A SYSTEM DYNAMICS ANALYSIS OF FLEET TECHNOLOGY AND POLICY OPTIONS FOR ENVIRONMENTAL IMPACT MITIGATION

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Abstract

Concerns over the environmental impact of aviation, as well as recently proposed and sometimes enacted policies that regulate aviation emissions, have fostered the interest of national and international regulatory and policy making bodies that rely on the understanding of aviation environmental impacts. Furthermore, research and development organizations are interested in assessing how far their technology portfolio can help reduce the environmental impact of aviation. The range of current methodologies ranges from low fidelity rapid assessments to high fidelity analyses that require significant data and computational effort to conduct. This paper presents a method that allows improved accuracy of environmentalassessments in real-time for policy and decision makers, by explicity presenting the system model structure while allowing interactive parametric variation of key assumptions.

1 Introduction

In recent years the environmental impact of aviation, espcially the greenhouse gas emissions, local air pollutant emissions, and noise, have been under scrutiny repeatedly. This is happening at a local level due to noise and air quality concerns and at a global level for greenhouse gas emissions, even though aviation only contributes 2-3% of man-made emissions[4]. Some of the concerns, for example, such as that aviation emissions happen at higher altitude and therefore have an higher impact, are only somewhat true. Another point of concern is the long term growth rate exhibited by aviation has historically tended to exceed other transportation sectors and industries. Even though this growth is at the same time also threatened by air trafic system capacity constraints and economic and fuel price risks. Nevertheless, aviation R&D has – even if unwillingly – been pushed to the forefront of research into how to mitigate environmental impacts.

Traditionally, aircraft technologies have made vast improvements in fuel efficiency, emissions, and noise footprint, even though they are mostly in opposing directions of improvement. However, some recently proposed climate policies, will potentially demand vast reductions in greenhouse gas emissions. These policy options have also evolved and adapted to include market based approaches. The availability of very different types of solutions begs the question of what is the best mix of solutions and measures that offer a good compromise across stakeholders of air transportation and the countervailing objectives on environmental impact, airline economics, demand/traveller satisfaction, manufacturing considerations, and technology development, among others.

The core of this effort is to provide a high accuracy method to explore future aviation scenarios through an interactive dynamic simulation. This is opposite to the traditional paradigm in the analysis of this type of problems, which makes it difficult to characterize behaviors across components (tradeoffs, sensitivities), in turn making it difficult to perform analyses that seek to find good solution for mixed objective problems.

In this type of analysis we want to capture high accuracy system level metrics as wells as show the impact of individual aircraft level changes and how those can affect the overal air transportation system as a whole. Additionally, we want to be able to take real program goals, such as the NASA Technology program goals[3], and assess their affect on the whole of aviation. Table 1 shows these goals for aircraft level environmental characteristic improvements from technologies under study for the next three generations of aircraft.

Table 1 – NASA's Technology Goals for Future Subsonic Vehicles

CORNERS OF THE TRADE SPACE	N+1 (2015)*** Technology Benefits Relative to a Single Aisle Reference Configuration	N+2 (2020)*** Technology Benefits Relative to a Large Twin Aisle Reference Configuration	N+3 (2025)*** Technology Benefits
Noise (cum below Stage 4)	- 32 dB	- 42 dB	- 71 dB
LTO NOx Emissions (below CAEP 6)	-60%	-75%	better than -75%
Performance: Aircraft Fuel Burn	-33%**	-50%**	better than -70%
Performance: Field Length	-33%	-50%	exploit metroplex* concepts

*** Technology Readiness Level for key technologies = 4-6
** Additional gains may be possible through operational improvements
* Concepts that enable optimal use of runways at multiple airports within the metropolitan areas

The air transportation system is a complex system that especially with regard to environmental impacts is subject to a variety of time dependent effects, where the rates of change are controlled by key parameters. Therefore, this lends itself to a System Dynamics modeling approach that will be explored in this paper. The benefits of such a modeling approach is that the result is a highly visual system model that allows for much easier under standing of how the system behaves and what assumptions drive the system level behaviors of key parameters.

1.1 Systemwide emissions modeling

The modeling of how much is emitted by aviation as a whole has been approached from two different perspectives. One approach stems from the effort to produce accurate emissions inventories largely to have an accurate historical record of how much was emitted by aviation in a given year. The way this is accomplished is through either a bottom-up modeling of every historical record of a flight between airports, either with a cycle and per distance average based model or with a performance-based model of the aircraft performing those flights. The performance based models are capable of estimating fuel burn and emissions of a number of emissions species more accurately than simple cycle and distance average based models. This is mainly due to the variability of fuel burn and emissions with higher order effects such as varying weight than simple distance and cycle based constants. Unfortunately, performance based models involve a much larger effort, since there many million commercial flights that are recorded. Based on a variety of information sources that has to be decided which specific aircraft model to use and calculate the resulting environmental effects. This has to be repeated for every single flight. It is quite obvious that this involves a large-scale data transformation exercise that due to differences in categorizations can involve numerous conversions of mappings and overall can be quite cumbersome and labor-intensive. Using this method to analyze future predictions of inventories is equally if not more cumbersome and labor-intensive because multiple out years for many scenarios have to be computed. The European Environment Agency (EEA) in their Inventory Guidebook [18] defines this detailed method for aviation as Tier 3b methodology. This is the type of analysis that is currently used to create aviation inventories in some countries on either a per country or world wide dataset [6, 9, 5, 15]. The software used varies widely and has evolved over the years significantly [6, 15]. The recommended Tier 1 and 2 methodology consists of simply using fuel sales as a method to approximate emissions inventories. The Tier 2 methodology modifies this by using LTO cycles by aircraft type to estimate emissions as opposed to simply using fleet averages. Some studies have shown that accuracy of these estimate can vary widely [16].

