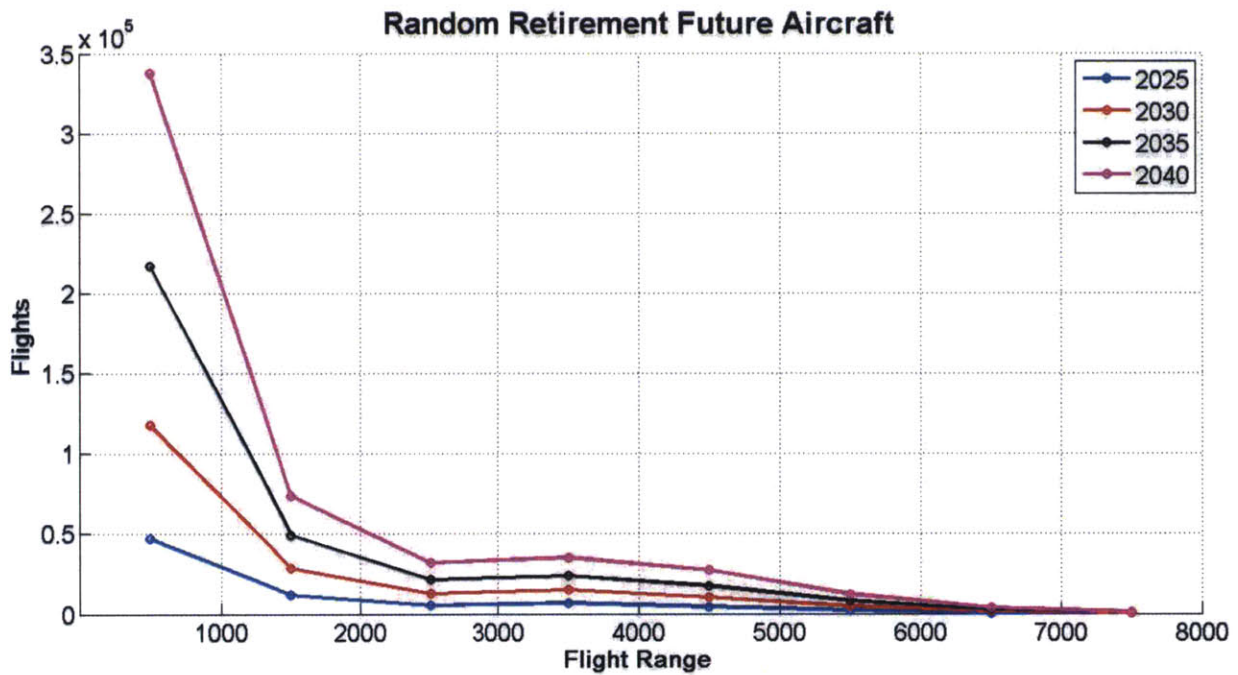

Figure 19: Future Technology Aircraft Operation Ranges Under Random Retirement
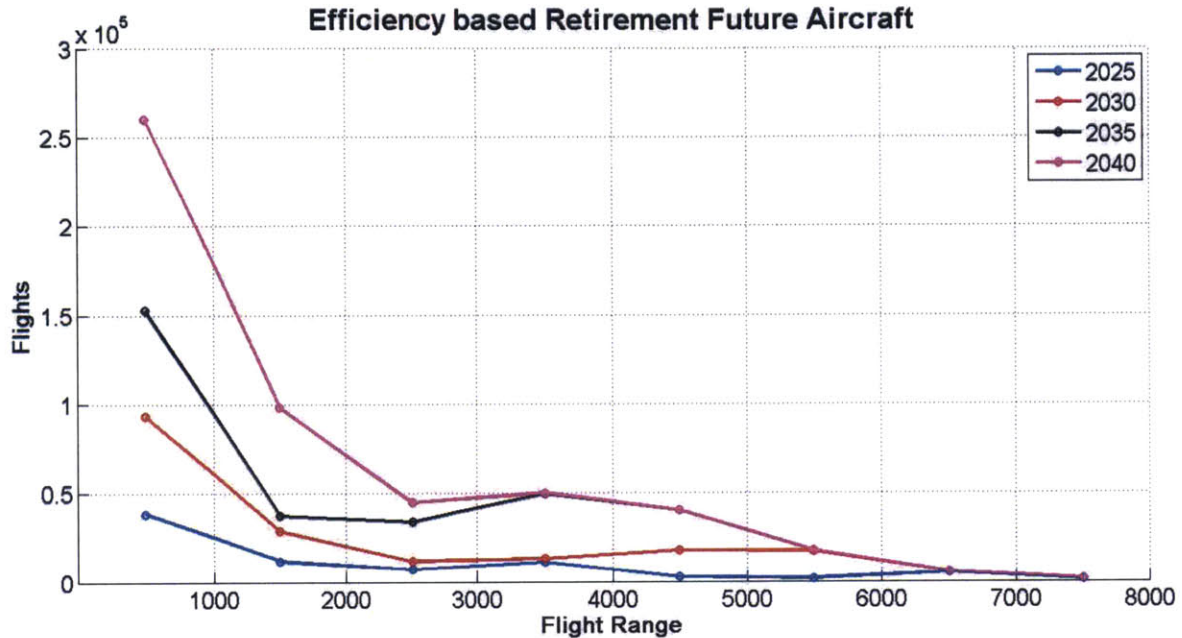
Figure 20: Future Technology Aircraft Operation Ranges Under Fuel Burn Efficiency Based Retirement

As expected, in the random retirement case the number of flights covered by the future technology aircraft increase proportionally across all ranges. In contrast, the number of long range flights increase faster, and the number of short range flights lag behind the random retirement case, and do not reach the same maximum even at the end of the analysis.

It can be seen that the total number of available long range flights is reached at different years in the analysis under the efficiency based retirement strategy. For example, the total number of long range flights available greater than 6000 nautical miles is reached immediately in 2025. In 2030, the number of flights between 5000 and 6000 nautical miles is maximized. And in 2035, the number of flights of range greater than 3000 nautical miles is taken on by future technology aircraft. In contrast, the random retirements model shows an increase in the number of flights in all ranges even in the final year of the analysis.

Furthermore, it is of note that the total number of the shortest range flights covered by the future technology aircraft is lower in the efficiency based retirement model than in the random retirement model. This occurs because the current technology aircraft in the efficiency based retirement model retain a greater number of short range flights at the end of the analysis than they do in the random retirements model.

By focusing the flight coverage of the most efficient aircraft in the fleet to the most fuel burn intensive missions available, the efficiency based retirement model is intended to produce net fleet-wide fuel burn savings over the random retirements model.

3.3.4 Fleet-Wide Fuel Burn Performance

Given the impact on fleet assignment presented in the previous sections, analysis can be conducted on the essential question of fuel burn savings. Without making any updates to aircraft technology, total fuel burn savings between the random retirement and efficiency based retirement models can be solely attributed to the retirement strategy modifications between the two cases.
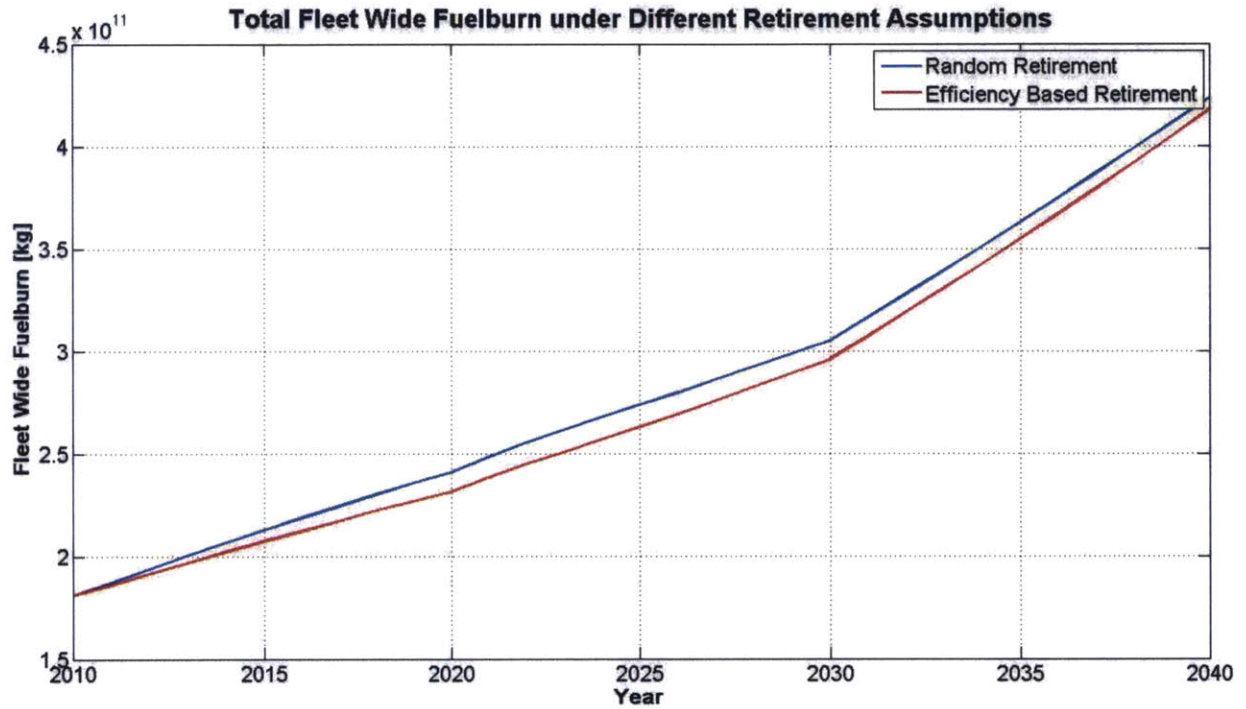

