TECHNOLOGY-ENABLED IMPROVEMENTS FOR TERMINAL AREA CAPACITY AND ENVIRONMENTAL IMPACT

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Abstract

The tradeoffs between air transportation system capacity and local environmental impact are at the crux of today's challenges in strategic technology planning for civil aviation. This paper documents the development of a modeling capability that addresses these challenges and is integrated into visually interactive decision support tool. The latter enables decision makers to discern complex system sensitivities and gain insight on its behavior.

1 Introduction

Air transportation plays a vital role in modern society, serving as a major economic driver by generating employment and revenues, as well as a significant source of government revenues through tax contributions. It is also responsible for leveraging the development of adjacent industries in the global marketplace such as tourism [1]. Compared with these economic figures the societal benefits of air transportation are often difficult to quantify but are nonetheless just as important. Freedom of mobility granted by air transportation is a key element in the way of life and living standard of most modern societies, providing a fast, safe form of personal and business travel [6, 25]. In the United States the government recognizes air transportation as "vital to the economic stability, growth and security of the nation" [27], as well as part of its critical infrastructure [23].

These observations provide a compelling incentive to safeguard aviation and support its growth so that society as a whole can continually capitalize on its benefits and sustain development. Fortunately demand for air transportation has experienced steady growth as observed by historical trends, and is predicted to continue growing over the next 20-30 years according to a variety of industry forecasts [14, 7, 19]. There are however two critical challenges that will no doubt hinder system growth unless they are properly addressed: insufficient system capacity and environmental impact.

Capacity refers to the system's ability to hold or accommodate aircraft operations by performing system functions and providing the necessary resources [21, 16]. When existing capacity is insufficient for a given level of demand the air transportation system experiences losses in the form of missed opportunity, operational congestion, elevated levels of delay, degradation of safety, and associated economic losses among others [16, 9, 8]. Though capacity can be defined for a variety of system segments, the terminal area has been consistently identified as a key component where capacity limits are often reached or exceeded due to the natural convergence of operations. System choke points have consequently been identified in large connecting hubs such as New York, Chicago and Atlanta [17]. A variety of solutions have been proposed to increase system capacity. Examples include the expansion of airport surfaces like runways or taxiways, construction of new airports [10], or the safe reduction of aircraft separation by means of superior navigation accuracy such as Required

Navigation Performance (RNP) [18].

Environmental impact by aviation activity is commonly described by its two main components: emissions and noise. Primary aircraft emissions such as carbon dioxide and water vapor act as greenhouse gasses which have been linked to climate change. Others, such as nitrogen oxides (NO_X) and unburned hydrocarbons, act as precursors of ozone, another known greenhouse gas [28]. Of particular relevance to this study is the negative effect that some species have on local air quality, such as carbon monoxide (CO) whose noxious effects on human health, wildlife and surrounding ecosystems are well documented [35, 33]. Likewise aircraft noise is mostly considered a local phenomenon, primarily affecting communities near airports and within the terminal area where aircraft operate at low altitudes. Noise has been shown to cause a variety of negative effects on human health and wildlife, also resulting in indirect losses such as property devaluation and degradation in quality of life [3].

Both emissions and noise are primarily driven by aviation activity levels [34]. Important advances have been made to mitigate environmental impact, particularly in terms of engine technology and more recently by new operational concepts such as Continuous Descent Approach (CDA) [4]. Thus far, however, the effect of activity growth has outweighed that of environmental technologies, leading community groups and lobbyists to strongly oppose aviation growth in their localities [2]. The basic relationship between demand growth, capacity increase, and environmental impact reveals the crux of the problem at hand: capacity solutions to support growing aviation activity and meet future demand exacerbate environmental impact which currently cannot be sufficiently addressed by aircraft technologies alone. Key research questions arise from this observation: 1) How can different solutions be combined to concurrently address the competing challenges of capacity and environment? 2) What different aspects of the system and its externalities can/should be considered in the formulation and solution of this problem? 3) What is the sensitivity of system performance to the various external and internal elements under consideration? 4) How can state of the art techniques and methods be used to gain insight about the system and support decision-makers in their endeavor of formulating a solution portfolio? 5) What are the key enablers?

This paper describes the efforts aimed at answering these research questions. The scope and focus of the study is limited to technology-based solutions at the aircraft and operational level, motivated by the need of government and private industry to identify and support the technology programs that provide the biggest "bang for the buck" across a wide variety of aviation growth scenarios. First, the problem is characterized in section 2 to properly identify necessary components in the proposed approach. The methodology and its implementation are then described in detail in sections 3 and 4 respectively. A description of the resulting decision support tool and discussion of sample results are then presented in section 5.