1.2 Forecasting systemwide emissions

In light of recent policy goals, it has become more important than ever to be able to forecast systemwide aviation emissions to be able to properly assess how growth and technology development will impact the amount of emissions aviation contributes to the overall amount of emissions. In 2012 Europe will cover aviation under the European Cap and Trade system. In the United States there has been no bill passed that would have included aviation, however several have been under debate. In 2009, the "American Clean Energy and Security Act of 2009"[17] was passed by the House of Representatives, but never by the Senate. In some of its original versions it did include language that would have covered some or all of the aviation sector, but that was removed at the last minute and replaced with language that seeks cooperation within ICAO to establish an international aviation cap and trade system. Similarly the "American Power Act"[11] – which is an evolution the 2009 bill – is currently under debate. Nevertheless, studies have shown that it would be impossible to achieve these goals without significant demand reduction or rapid large scale introduction of a very low life-cycle-carbon alternative fuels[13].

Other commonly used method approaches for the computation of future systemwide emissions inventories of aviation approach this from a top down system level perspective. An often used approach is to simply use passenger growth forecasts to directly scale current inventories or produce fuel burn or Green House Gas (GHG) projections based directly on the passenger growth. It should be noted that this approach assumes that the entire system of aviation scales photographically. This implies that the current network structure stays the same as well as that the aircraft fleet mix scales proportionally, and the route structure stays exactly the same and is scalable to the extent desired. These assumptions are clearly incorrect because just assuming a constant fleet mix implies that out of production aircraft are proportionally performing more flights to meet the passenger demand which is clearly not possible. Additionally, load factor and utilization of the aircraft might change, further increasing the deviation from the passenger demand trend. Therefore, assuming aviation fuel burn behaves exactly like passenger demand is incorrect. So in order to achieve a rapid evaluation of future aviation systemwide emission trends based on the accurate acitivity based Tier 3b type models that at the same time correctly translates passegner demand into systemwide emissions, a new type of model is required.

2 System Dynamics Model Overview

System Dynamics is a method of modeling complex systems[7, 14]. It originally derived its origins from analogies in control system theory. It has over the years evolved into a top-down visual system modeling method rooted in computer based modeling and simulation. In contrast with spreadsheet based methods, it de-emphasizes numbers and instead focuses on showing the model structure and how system elements relate to each other. System Dynamics models focus on expressively modeling "stock" and "flow" variables that describe the state of the system as well as the rates of change of these states. Additionally, the connections between variables are expressed as links such that feedback loops determining the system behavioral modes can be easily modeled, expressed and explored. As a modeling method, it was at the core of probably one of the first global models, exploring the state of growth and environmental impact on a worldwide basis[8, 12].

Using this method, a model was developed allowing the dynamic forecasting of the environmental attributes of the future state of aviation. This model is shown in Figure 1 and is explained step by step in detail inf the following section.

The starting year for the model was decided to be 2006, since a number of data sources that have to match were available. This meant that existing historical data was used to force the model behavior to match the historical data. The exact details of this are described in the appropriate sections later. The end year of the model was selected to be 2050, since the FESG forecast[2] is technically only valid to 2036, but has been used further in some applications. This also gives the last generation of aircraft some time to be intro-