Figure 21: Total Fleet Wide Fuel Burn per Year Under Different Retirement Assumptions
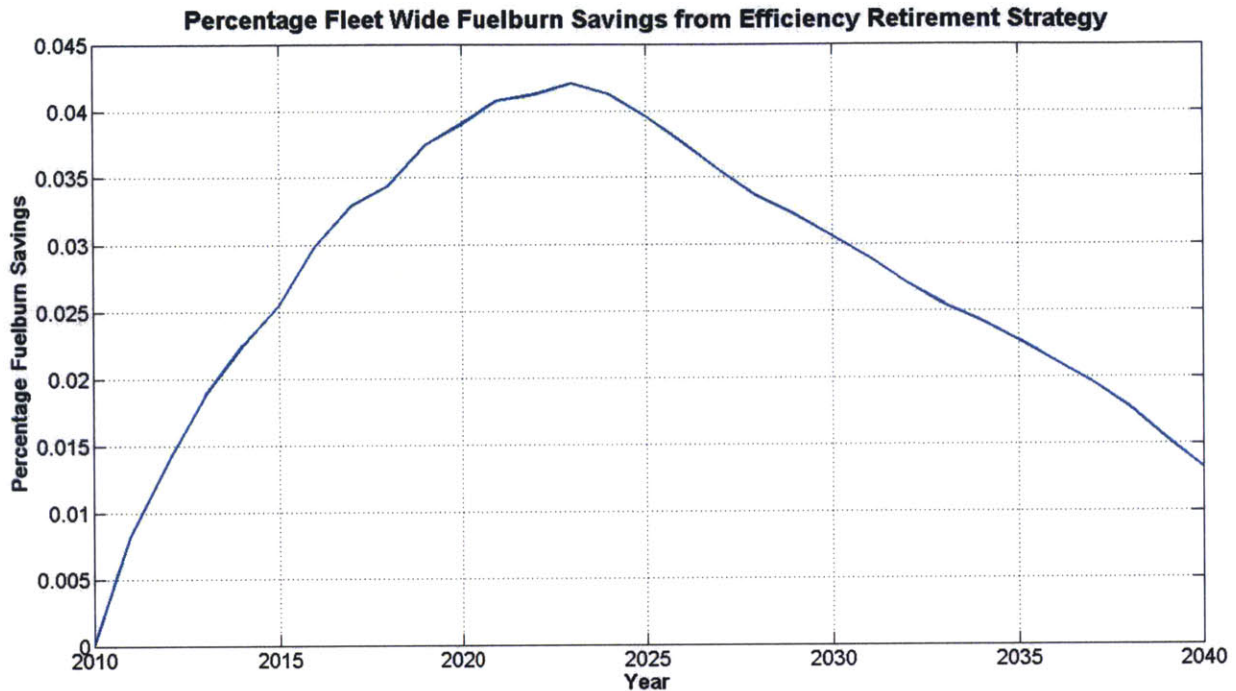
Figure 22: Percentage Fuel Burn Savings of Efficiency Focused Retirement Model over Baseline Retirement Model

Figure 21 depicts the total yearly fuel burn of the fleet under the different retirement assumptions described above. As expected, this plot shows that the efficiency based retirement strategy provides fuel burn savings versus the random retirement strategy. In particular, fuel burn savings begin immediately, and the gap between the two methods increases steadily over the first roughly fifteen years of the analysis. After this, the total savings diminish for the later years of the analysis, but efficiency based retirement is always beneficial. In total, an estimated 200 billion kilograms of fuel are saved throughout the analysis, compared to a total 9 trillion kilograms burned in the random retirement analysis.

Figure 22 presents the percentage yearly fleet wide fuel burn savings realized by the efficiency based retirement model over the random retirement model. This value is calculated by comparing the total fuel burn saved for a given year compared to the total fuel burn consumed by the random retirement strategy in that year. The graph shows that savings climb from 0% to 4.25% throughout the first fifteen years of the analysis before reaching a maximum and then descend back to roughly 1.5% in the last year of the analysis. The overall percentage fuel burn savings of the efficiency based retirement model over the random retirement model is 2.7%.

One interesting result of this analysis is finding that the fuel burn savings reach a maximum roughly fifteen years into the analysis before declining for the remainder of the analysis. This occurs because only one round of technology advancement is introduced in the timeframe of the analysis, and also because only one full round of retirements occurs. The fuel burn savings in the efficiency based retirement model occur because long range flights are more quickly taken over, first by the current technology aircraft that are more fuel efficient than the baseline fleet, and second by the future technology

aircraft that are more fuel efficient than the current technology aircraft. Once the majority of long range flights have been assigned to future technology aircraft, replacing short range flights with these aircraft does not have as much of an impact, and the randomized retirements in the baseline strategy are able to normalize the fuel burn benefits. If this analysis were allowed to run for many more years, eventually all missions would be flown by the most fuel efficient future aircraft and the yearly fuel burn of both the retirement strategies would be equivalent. This equilibrium state, however, is unlikely to be realized in the future, as new aircraft models that are outside the scope of this analysis' timescale would likely be introduced to continue providing opportunities for further benefits.

This analysis shows that assigning more fuel burn intensive missions to more fuel efficient aircraft has the effect of front-loading fuel burn benefits. This has value for two reasons. Firstly, the transient benefits of producing less fuel burn during the number of years before the two fleets reach the same equilibrium provides a net fuel burn benefit. Secondly, since the fleet is not static, it is reasonable to assume that fleet evolution will not stagnate in the future, and that new, more efficient aircraft will continue to be produced. As shown by considering the current technology aircraft, even though advantages can be garnered by using this aircraft when it is the most efficient available, those advantages can be replicated again when a new aircraft, such as the future technology aircraft in this model, enters into production.

This analysis has shown that assigning aircraft to missions based on fuel burn considerations, even without changing procurement strategies, demand forecasts, or future aircraft technologies, can show multiple percentage points of yearly fuel burn savings across the commercial fleet.

Chapter 4: Procurement Strategy Sensitivity Analysis

Another major decision in the process of fleet evolution is aircraft procurement. Once the decision has been made to expand the fleet, the decision of which aircraft to procure in order to meet shortfall needs must be made. This decision is influenced by factors including aircraft performance, price, and customer experience. It is beyond the scope of this model to emulate a full procurement model including all these factors, but it is important to consider how much of an impact fuel burn performance affects procurement decisions. As such, an analysis is performed to study the fleet-wide impact of procurement strategies that prefer more fuel efficient aircraft.

In order to test this effect, an analysis is performed that utilizes different procurement strategies. Two different procurement strategies will be analyzed, and the fleet evolution and particularly the fuel burn impacts of these two different strategies will be considered. These procurement strategies will not alter which aircraft are considered eligible to cover a mission, but will only affect the number of missions each eligible aircraft type covers, and therefore the number of aircraft of that type which must be purchased.

The first procurement strategy, used as a baseline, will be an equal market share strategy. Under this strategy, all the aircraft available to cover a given set of missions will be provided with an equal share of those missions. This strategy places no premium on the fuel burn performance of an aircraft type when making procurement decisions.

The second procurement strategy is an efficiency weighted procurement strategy. Under this strategy, the number of aircraft procured is based on the efficiency of an aircraft, such that more efficient aircraft are purchased more frequently and less efficient aircraft are purchased proportionally less. This strategy assumes a premium of aircraft efficiency as it preferences purchasing more efficient aircraft over less efficient aircraft.

4.1 Model Specifications

This analysis focuses heavily on aircraft procurement and future aircraft fuel efficiency performance. For this reason, other major inputs and assumptions will be held to baseline values. The process for determining shortfall will be held constant between different cases in this analysis. This section will focus on the future aircraft set as well as the procurement strategies to be tested.

4.1.1 Future Aircraft Set

This analysis focuses heavily on the fuel burn performance of future aircraft entering the fleet. For this reason, a more detailed approach to the future aircraft set is performed than in the previous analysis. The process for future aircraft is repeated for each seat class, with the current technology aircraft for that seat class used as a baseline. In order to accurately portray the importance of this modeling assumption, multiple aircraft with a variety of fuel burn performance parameters are necessary to be selected from.

As such, three future aircraft will be added to each seat class with 7%, 12%, and 15% fuel burn savings over the baseline model respectively. These aircraft will go into production at different times, with first production years of 2015, 2020, and 2025 respectively. This analysis is also the only analysis in

which the current technology aircraft do not go out of production, but remain in production for the duration of the analysis. This is to allow for multiple aircraft of varying performance to be considered eligible to complete each mission, with four aircraft available in each bin starting in 2025. The data for these aircraft is presented in Table 3.

Table 3: Aircraft Procurement Test Fleet

Technology Level	In-Production Year	Out-of-Production Year	Fuel Burn Performance
Current Technology Aircraft	Pre- 2010	Post- 2040	Baseline Values
Future Technology Aircraft 1	2015	Post- 2040	7% Fuel Burn Efficiency Improvement
Future Technology Aircraft 2	2020	Post- 2040	12% Fuel Burn Efficiency Improvement
Future Technology Aircraft 3	2025	Post- 2040	15% Fuel Burn Efficiency Improvement

4.1.2 Procurement Modeling Assumption

This analysis will test two procurement strategies. The use of a procurement strategy is to determine, given a number of eligible aircraft and a number of missions within a mission bin, the proportion of missions to award to each aircraft. Determining how many missions to assign to each aircraft determines how many of each aircraft type to purchase and therefore this decision directly influences fleet makeup and also has a significant effect on the fleet-wide fuel burn performance output by the model. The two procurement strategies tested here place different levels of importance on the fuel burn performance of the aircraft considered.