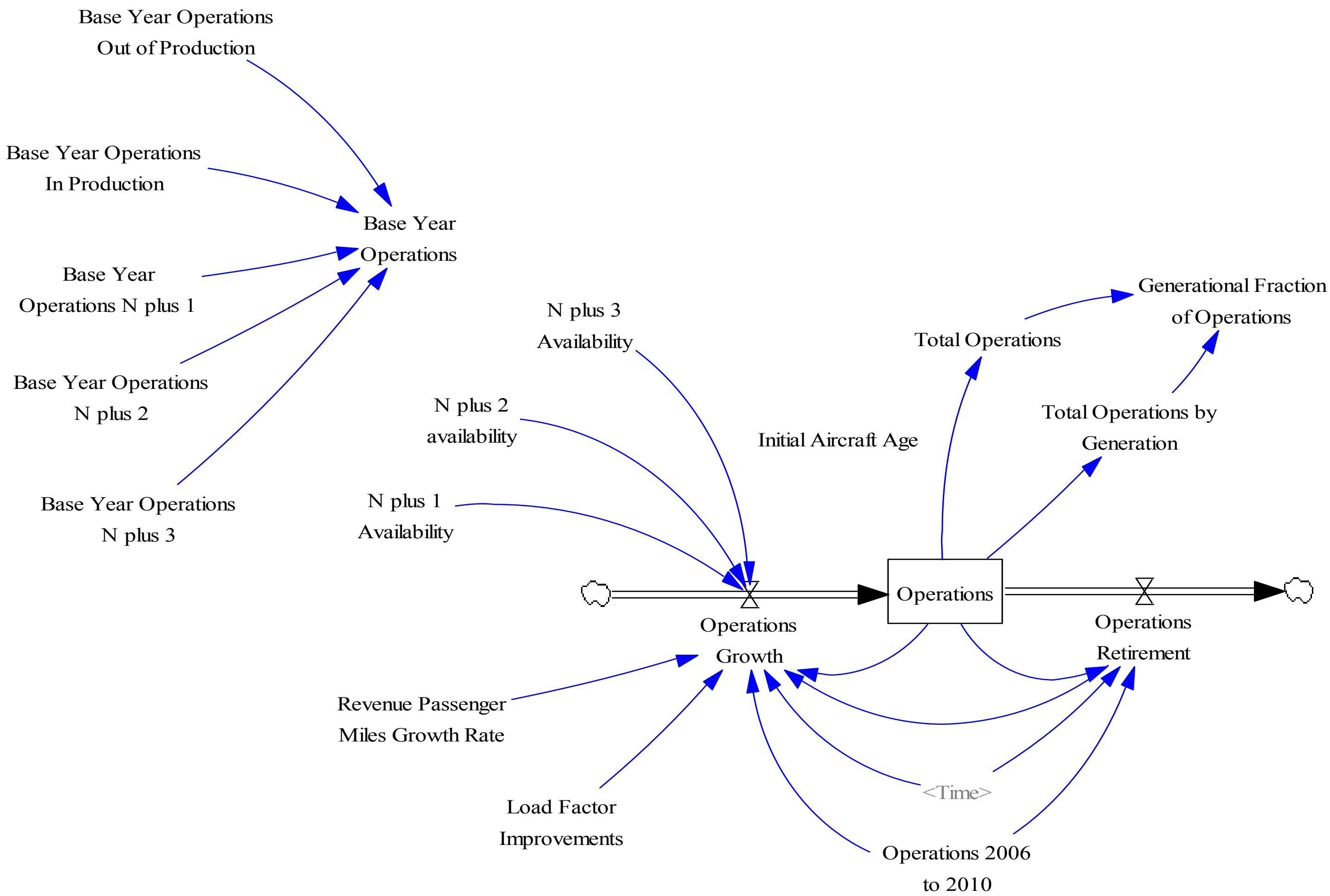

Fig. 1 System View of Model Structure

duced into the fleet since the introduction date for the N+3 generation of aircraft is 2035.

3 Operations and Fleet Evolution Logic

Fundamentally, passengers create demand by being willing to pay for a transportation service that is provided by airlines. This means that actual demand depends on the cost to airlines and the willingess of travelers to accept a certain price for this service. Airline operating costs again depend on the peculiarities of a given aircraft. Currently, the operating cost is dominated by capital investment costs and recently more and more by fuel cost. Emissions or noise do not directly affect operating cost, except in cases where there is an emissions or noise surcharge that airlines have to pay. This means that in order to properly model the commercial aviation sector, it is necessary to rely on a large number of cost information. However, much of this data is not available due to competitive or proprietary advantage derived from it. Therefore, one way of eliminating nearly all of the cost information requirements, is to primarily focus on flights and which aircraft certain routes are being serviced by. This means that passegner growth scenario assumptions as well as aircraft usage is translated to operations, which represents a time based metric of unique flights, where uniqueness is defined by any desired number of characteristics, but is normally limited to route and aircraft combinations. Therefore, the fleet evolution process is greatly simplified and only requires assigning growth and aircraft to particular routes.

3.1 Age Based Retirement

Age based retirement is a simplification of actual airline behavior that removes any specific cost and operational assumptions from the forecasting process. While this is a significant simplification, it allows forecasting of the future fleet mix of aircraft based on historical behavior. This type of forecasting has been used extensively in international rule making and standard processes [10]. Therefore, the model includes the operations as the central model component. It consists of an in-flow of growth plus replacements and an out-flow of retirements. Using the specified age based fleet survival percentage requires knowledge of the existing fleet age, therefore, the CAEP/8 analysis runs made use of existing aircraft production and in service data. For the purposes of this analysis this data was grouped into the standard FESG seat classes and either in-production or out-of-production aircraft based on the ICAO in-production database [1]. The resulting age distributions are shown in Figures 2 and 3.

Since it is necessary to track the age of the aircraft that are assigned to certain operations, a simple stock variable cannot be used to represent operations. This implementation of the operations uses a FIFO queue, central to the model shown in Figure 1. This means that the queue needs to not only be intialized with intial operations, but also and intial age distribution. The queue has a maximum length of 50 years because historical data shows that irregardless of type of aircraft no commercial type remains in service after 50 years, therefore this model limitation is sufficient of accomodate all types of aircraft ages. The retirement rates are not the same as the FESG survival curves[10]. The survival curves describe the percent aircraft remaining in service after having obtained a certain age. However, the system dynamics model is based on specifying rates. Therefore, it was necessary to modify the functions specifying the absolute percentage remaining into functions that specify the rate of change of surviving aircraft as a function of age. This was accomplished by taking the derivative of these functions, which are then used - driven by the queue age function - to determine the rate at which aircraft are being retired for a given category. It should be noted that typically newly introduced aircraft in conventional analyses are never retired, whereas in this model this retirement happens automatically for the in-production generation of aircraft. At the moment it was decided that the future aircraft generations are not retired, because that would require knowledge about how future aircraft would be retired. However, it would be very simple to specify similar functions as for the current aircraft generations is such is desired, but for the moment the retirement rates have been fixed at zero.

The operations are central to this type of model. They contain the essential information about which aircraft is operated on which route and how often. Here this is represented as a third order tensor that is composed of:

- Aircraft Generation
- Aircraft Size
- Route Group

The aircraft generation is a way of representing technological improvements in relatively discrete steps. Primarily, this usually happens through the distinction of out-of-production and in-production aircraft. Therefore, this standard definition was also used here and is based on CAEP specifications, specifically the In-Prdocution Emissions Database[1] as well as the retirement and age assumptions[10]. To this separate categories were added to be able to represent a number of ongoing research programs, that are one, two, or, three generations out, commonly referred to as N+1, N+2, and N+3. This means that there are a total of five generations. The intital in-prodcution and out-of-production distributions are as described before, while the future generation distributions are assumed to be zero. Similarly, the operation counts for each category are intialized with counts based on the 2006 inventories. This properly defines the initial conditions.

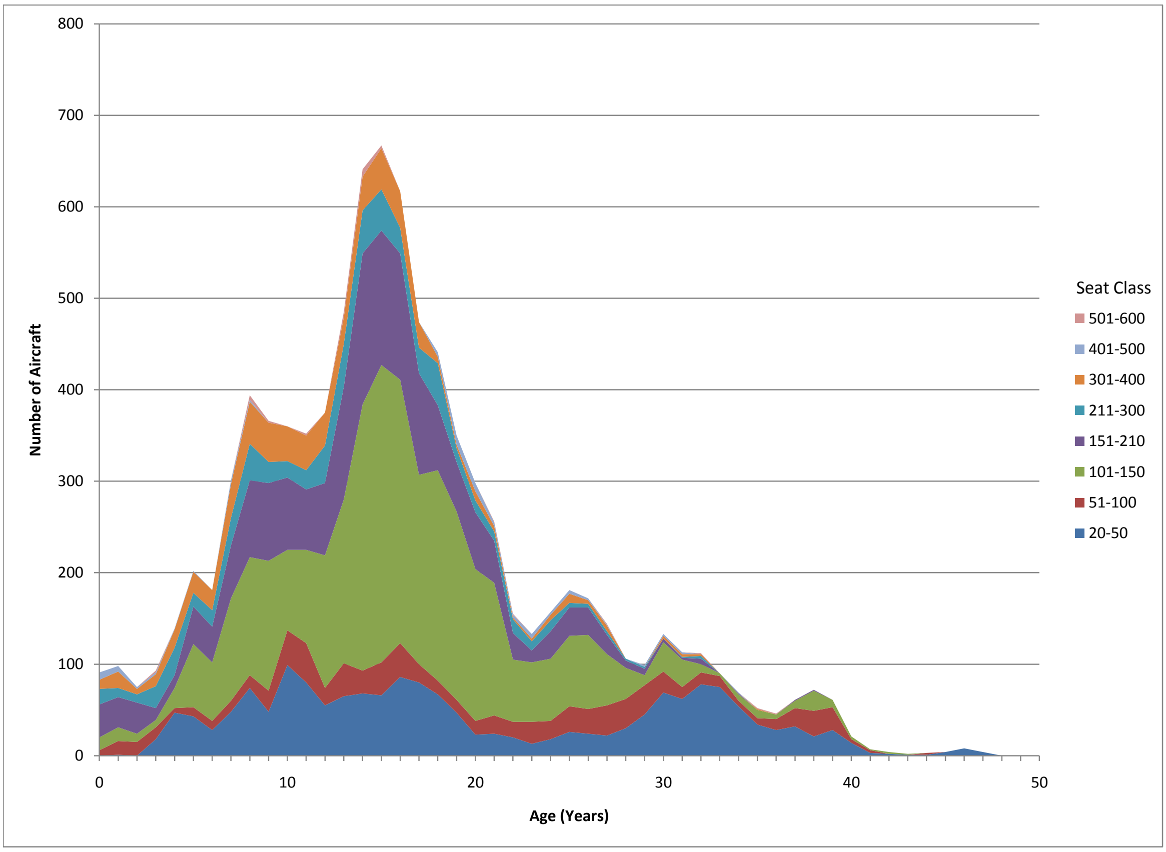

Fig. 2 Age Distribution of Out-of-Production Aircraft

There are a number of ways to represent aircraft size. This includes weight, aisles count, seats, and other size based categorizations. This model uses seat classes similar to the FESG data. It should be noted that this is not necessarily the best way of categorizing aicraft, since in reality airline decisions are based on a combination of payload and range capabilities. However, it represents a reasonable trade-off with data requiremnents versus accuracy.

Initialy, the categorization of distances and routes was planned to be purely based on statistical distributions. However, early experimentation showed that it is actually advantageous to retain the route grouping because it enables a better fit of distributions as well as a better representation of the forecast growth rates that are often very different.