The first option, intended to be used as a baseline analysis, is to use an equal market share assumption. Under this assumption, each aircraft type is granted an equal portion of the total missions. By equally splitting the available missions between aircraft types, this assumption ignores the relative fuel burn performance of these aircraft when making procurement decisions.

The first competition system implicitly assumes that the cost of procuring a new aircraft is well balanced with the savings provided by reduced fuel burn due to technology advances. In particular, this assumes that an aircraft with lower fuel burn savings will cost less in order to make up the difference in value to the airline purchasing the aircraft. The second option, however, assumes a more forward-looking procurement methodology, which places a premium on more fuel efficient aircraft. This methodology is justified in situations where airlines predict that the long term costs associated with burning more fuel outweigh the one-time cost of purchasing the aircraft.

This second model attempts to forecast a procurement system in which aircraft with better fuel burn performance are purchased more frequently than similar aircraft with comparable capabilities but lower performance. This subsystem uses fuel burn per seat-kilometer as its measure for fuel burn performance. This model uses the percentage efficiency difference between aircraft in order to determine what percentage of missions to award each aircraft type.

This model uses a variable weighting function in order to determine the percentage of missions to assign to each aircraft. The weighting function uses the least fuel efficient aircraft as a baseline, and uses the percentage better efficiency that each other aircraft has over the baseline aircraft as the weighting function basis. This percentage value is multiplied by a significance parameter, which can be adjusted to determine how aggressively to preference more fuel efficient aircraft. This analysis found that a parameter of 10 produced desirable mission assignments. Once variable weights are assigned based on the multiplication of the significance factor to the basis values for each aircraft, each weighting is normalized by the total to provide the final percentage of missions that each aircraft will receive.

In order to illustrate this process, Table 4 has been produced using different numbers of aircraft to give examples of how the algorithm works. It can be seen in this table that the most efficient aircraft receive an advantage based on the number of aircraft considered, but that the inclusion of more aircraft reduces the share of all the aircraft considered. It can be seen, especially in scenario 3, that the algorithm preferences higher efficiency more, since the two most efficient aircraft take up 63.1% of the market share, while the three remaining aircraft all only take up 36.9% of the market share.

Table 4: Mission Allocation for Performance Based Competition Model

Scenario	% of Missions assigned to each Aircraft
2 aircraft, aircraft A is 12% more efficient than aircraft B	A: 67.4%; B: 32.6%
3 aircraft, A is 5% more efficient than B, which is 7% more efficient than C	A: 47.9%; B: 32.5%; C:19.6%
5 aircraft, each aircraft is 5% more efficient than the previous	A: 37.6%; B: 25.5%; C: 17.3%; D: 11.7%; E: 7.9%

4.2 Procurement Strategy Analysis Results

4.2.1 Market Share Analysis

The direct effect of the different procurement methods studied will be to influence the market share of different aircraft types. The analysis presented here is an aggregate of all seat classes, however it should be noted that, since each seat class has identical technology levels, first delivery dates, and fuel burn efficiency, the overall values will be replicated in each seat class (proportional to that seat class' total market share).

First, consider the market share of each aircraft type for the newly procured aircraft in a single year. Presented is data for 2030, once all aircraft have gone into production. This data excludes all flights that recur from the previous year to visualize the instantaneous difference in procurement between an equal market share and an efficiency weighted procurement strategy. This proportional input is replicated each year of the analysis, potentially with different numbers of aircraft, in order to produce total procurement throughout the analysis.

Figure 23 presents the percentage market share for each aircraft technology level. As can be seen in this figure, the equal market share assumption provides 25% of missions to each of the four technology levels, while the efficiency weighting strategy provides greater market share to more efficient aircraft and smaller market share to less efficient aircraft.
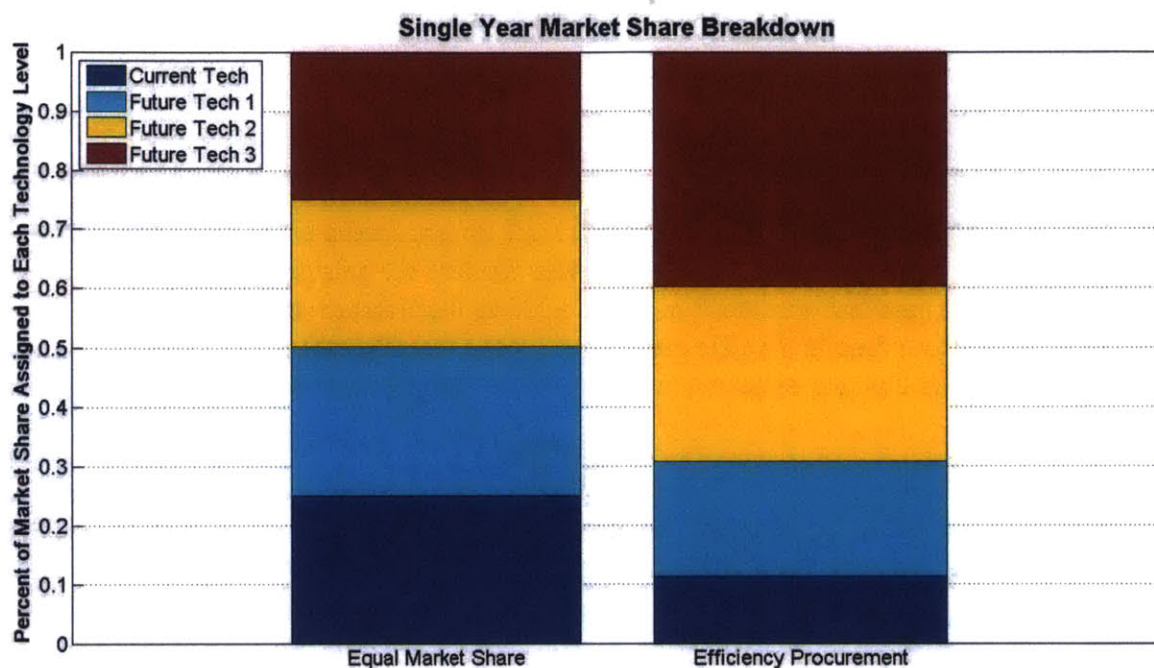
46

Figure 23: Comparison by Procurement Strategy of New Market Share Breakdown

Also of interest is the overall market share for aircraft of different technology levels as it evolves over time. In particular, analyzing the tradeoff between earlier introduction into the fleet and lower fuel burn performance on overall market share explains trends in fleet-wide fuel burn makeup. Differences in the overall market share of more efficient aircraft versus less efficient aircraft produce the fleet-wide fuel burn performance differences between the two procurement strategies that will be considered in the next section.