The core of the model is a simple flow model of a "stock" variable being fed by an inflow and an outflow, both of which are controlled by their respoective feedback loop. The growth representation depends on the aicraft generation. Out-of-production aircraft are never grown. However, the newer generation aircraft are used for growth. Fundamentally, growth is specified as an annual percentage of revenue passenger kilometers or miles (RPK/RPM) because this can be computed from econometric models based on economic growth scenarios. This is then simply converted into a percentage operations growth based on the assumption that revenue passenger miles convert to operations based on systemwide averages. The only variable that changes is the load factor. Since the percentage growths are based on ratios, the load factor improvements stated for the different route groups in the FESG forecast can be used to derive out year to start year ratios of load factor ratios that are spread out over the duration of the improvements. After the end of the load factor improvements this is simply assumed to be unity, since load factors can realistically only be improved up to a limit. This is shown in Figure 1 as the Load Factor Im-

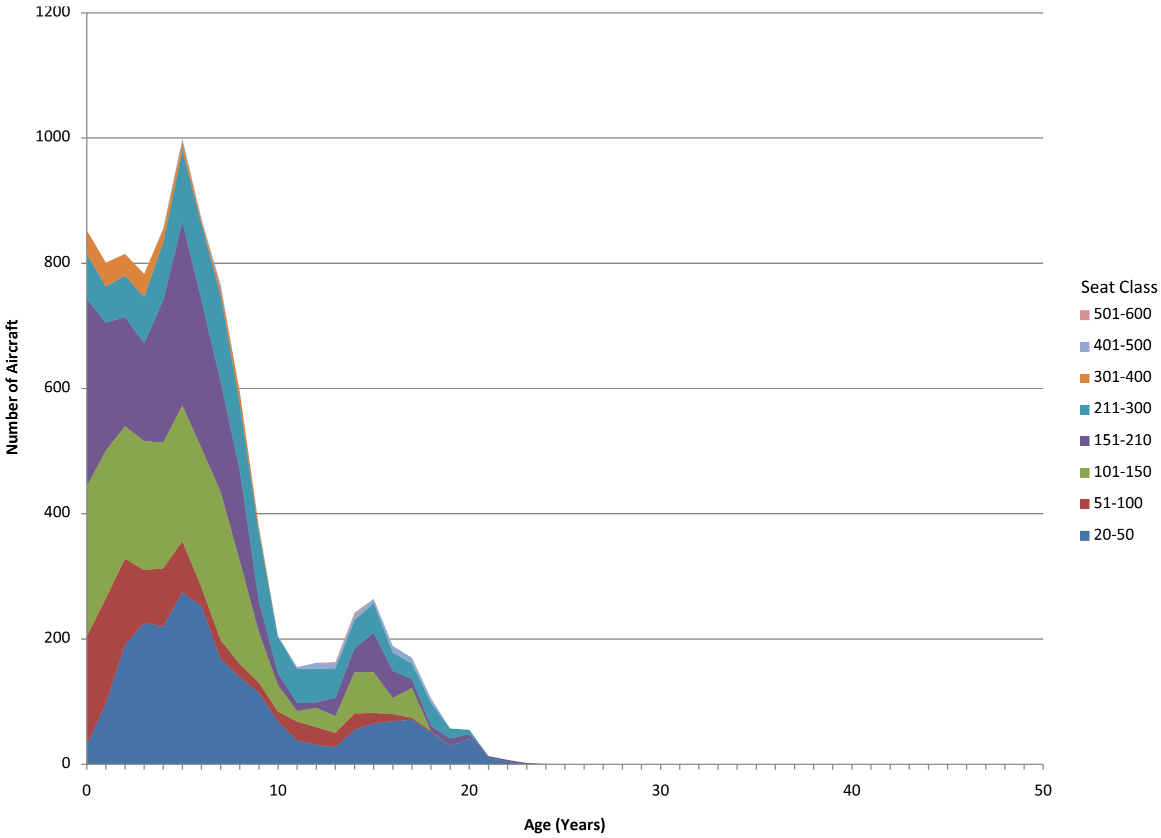

Fig. 3 Age Distribution of In-Production Aircraft

provements.

The growth is assigned depending on which generation aircraft is available. The availability is controlled by the availability variables, which are used to enter the availability dates for the new technology aircraft. The model is structured such that only one of the generations of aircraft are available at any given time and no two generations are available during overlapping years. Furthermore, the availability is immediate over all sizes of aircraft. This might not necessarily realistic, however, it is difficult to know otherwise. This represents a best case scenario in terms of technology adoption. The most conservative assumption would be to make a new technology aircraft only available in a single size of aircraft. In reality due to R&D investment constraints it is likely that new technology aircraft are introdcued staggered through the sizes, but also somewhat staggered through technology generations.

The model is using data starting in 2006, however partial information such as the variations in operations are available as historic data records. Therefore this information can be embedded into the model. The logic that most closely approximates real airline behavior is to assign expansion by growing in-production aircraft and contraction to retiring out-of-production aircraft. This is accomplished by computing the ratio of operations relative to the baseline year and then retiring an appropriate percentage of out-of-production assigned operations without feeding them to be replaced, if the ratio is less than one. If the ratio is greater than one, the operations growth is simply assigned to in-production assigned operations.

This completes the fleet evolution model and now makes it possible for the simulation model to predict which aircraft generation ans size is operation on what route groups. This simulation can be run in real time on a modern computer because it only requires numerical solutions to an order 3 tensor system of ordinary differential equations, as long as the size of each tensor dimension is reasonable.

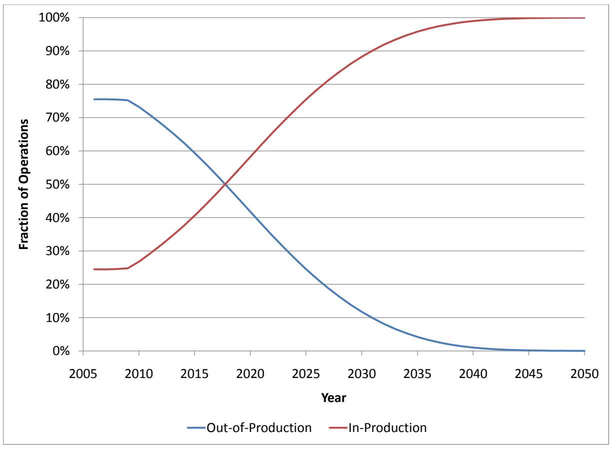

Fig. 4 Fleet Evolution with no new technology aircraft introductions

Figure 4 shows the fraction of operations in a scenario where no newer technology aircraft are introduced beyon current in-production aircraft. This means that out-of-production aircraft are slowly retired as they age until all of the operations are serviced by in-production aircraft. It should be noted that the fraction of out-of-production to in-production aircraft does not change too significantly due to spiking retirements to adjust to the market contraction, this shows significantly in absolute numbers but only marginally in relative percentages.

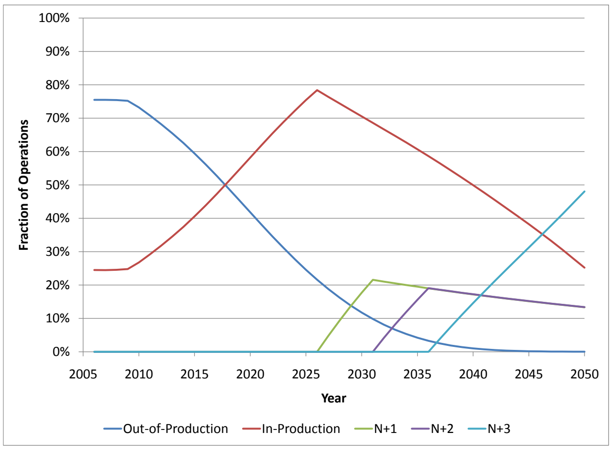

Fig. 5 Fleet Evolution with no new technology aircraft introductions

Figure 5 in contrast shows the fleet evolution with all new technology aircraft being introduced at their respective dates. The result is that in-production aircraft get retired at an accelerating rate once they go are no longer available and are replaced by N+1 aircraft. It should be noted that the fraction of new technology aircraft once they are no longer available is reduced at a decelerating rate since they are not being retired, instead new growth reduces their fraction of the oeprational fleet.

4 Emissions Calculations

In some of the simpler Tier 1 and 2 systemwide emissions computations described earlier the number of operations is simply multiplied by the LTO characteristics or at best the great circle distance for certain routes multiplied by the average fuelburn or emissions per unit distance or similarly the RPKs divided by aircraft size and multiplied by the same average distance based metric. As shown earlier, this can lead to significant discrepancies in the sytemwide results of such modeling. However, the solution of the Tier 3b type methods require significant amounts of data and computational effort as well as detailed aircraft characteristics beyond just averages. Further discrepancies are caused by weight and weather information, which truely do require detailed modeling due to significant localized differences.

However, the goal for this analysis is to provide a mathematically closed form solution that with relatively little data can provide systemwide results that closely match a Tier 3b methodology without detailed weather or weight difference information. This requires a closer look at the aircraft and trip characteristics in question.

The standard aircraft characteristics - as mentioned earlier - are often provided as an average. This looses a significant amount of information since there is a significant second order effect cause by the fact that similar aircraft on average tend to have slightly lower operating weights at short ranges than at longer ranges. Additionally, the take-off and landing phases do expend a significant amount of fuel, more than crusising at an on-design cruise condition. This means that short flights on average tend to burn more fuel than the average cruise fuelburn rates would show. This is somewhat addressed in the Tier 2 methodologies, but compounded by the fact that shorter range flights tend to cruise at significant lower altitudes where the average fuelburn rate again is higher than expected.

Therefore, significant accuracy can be gained by fitting aircraft characteristics to a second order quadratic polynomial without introducing a lot of additional data requirements.

$$\theta(x) = a + bx + cx^2 \tag{1}$$

Where θ is the aircraft characteristic such as fuelburn or emissions species and x is the actual flight distance.

As mentioned earlier, some of the systemwide discrepancies stem from lack of exact weight information for each flight. The conventional assumption is to simply assume a constant load factor and then derive the take-off gross weight from that. This represents a slice through the payload range diagram, which can be approximated quite well with the previous equation. The true systemwide results would actualy be a combination of a characteristic function with respect to the payload-range diagram of each individual aircraft. Since, the aircraft characteristic was already compressed to only be a function of distance, the same can be done for the operational characteristics. This makes the systemwide result equal to:

$$T = \int N\theta(x)\,\delta(x)\,dx \tag{2}$$

where δ is the likelihood distribution as a function of distance

The goal is to derive a function that covers the variation over operational distances. This can be done in a number of ways, but the goal is to choose a function carefully such that the product of the aircraft characteristics and the operational characteristics can be easily summed or in closed mathematical form integrated. Therefore, it is advantageous to choose a gamma distribution for the operational characteristics. This, combined with the previous function and the operations count N, is shown in equation 3.

Once this is solved by integration by parts, the solution can be expressed by equation 4. This leaves us with a closed form function that has only five parameters. One parameter is used to scale the overall system activity or operations. Two parameters are used to define the operational characteristics of aircraft. These can be optionally adjusted to represent shifts in operational network changes such as route structure changes or operational improvements by more closely approximating great circle distance distributions. Finally, three parameters are used to describe the aircraft characteristics as shown earlier.