Figure 24 and Figure 25 present the yearly market share in available seat kilometers (ASKs) for the equal market share and efficiency weighted procurement strategies respectively. While the total yearly ASKs covered by these aircraft is equivalent in the two plots, the proportions of market share assigned to each technology level are different.
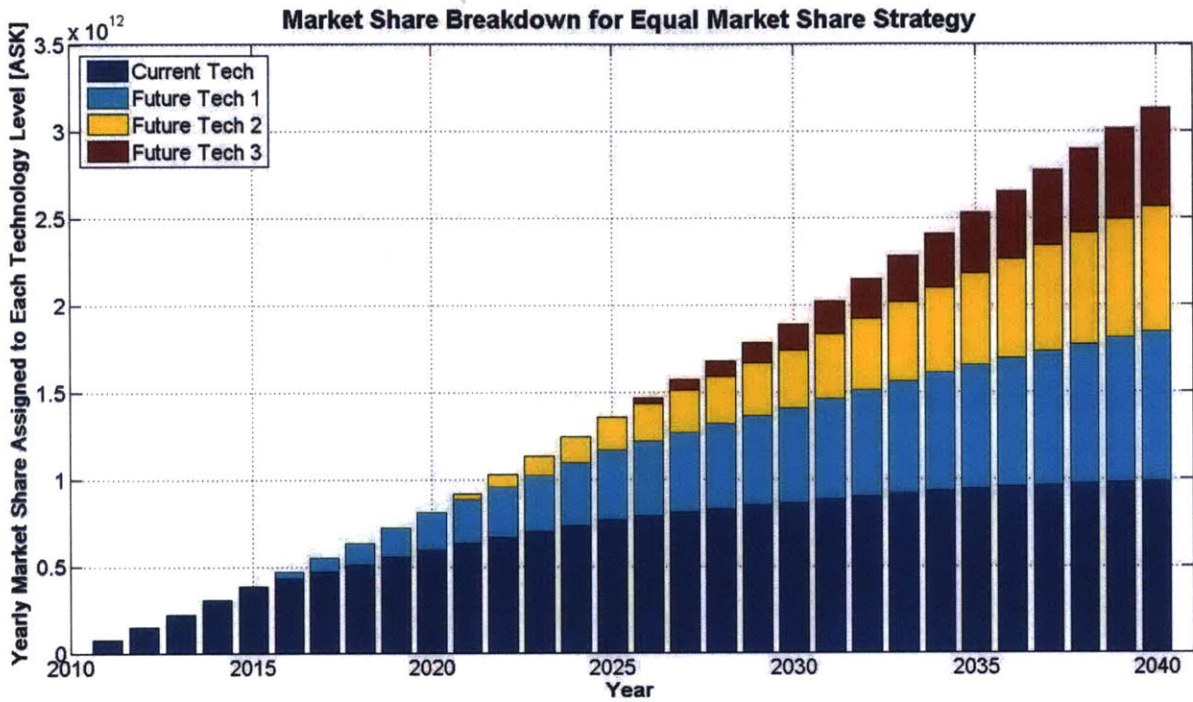
Figure 24: Yearly Market Share of Different Technology Levels for Equal Market Share Procurement Strategy
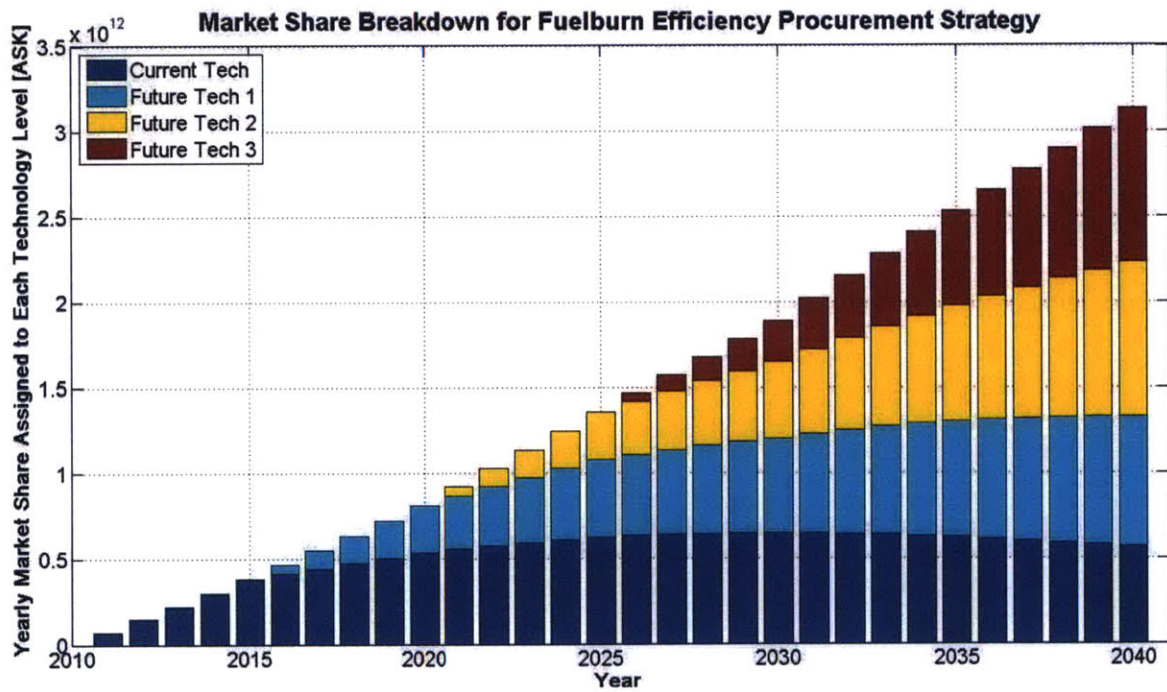

Figure 25: Yearly Market Share of Different Technology Levels for Efficiency Weighted Procurement Strategy

It can be seen from the plots above that the market share for more efficient technology levels are significantly affected by the procurement strategy used. The equal market share strategy provides less market share to the most efficient technology level and provides more market share to less efficient technology levels than the efficiency weighted strategy.

Of particular interest is the difference in the current technology level between the two strategies. It can be seen that the efficiency weighted procurement strategy leads to an interesting scenario where the rate of retirement of current technology aircraft overtakes the rate of procurement, and the overall market share of aircraft of this technology level decreases in the later years of the analysis. This is not seen in the equal market share strategy, where a much larger market share is covered by the current technology aircraft even in the final years of the analysis.

These plots also show that the earlier introduction of less efficient aircraft has a significant impact on the total ASKs distribution. In both the equal market share and the efficiency weighting assumption, the earliest introduction aircraft controls a greater market share than more efficient aircraft. As expected, the weighting function assumption does lead to more market share for more efficient aircraft than the equal market share assumption.

4.2.2 Fleet-Wide Fuel Burn Performance

It is clear that an efficiency weighting strategy, which preferences procurements for more efficient aircraft, will provide greater fuel burn benefits than the equal market share strategy, but it is important to understand the magnitude of the impact. As with the previous analysis, the technology level of aircraft in both cases are equivalent, and all fuel burn benefits are a product of the procurement assumptions tested.
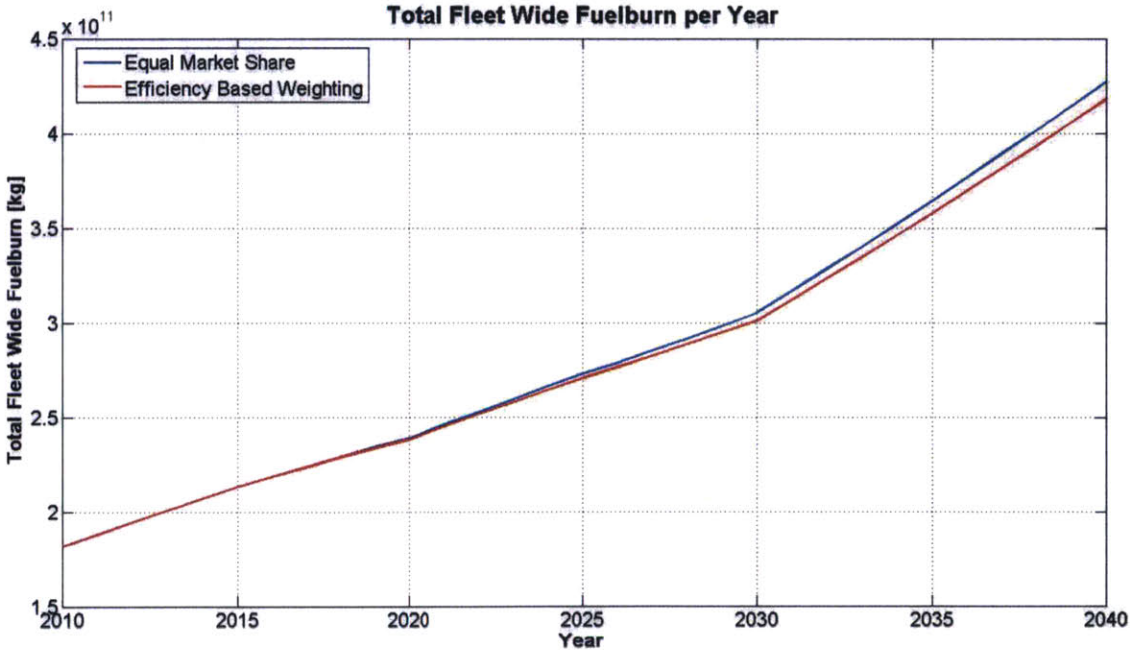

Figure 26: Total Fleet Wide Fuel Burn per Year Under Different Procurement Assumptions
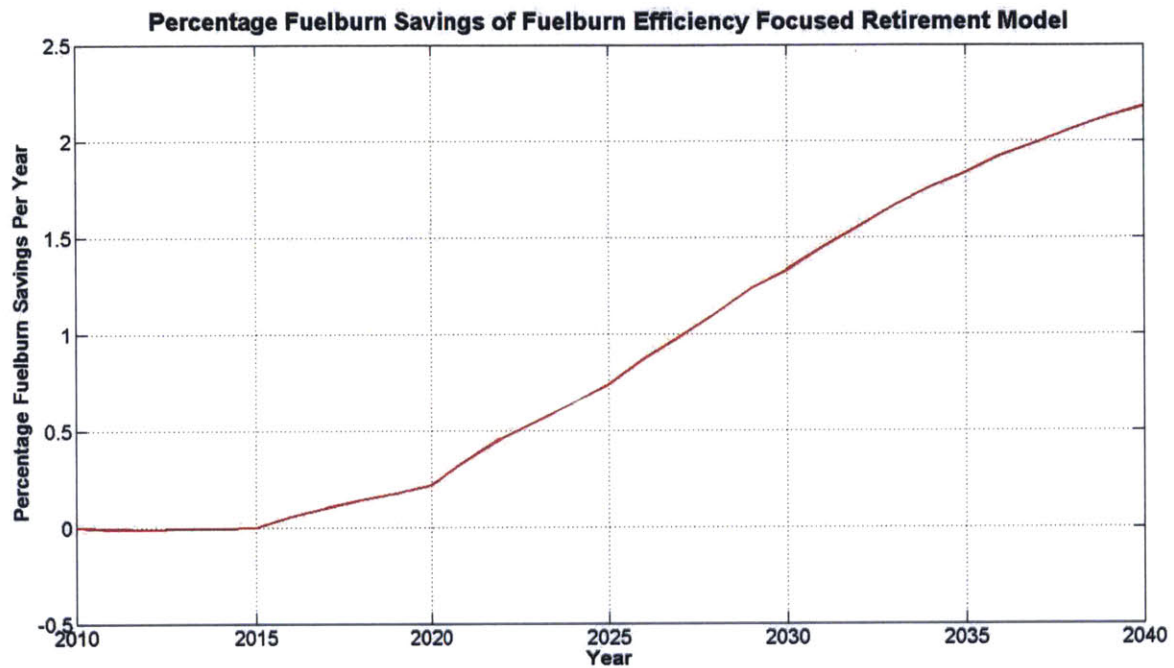
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Figure 27: Percentage Fuel Burn Savings of Efficiency Weighted Procurement Model over Equal Market Share Procurement Model

Figure 26 presents the total yearly fleet-wide fuel burn of the two different procurement models. These results do show that the efficiency weighted procurement results in reductions in total fuel burn over an equal market share model. No benefits are realized before 2015, the introduction year of the second set of aircraft with upgraded technology. Before 2015, there is only one aircraft able to cover each mission, so no benefits can be gained through different procurement assumptions. It can also be seen in this figure that fuel burn savings are monotonically increasing throughout the analysis years, and the fuel burn of the two models would continue to diverge into the future if the analysis were extended since more efficient aircraft would continue to cover a greater market share in the efficiency weighting model. The total fuel burn savings of the efficiency weighted procurement model over the equal market share model is 94 billion kilograms of fuel, which amounts to a 1.1% total fuel burn savings over the total equal market share fuel burn.

Chapter 5: Aircraft Technology Sensitivity Analysis

The previous chapters have considered the impacts that modifying modeling assumptions will have on the outputs of the model. Chapter 5 will shift focus and consider instead the impact of modifying inputs. In particular, this chapter will consider the effects that the in-production fleet input has on the fleet evolution model. As discussed previously, this input estimates the types and performance of aircraft that will be made available by manufacturers throughout the duration of the analysis. Modifying this input directly modifies the fuel burn performance of the aircraft that will make up the fleet, and therefore will impact fleet wide fuel burn.

This analysis will consider two cases with which to test the sensitivity of the model to this input. The first case will model incremental aircraft improvements. In this model, multiple new aircraft will enter the fleet at regular intervals, each with an efficiency increase over the previous model. This scenario models a decision to continue finding fuel burn benefits by making modifications or moderate design changes to the existing general tube-and-body aircraft type. These modifications are lower risk and therefore can be completed on a short timeframe, but provide only moderate fuel burn performance improvements.

The second scenario will instead consider a disruptive new aircraft design. In this analysis, only one new aircraft will enter the fleet for each seat class, but this aircraft will provide significant fuel burn benefits over previous models. This scenario models a scenario in which a new design is completed, possibly moving away from the standard aircraft designs of today. This scenario would be high risk and therefore it will take longer for the aircraft to enter the fleet, but the fuel burn efficiency benefits over previous aircraft types will be better than achieved by incremental designs.

5.1 Model Specifications

The focus of this model is testing different in-production aircraft sets, and other values will be held to the baselines described above. An efficiency based weighting scheme will be used for this analysis. As with previous analyses, other inputs will be held constant, particularly the demand growth forecast. It is possible that a significant change in the capabilities of new aircraft as suggested in this analysis could have an impact on the demand for commercial travel, but this feedback goes beyond the scope of this analysis and will not be modeled here.

5.1.1 Future Aircraft Set

Unlike previous analyses, this analysis will use a different future aircraft set for each case studied. The current technology aircraft will, however, still remain the same. In order to ensure that the output differences are attributable to the future aircraft set, all current technology aircraft will go out of production at the same time in both cases.

The incremental improvement future aircraft set will introduce three technology levels, being 7%, 12%, and 15% more efficient than the current technology models for each seat class, and entering the fleet in 2015, 2020, and 2025 respectively. The data for these aircraft types is presented in Table 5.

Conversely, the disruptive improvement future aircraft set will introduce only a single technology level. These advanced aircraft will come into production in 2025 and will boast a 20% fuel efficiency

improvement over the current technology aircraft. These aircraft will be more efficient than the most efficient incremental improvement technology aircraft.

Table 5: Incremental Performance Advancements Test Fleet

Technology Level	In-Production Year	Out-of-Production Year	Fuel Burn Performance
Current Technology Aircraft	Pre- 2010	2030	Baseline Values
Future Technology Aircraft 1	2015	Post- 2040	7% Fuel Burn Efficiency Improvement
Future Technology Aircraft 2	2020	Post- 2040	12% Fuel Burn Efficiency Improvement
Future Technology Aircraft 3	2025	Post- 2040	15% Fuel Burn Efficiency Improvement

Table 6: Disruptive Performance Improvement Test Fleet

Technology Level	In-Production Year	Out-of-Production Year	Fuel Burn Performance
Current Technology Aircraft	Pre- 2010	2030	Baseline Values
Future Technology Aircraft 4	2025	Post- 2040	20% Fuel Burn Efficiency Improvement

5.2 Future Aircraft Analysis Results

5.2.1 Market Share Analysis

It is clear that the most efficient aircraft in either fleet comes in the disruptive improvement analysis. However, this aircraft doesn't enter the fleet for many years of the analysis, and so, even with the use of the fuel burn efficiency weight procurement strategy, this aircraft will not be eligible to cover a significant portion of the overall ASKs served throughout the analysis. On the contrary, the incremental improvements model has an updated model begin to take a share of the market much earlier in the analysis, but this aircraft does not have nearly the fuel burn efficiency savings of the disruptive aircraft. This tradeoff of entry year versus fuel burn efficiency can be studied in Figure 28 for the incremental future aircraft assumption and Figure 29 for the disruptive future aircraft assumption.

In these figures it can be seen that the current technology aircraft takes up nearly double the market share in the disruptive analysis than in the incremental analysis. Conversely, the very efficient aircraft in the disruptive model has nearly double the market share of the most efficient aircraft in the incremental model, and has roughly the same market share as both the second and third technology levels combined.

This analysis shows that the numerical values chosen for fuel burn estimates are important to the conclusions drawn. The amount of efficiency benefit that the disruptive aircraft has over the most advanced aircraft technology level in the incremental model will determine how much more fuel efficient the disruptive model will be in the later years of the analysis. Furthermore, the efficiency benefit available in the incremental model for transitioning from the current technology model to the earliest future model

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determines how much fuel burn is saved in the early years of the analysis, before the disruptive aircraft ever enters the fleet in the second model.
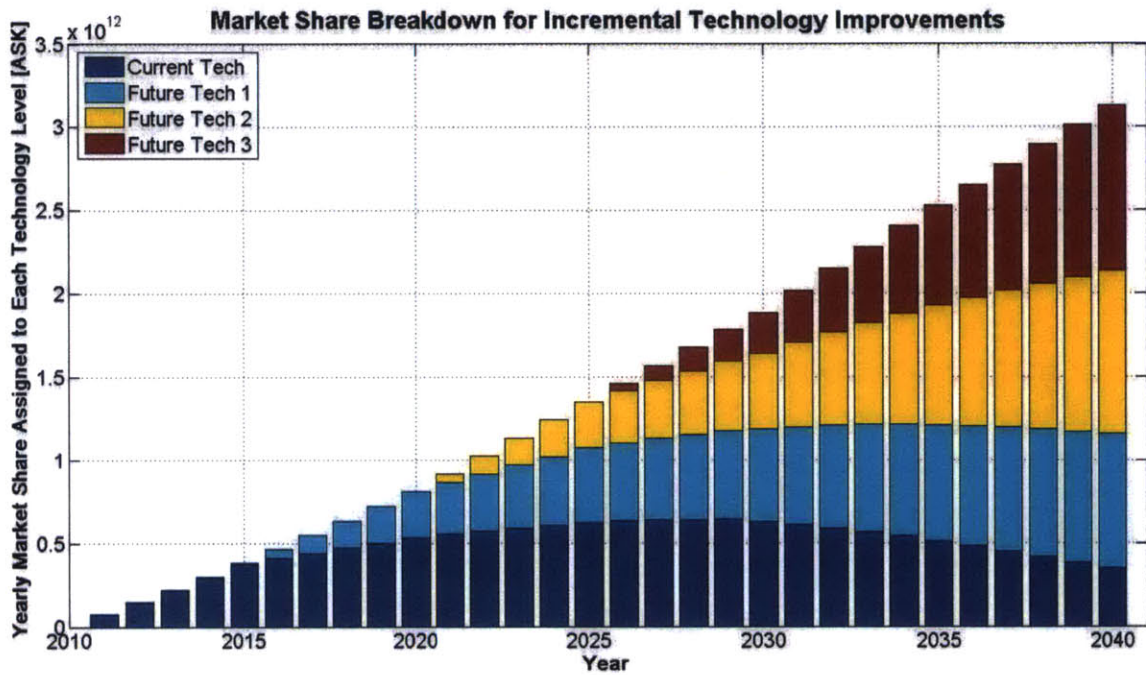