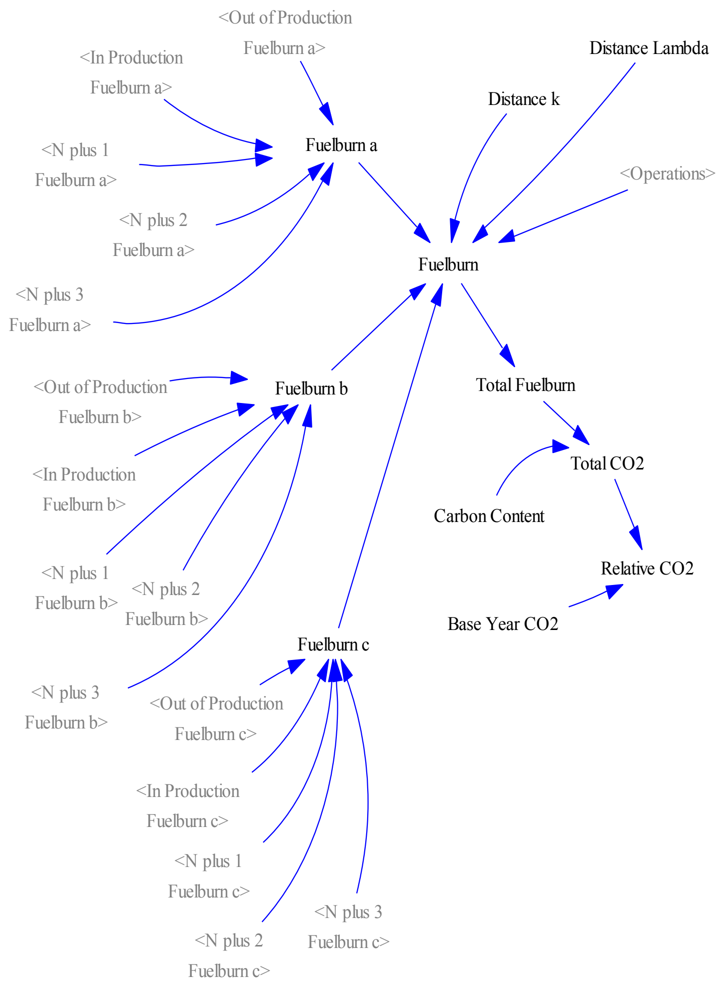

Fig. 6 System View of Environmental Charactistic Estimation

The implementation in the system dynamics model is shown in Figure 6. This also allows a relatively easy implementation of scaling factors to define the future technology generation aircraft

$$T = \int_0^{\infty} N\left(a+bx+cx^2\right)\left(\frac{x}{\lambda}\right)^{k-1}\exp\left(-\left(\frac{x}{\lambda}\right)^k\right)dx \tag{3}$$

$$T = N\left(a+b\left(\left(\frac{1}{\lambda}\right)^k\right)^{\left(-\frac{1}{k}\right)}\Gamma\left(\frac{1+k}{k}\right)+c\left(\left(\frac{1}{\lambda}\right)^k\right)^{\left(-\frac{2}{k}\right)}\Gamma\left(\frac{2+k}{k}\right)\right) \tag{4}$$

based on current aircraft characteristics. This is where the separation of the three aircraft parameters by aircraft generation stems from. Using the reductions in environmental characteristics shown in Table 1, it is now possible to to evaluate how systemwide environmental scenarios develop under differing assumptions.

5 Preliminary Results

First, the scenarios are to compare the standard forecast with only in-production growth and replacements with the introduction of all new generation aircraft. This is shown in Figure 7.

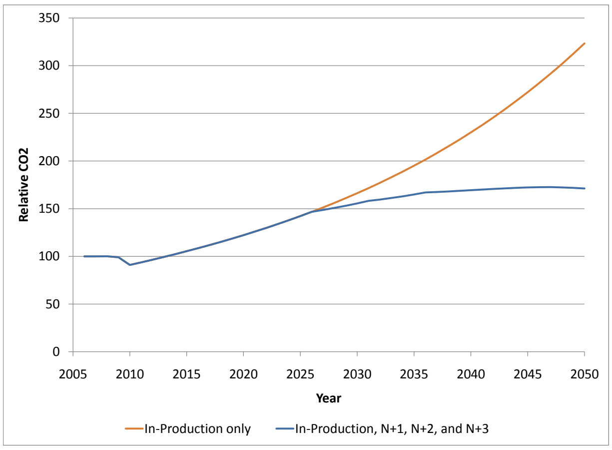

Fig. 7 Effect of technology introduction into aircraft fleet

The results show that the growth can be counteracted by agressive technology introduction, but this still comes nowhere near the goal of overal reduction environmental characteristics of aviation as a whole. However, it should be noted that the assumptions are that the relative improvements are true across all size classes as well as against the current in-production fleet. This is not necessarily true, because the system level benefits of new technologies strongly depend on the system size and hence can be vastly different. Furthermore, the in-production fleet is not exactly at the same level of technology across all size classes and the introduction of new technology aircraft is unlikely to happen simultaneously across all size classes. Therefore it is very aggressive to assume applicability across all size classes. Previous stidies have shown that introducing only one or two specific sizes of aircraft only yield modest system level benefits[13].