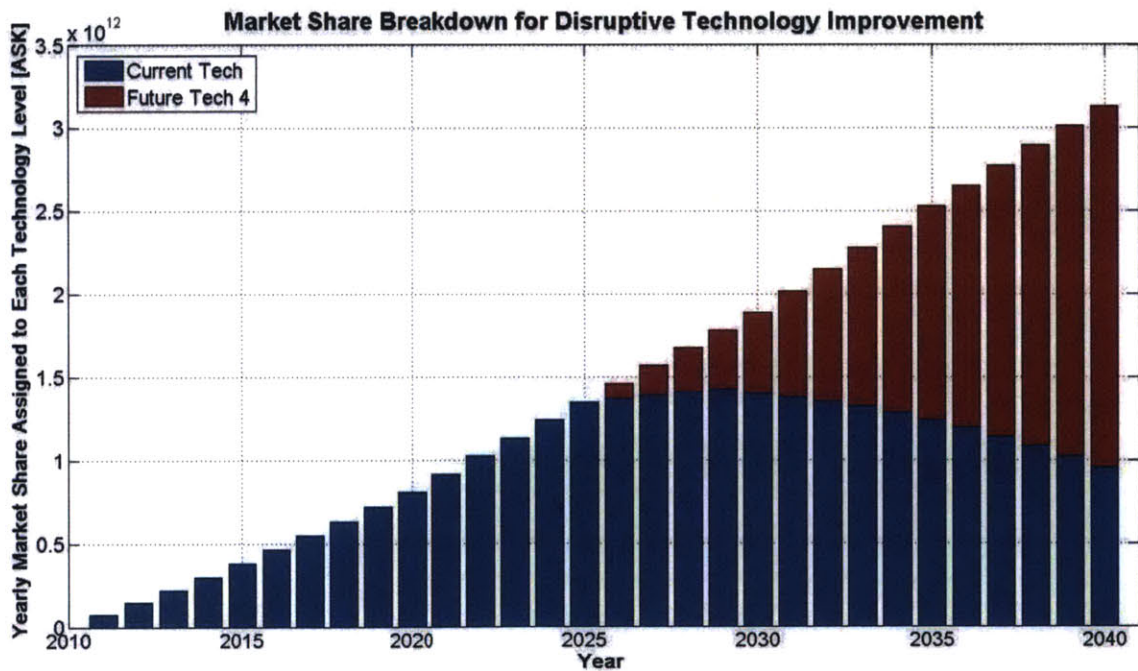**Figure 28: Total Market Share per Aircraft Type Under Incremental Future Aircraft Analysis**

Figure 29: Total Market Share per Aircraft Type Under Disruptive Future Aircraft Analysis

5.2.2 Fleet-Wide Fuel Burn Performance

As discussed previously, the overall fuel burn results presented in this section are sensitive to the specific input values chosen for this analysis, and using different inputs can lead to different results. The question of interest in this fuel burn analysis is whether the fuel burn savings of introducing new, moderately more efficient aircraft early in the analysis can outweigh the fuel burn advantage of a very fuel efficient aircraft entering the fleet later in the analysis. With the given inputs, the fuel burn performance of the two scenarios can be seen in Figure 30
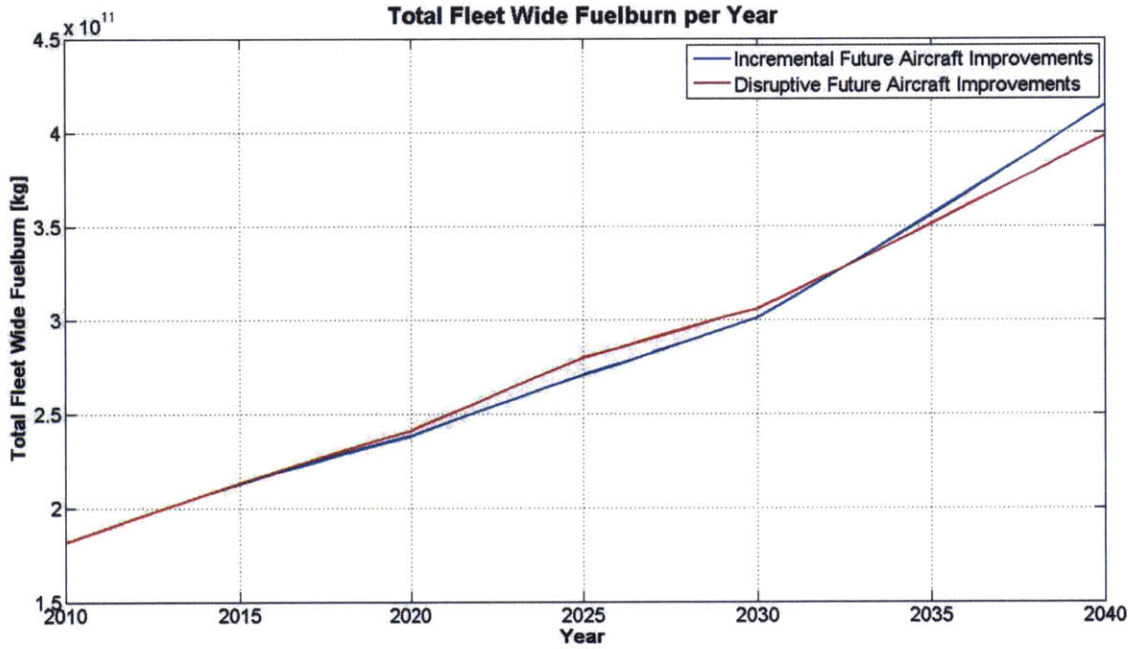
Figure 30: Total Fleet Wide Fuel Burn per Year Under Different Future Aircraft Assumptions

As expected, the incremental model shows fuel burn improvements in the early years of the analysis, but after 2025 the disruptive model sees greater fuel burn savings and by 2040 has better yearly fleet wide fuel burn performance. The transition year when the disruptive fleet becomes more fuel burn efficient on an annual basis occurs in 2033. The overall fuel burn of the incremental case is 8.68 trillion kilograms while for the disruptive case is 8.69 trillion kilograms. For the given input assumptions, the overall fuel burn difference between the two models is a small fraction of total fuel burn, but the annual performance of the two models behaves differently.

Chapter 6: Demand Growth Sensitivity Analysis

Another input that can have an impact on the outputs of this model is the demand forecast. This forecast is used to determine the number of new flights that will need to be flown throughout the analysis. This test will consider two main ways that the growth forecast can change.

Firstly, the demand forecast can change in magnitude. By increasing or decreasing the total number of ASKs provided by the commercial fleet, a change in fleet dynamics can be forced. The most fundamental output of the commercial fleet is the number of ASKs provided, and so a change to the amount of output required of the fleet should be expected to require a change in the input, or fuel to carry passengers.

The demand forecast can also be subjected to significant modifications without changing the overall ASKs provided by the fleet. By modifying where within the payload and range mission bins new demand is forecast, changes to the type of aircraft required to fly those missions can be changed. This can clearly have an impact on fleet makeup, but can also alter fuel burn performance if aircraft with different mission capabilities within the fleet also have different fuel burn performances.

This analysis will study two scenarios. In the first scenario, the demand forecast will be scaled up across all mission bins to simulate an overall increase in demand for air travel. In the second, the overall number of ASKs provided by the fleet will remain constant, but the demand for short range flights will be modified such that large capacity aircraft are demanded over low capacity aircraft.

6.1 Model Specifications

Similarly to the future aircraft test, this analysis focuses on the impacts of specific input variations. For this reason, baseline cases will be used for other assumptions, including the retirement and aircraft procurement strategies. This section will briefly discuss the future aircraft set used and then focus on the demand growth assumptions to be tested.

6.1.1 Future Aircraft Set

Because the demand growth variations being studied will not have a time component (all variations will be equally spaced across all years of the analysis), aircraft technology levels will not be a focus of the analysis. For this reason, a simplified future fleet provides an effective level of resolution for testing the fleet. Similar to chapter 3, a single future aircraft will be assigned for each seat class, and these aircraft will all enter into production simultaneously 10 years after the beginning of the analysis, in 2020. The aircraft in each seat class will be 10% more efficient than the current technology aircraft in that seat class. This data is presented in Table 2, and will not be replicated here.

6.1.2 Demand Growth Forecast

As discussed previously, the demand growth forecast is defined by mission bins, with a specific number of ASKs per bin to be covered in each year of the analysis. The number of ASKs is translated into a number of flights based on the range and number of seats of aircraft in that missions bin, and that number of new flights is added to the shortfall of the given year's analysis.

Both analyses presented here will test a perturbation from the baseline demand forecast used in all other analysis in this thesis. In the first analysis, an overall demand increase is presented, increasing

the number of ASKs in each bin for each year by a set 10%. This change will test how much additional fuel must be used to increase the commercial fleet's travel output.

The second analysis, on the other hand, will show no overall change in the total number of ASKs provided by the fleet. Instead, this demand forecast will test the effects of changes to the makeup of demand. In particular, 20% of demand for short range flights flown by low capacity aircraft will be transferred to high capacity aircraft. This is intended to model a consolidation of flights, which could occur if airport saturation forced restrictions on the number of landings that could be performed at busy airports. In particular, 20% of ASKs in the first 3 seat classes (between 20 and 150 seats) and first 3 range bins (between 0 and 3000 nmi) will be transferred to the 5th and 6th seat classes (between 210 and 400 seats). These changes to the demand forecast are presented in Table 7.