The rapid evaluation this type of model enables can be used to explore a range of values and scenarios to explore sensitivities to these assumptions. The most uncertain feature is the forecast of aviation growth. Therefore, it would be advantageous to explore a wide variety of demand growth scenarios. In order to support this, it is necessary to run a sweep of values of demand growth parameters. In order to show how sensitive aviation growth is to technological advancements, it has been common to simply assume an one to one relationship between growth and fuelburn. This is shown in Figure 8. Furthermore, annual average fuelburn improvements can be applied to this one to one relationship, this is also shown in Figure 8. The same figure also shows the results of the system dynamics fleet evolution model with only in-production as well as the addition of each of the new generation aircraft. Thesystem dynamics model results lines show that the fuel use ratio relation to demand growth has a slope of much less than one, which means that demand does not directly translate to fuel use. This also means that in high growth scenarios the fuel use is less pronounced than would be expected with a simple one to one ratio. Furthermore, the figure shows that in high growth scenarios the new technology aircraft introductions drive the fuel useage down to the commonly used

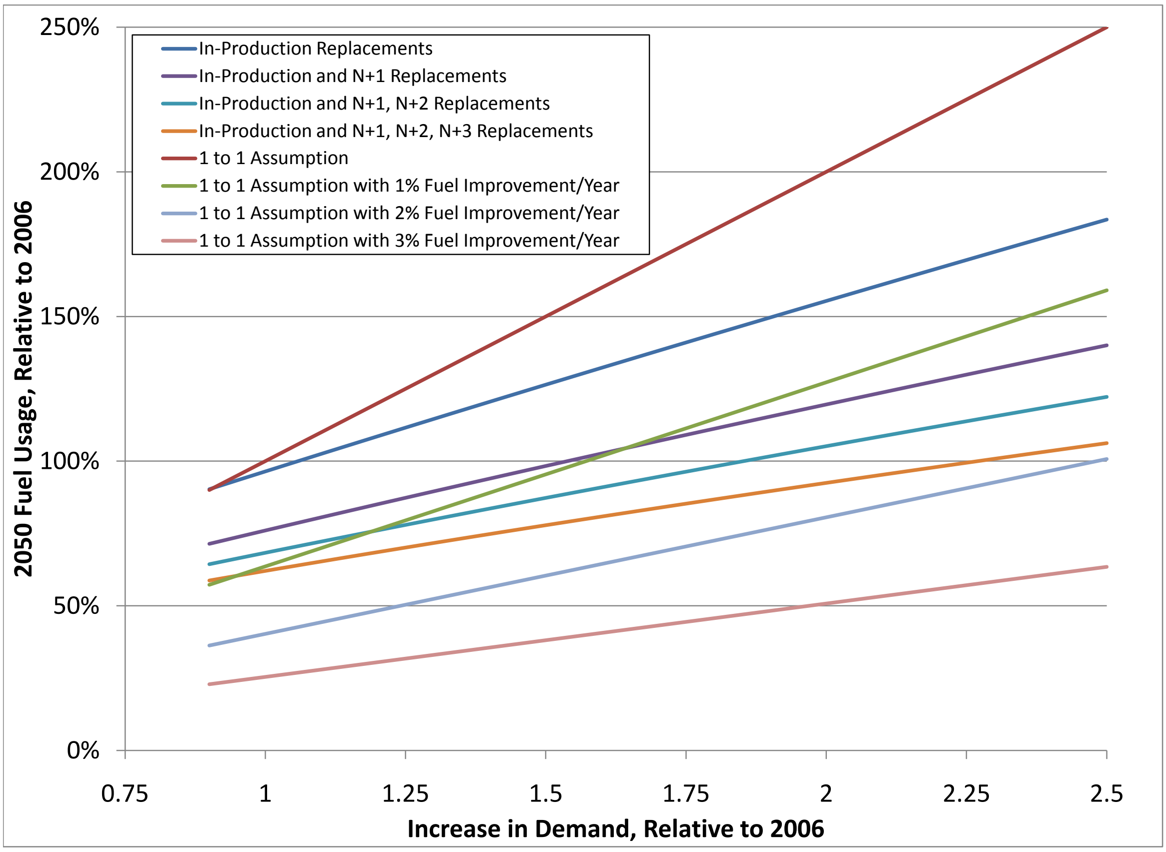

Fig. 8 Relation Between Growth in Demand and Fuel Use in 2050 Relative to 2006

average annual fuel efficiency improvements of betweenone and two percent, while in low growth scenarios the new technology aircraft introductions are the equivalent of the under one percent per year improvement assumption. This is due to the long service life of aircraft, such that low growth scenarios have a much older aircraft generation fleet, which increases the fuel usage. This figure also shows that a simplified model will yield very unrealistic results, especially without assuming efficiency improvements. Addtionally, the ratio of fuel usage growth to demand growth is definitely less than one. The assumptions as stated put the ratio at between 0.5 to 0.7 depending on the amount of new technology aircraft introductions.

6 Concluding Remarks

In summary, a system dynamic fleet evolution model su as presented here can be invaluable to study the effects of technology investment and the effects on the environmental effects of aviation. Furthermore, a model such as this enables the interactive exploration of scenarios as desired by decision makers as well as the application of statistical techniques such as monte carlo simulation to enable the study of the effects of uncertainty in the scenario forecasts, the technology trends, dates as well as modeling accuracy.

This model also lends itself to be matched with an economic model of the economic environment aviation operates in and therefore would allow assessment of the impact of various external price and demand shocks as well as the effect of various policies that have been described earlier.

7 Acknowledgments

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7.1 Copyright Statement

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