Table 7: Demand Forecast Edits for Demand Growth Analysis

Seat Class	Demand Scaling Affected Ranges	Demand Scaling Δ	Augmented Demand Ranges	Augmented Demand Δ
1			0-3000 nmi	20% decrease
2			0-3000 nmi	20% decrease
3			0-3000 nmi	20% decrease
4			No change	No change
5	All Ranges	10% Increase	0-3000 nmi	Increase equivalent to ½ of total decrease
6			0-3000 nmi	Increase equivalent to ½ of total decrease
7			No change	No change

6.2 Demand Growth Analysis Results

6.2.1 Demand Scaling

Increasing the total number of ASKs covered by the commercial fleet is expected to increase the total fuel burn of the system. Figure 31 shows the annual fuel burn of the two scenarios. The scaled demand forecast shows increased fuel burn throughout the analysis and the difference in fuel burn between the scenarios increases over time. Furthermore, Figure 32 shows the percentage difference in fuel burn due to the increase in demand. It can be seen from this figure that the percentage difference in fuel burn increases steadily throughout the analysis up to roughly 7.5% in the final year of the analysis. The total fuel burn increase throughout the analysis is roughly 425 billion kilograms of fuel, which amounts to a total percentage increase of 4.9% over the baseline demand forecast. This means that a 10% increase in the demand forecast has a nearly 5% impact of total fuel burn consumption.
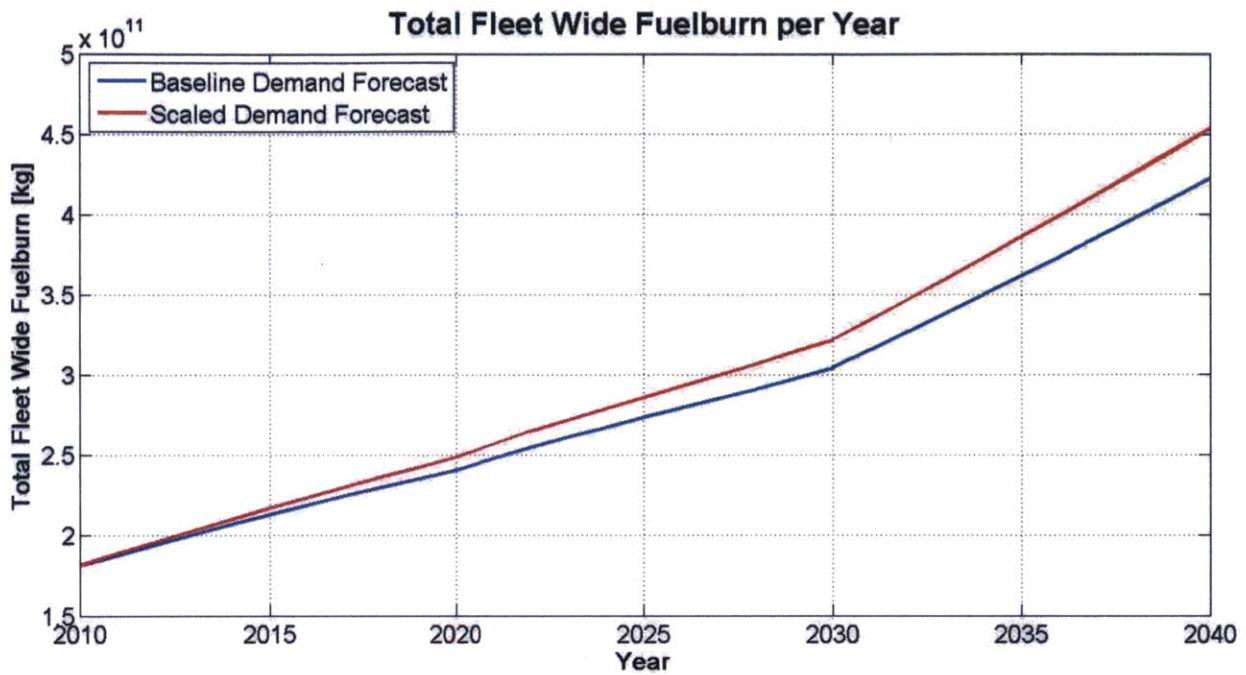
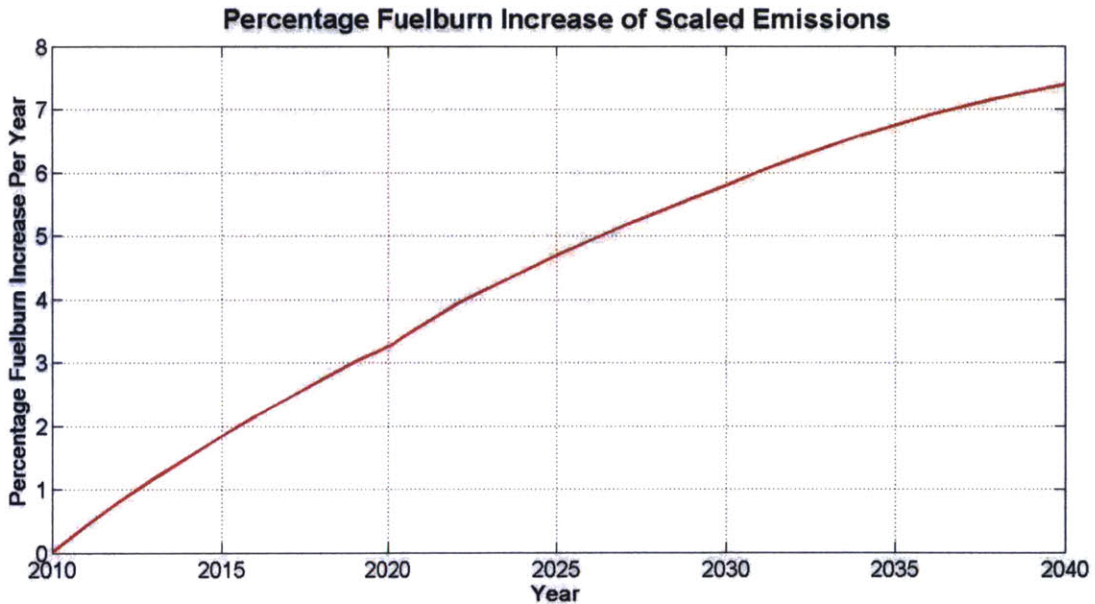**Figure 31: Total Annual Fuel Burn Caused by a 10% Increase in Demand Growth**

Figure 32: Percentage Increase in Annual Fuel Burn Caused by a 10% Increase in Demand Growth

6.2.2 Demand Shift Toward High Capacity Short Range Flights

The second analysis considers a scenario that shifts what types of flights are demanded without changing the overall demand for air travel. In order to model this, a portion of ASKs are taken from short range low capacity flights to short range high capacity flights. This model assumes that fewer large

aircraft will fly fewer missions to transport the same number of passengers along the same distances. This trend can be seen in Figure 33.

It can be seen clearly in this figure that the augmented demand forecast does lead to a variation in the market share distribution of different aircraft types, however, the impact this variation will have on the fleet-wide fuel burn performance depends on the specific aircraft available in the seat classes of interest. In particular, if the fuel burn per ASK provided by the high capacity aircraft differs from that of the low capacity aircraft, then a difference in overall fuel burn will be seen. On the contrary, if the general technology level of the aircraft are roughly the same, and the fuel burn per ASK values of the aircraft chosen for this analysis are similar, then the fuel burn results will not show a significant impact.

The fuel burn results for the given analysis are shown in Figure 34, and from this plot it can be inferred that the technology level of aircraft in different seat classes of this fleet are very similar since almost no fuel burn difference is seen between the two models.
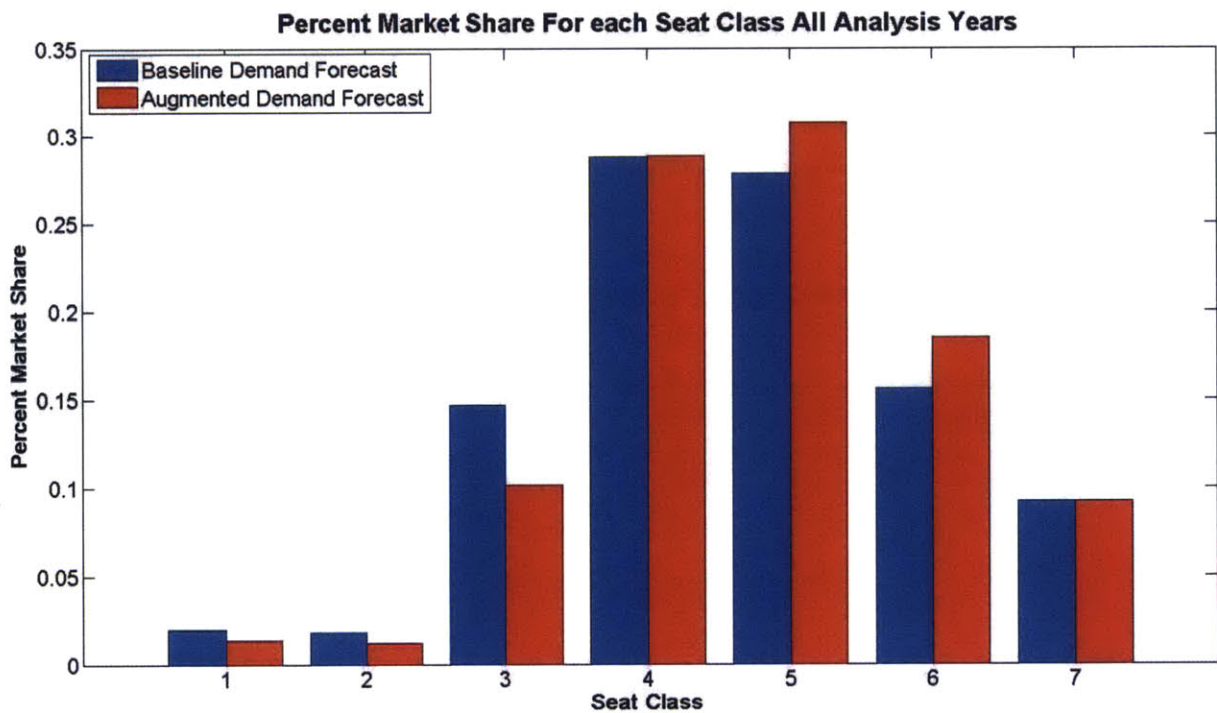

Figure 33: The Augmented Demand Forecast Reduces the Market Share for Low Capacity Flights and Transfers this Demand to High Capacity Aircraft Types
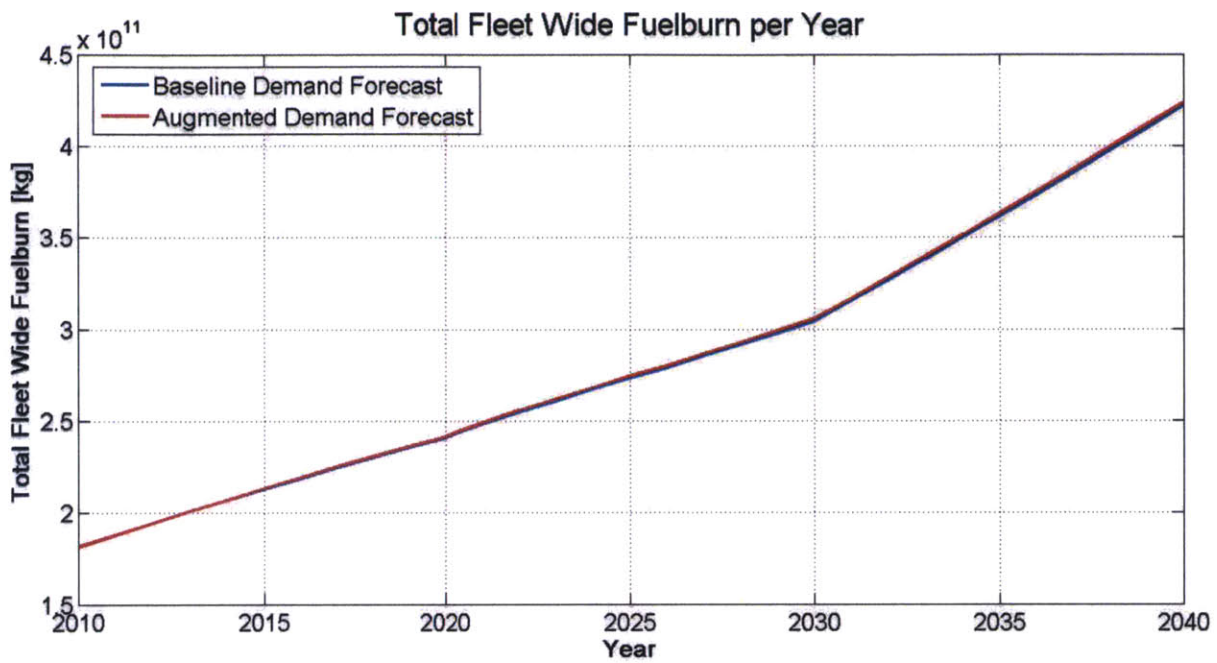
Figure 34: Total Fleet Wide Fuel Burn for Different Demand Forecasts

Chapter 7: Conclusion

In order to study trends in fleet evolution, a model has been developed with the focus of providing insight on the potential effects of different input sets and modeling assumptions on the predicted make-up of the future fleet. This model performs a fleet evolution calculation on a yearly basis, modifying the commercial network of flights and aircraft to account for aircraft retirements, aviation growth, and new aircraft entry into the fleet.

This model was employed in a series of sensitivity analyses to test model assumptions and inputs of interest. The retirement strategy and procurement strategy employed by the model were studied in chapters 3 and 4. Chapters 5 and 6 studied the inputs of the future aircraft set and the demand growth forecast respectively. In each analysis, multiple test cases are introduced and the fuel burn as well as fleet makeup results are studied for each scenario. The results of these studies provide insight on the relative importance of different assumptions on model outputs.

Chapter 3 considered the impacts of differing retirement strategies on overall fleet-wide fuel burn. It was seen through this analysis that utilizing an efficiency based retirement strategy that aimed to assign the most fuel burn efficient aircraft to the most fuel burn intensive missions provided fuel burn benefits over a randomized model that did not take into account efficiency considerations when retiring aircraft. The overall fuel burn savings amounted to 2.7% of the baseline fuel burn.

Chapter 4 considered two different procurement strategies. The first strategy, an equal market share procurement strategy, assigned all available aircraft to missions equally regardless of the relative fuel burn performance of different aircraft. In contrast, the efficiency weighted procurement strategy assigned aircraft with better fuel burn performance to a larger proportion of missions than less efficient aircraft. It was seen through this analysis that an increased focus on fuel burn efficiency in procurement decisions did lead to better fleet-wide fuel burn performance of 1.1%, but also that entry-into service dates for aircraft of different technology levels have a significant impact on fleet makeup and fleet fuel burn performance.

Chapter 5 studied the impacts of different future aircraft technologies by considering the differing fleet-wide performance of two design strategies. An incremental improvements design strategy was considered that had multiple new aircraft enter into production throughout the analysis, each with moderate fuel burn efficiency savings over the previous models. Also considered was a disruptive design strategy that only introduced one new model, but with more significant fuel burn efficiency improvements. This analysis showed that delaying the introduction of new aircraft, even though those new aircraft may have better fuel burn performance when introduced, may not provide overall fleet-wide fuel burn benefits, since older less efficient aircraft are required to enter the fleet at higher rates.

Finally, Chapter 6 considered the impacts of different demand forecasts. A demand scaling scenario was considered in which demand for commercial travel was increased by a set percent across all mission bins. A 10% increase in total ASKs led to an increase in overall fuel burn of the fleet of 4.9% required in order to provide more travel services. Also considered was a demand forecast augmentation, where the total number of ASKs were not altered, but the types of flights used to provide that travel was

altered. It was seen that, because the aircraft with different mission capabilities had similar fuel burn per ASK performance, the impact on fleet wide fuel burn was minimal, at less than 0.4%.

7.1 Future Work

There are two pathways for future work to be conducted. The first is to utilize the model as it currently exists to perform further tests of fleet evolution. Such analysis would involve modifying inputs and modeling assumptions in order to provide new insights into the dynamics of fleet evolution. One potential area for improvement is to consider unique aircraft introductions in different seat classes. All the analysis in this thesis presents future aircraft coming into the fleet in unison, with the same fuelburn savings and the same entry-into-service date. This does not model reality closely as manufacturers seldom release multiple new aircraft of varying capabilities at the same time. Such an analysis could be used to identify which seat class and range bins had the highest potential for providing fuelburn savings through newer aircraft introductions.

The second direction to build upon the work presented here would be to modify the fleet evolution model presented above. This model uses multiple simplifying assumptions to make the problem more tractable, but relaxing one or more of these assumptions could provide further insight into fleet evolution dynamics. One area of potential interest is the interaction between the commercial fleet and the missions flown. Currently, the model assumes that the set of missions that must be covered is prescribed externally, and aircraft procurement is modeled to fully meet the mission set. This modeling assumption does not capture the actual system because in reality the fleet and the mission set are determined together, with a feedback system leading each to be affected by the other. A more nuanced model that predicts how the mission set will fluctuate based on the fleet available could provide new and interesting insights into the process of fleet evolution.

Chapter 8: References

Airbus Global Market Forecast 2014, *Flying on Demand*, available at:
http://www.airbus.com/company/market/forecast/

Airline Data Project, MIT Global Airline Industry Program. Available at:
http://web.mit.edu/airlinedata/www/default.html

Anderson, John D. Introduction to Flight. 3rd ed. New York: McGraw-Hill, 1989. Print.

Boeing Current Market Outlook 2014, available at:
http://www.boeing.com/assets/pdf/commercial/cmo/pdf/Boeing_Current_Market_Outlook_2014.pdf

Eurocontrol (May, 2013) *Base of Aircraft Data (BADA) Revision 3.11*. Eurocontrol Experimental Centre, Project BADA

International Air Transport Association, IATA (March 2011) *US DOT Form 41 Operational Cost Analysis Report*. Available at: http://www.iata.org/whatwedo/workgroups/Documents/aoctf-FY0809-form41-report.pdf

International Air Transport Association, IATA (December 2014) *Fact Sheet: Climate Change*. Available at: https://www.iata.org/policy/environment/Documents/iata-factsheet-climatechange.pdf

International Civil Aviation Organization, ICAO *Achieving Climate Change Goals for International Aviation*. Available at:
http://www.icao.int/Newsroom/Presentation%20Slides/Achieving%20Climate%20Change%20Goals%20for%20International%20Aviation.pdf

International Civil Aviation Organization, ICAO (June 2009) *Group on International Aviation and Climate Change (GIACC) Report*.

International Civil Aviation Organization, ICAO (2010) *CAEP Environmental Trends Assessment to 2040*. Available at: http://www.icao.int/environmental-protection/Pages/AlternativeFuels-QuestionsAnswers.aspx

Kar, Rahul (June 2010) *Dynamics of Implementation of Mitigating Measures to Reduce CO2 Emissions from Commercial Aviation*. MIT Engineering Systems Division.

Tetzloff, Isaac J. and Crossley, William A. (September 2012) *Exploring Different Problem Formulations to Evaluate Environmental Impacts of Aviation*. Purdue University, School of Aeronautics and Astronautics. 12th AIAA ATIO Conference and 14th AIAA/ISSM, 17-19 September 2012, Indiana.

US Energy Information Administration, USEIA (2015) *Workbook: Weekly U.S. Gulf Coast Kerosene-Type Jet Fuel Spot Price FOB (Dollars per Gallon)*. Available at:
http://tonto.eia.gov/dnav/pet/hist/LeafHandler.ashx?n=PET&s=EER_EPJK_PF4_RGC_DPG&f=W