2 Problem Characterization

The problem at hand is directly comparable with that of policy definition, where a high-level plan guiding the selection of adequate measures and solutions to achieve a general objective is generated [22]. The adequacy of solutions depends on the conditions at the time, such as aviation demand levels. Another type of problem with similar construct is strategic planning, where a path of evolution for an entity or system is decided upon once the current state has been assessed and a long-term goal has been stated. Because the exact contextual conditions between the current state and goal are unknown, strategic planning provides a means to study variations of that path across a multitude of plausible scenarios [8]. Based on this characterization the following elements are identified as key components in a solution approach:

1. The current state of the air transport system must be assessed and sufficiently described so as to establish a point of reference from where the system will evolve and future states can be

compared with. A relevant scope for the problem must therefore also be defined.

2. The externalities that comprise the context in which the air transport system will evolve need to be adequately characterized in terms of relevant parameters such as demand growth.

3. Different technology solutions modify the system's behavior and performance as it responds to changing externalities. A Modeling and Simulation (M&S) environment that captures said behavior is necessary to evaluate the effect of implementing technologies on the system under a variety of contexts.

4. Given the complexity of system relationships and the abundance of data involved in this type of problem, a visual and interactive tool that supports decision makers discern trends and gain insight is highly desirable.

The next section describes the steps of a methodology that consolidates the aforementioned elements into a structured process that yields necessary analytical capabilities to assess technology portfolios for terminal area capacity increase and environmental impact reduction.

3 Methodology

3.1 M&S Environment Definition

Adequate modeling tools are required for the assessment of the current system state as well as for the evaluation of technologies across multiple growth scenarios. There are obvious implications regarding the necessary modeling capabilities which drive the researcher to seek a compromise between acquiring any missing resources and scoping the problem accordingly without compromising the value of the research effort. Thus, the objective of the first step in this approach is to strike such a balance, defining both the M&S environment and the scope of the problem.

3.2 Generation of a Parametric Demand Growth Function

Having defined the problem scope, the second step in the methodology addresses the characterization of system externalities. While the definition of a set of scenarios could fulfill this task, the implementation of a parametric demand growth function is recognized as a means to provide additional flexibility in the consideration of the system's context. As indicated by its name, a parametric demand growth function generates a notional demand set and specifies how it grows over time based on a set of descriptive input parameters. The dynamic nature of this approach enables the generation of a plethora of demand sets, which contrasts with the limitations of a few static, pre-defined scenarios. However growth functions require that the relationship between different demand attributes be properly captured so that realistic, internally consistent demand sets are produced. For instance, the relationship between passenger volume growth and operations growth must be adequately captured. Furthermore, because the resulting demand sets are a direct input to the M&S environment the construct of the demand function is driven by modeling capabilities set forth in the previous step.

3.3 Creation of Surrogate Models

In order to enable an interactive decision support tool, the M&S environment must be computationally inexpensive so that analysts can evaluate system performance almost instantaneously for any desired input set resulting from the demand growth function. Because modeling capabilities rarely feature such short run times, the present method calls for the usage of surrogate models which are generated in its third step. Surrogates are mathematical approximations that capture the behavior of the models they substitute by fitting functions of known form to empirical data samples through statistical methods. In all practical applications the mathematical complexity of the surrogate model is far lower than that of the original model, which translates to significant reductions in computational resources required. Also, since the mathematical form of the surrogates is completely known, sensitivities and trends may be calculated via the adequate partial derivatives. However, the creation of surrogates requires that some effort be made upfront in making available the necessary M&S runs for statistical model fitting, as well as in the verification of surrogate accuracy. These details and other important considerations, such as the selection of the adequate surrogate types, fitting techniques, and designed experimental sets, are beyond the scope of this paper and sufficiently documented in published literature (see, for example, references [24] and [15]).

3.4 Assessment of the Reference State

A characterization of the current system state is needed to provide a datum or reference upon which the development of the strategic assessment takes place. This fourth step in the methodology involves the definition of a representative demand data set and other contextual parameters such as assumed technology levels, as well as an assessment of system performance for those conditions. The latter may be produced with the original the M&S environment or with properly verified surrogates.

3.5 Integration of the Decision Support Tool

With the upfront investment in the generation of surrogate models, and the availability of a parametric growth function, system capacity and environmental performance can be instantly evaluated for any combination of scenario attributes and technologies, and expressed relative to the baseline or reference state. However the amount of alternatives to be evaluated and analyzed is unmanageable and the tradeoffs that need to be performed are fairly complex and nonintuitive. To address this shortcoming the fifth and last step of the method summons established multi-criteria decision making techniques [31] and visual analytics techniques [32] to guide the construct of an visually interactive decision support tool. Said tool integrates input and output data in a single environment, enabling analysts to discern trends and gain insight. Most importantly, the decision support tool produces results dynamically which allows decision makers to engage in electronic reviews where discussions are supported by instantaneous generation of the necessary information.

4 Implementation

4.1 Construction of the M&S Environment

For the present research the definition and construction of the M&S environment was conducted based on available resources as follows: The assessment of aircraft operations and quantification of delay is captured via the MIT Extensible Air Network Simulation (MEANS) tool. MEANS is an event-based simulation framework that models aircraft movements, airport capacity and the impact that weather has on it [5]. Environmental impact modeling included the calculation of full-flight and Landing and Takeoff (LTO) fuel burn and emissions of CO and NO_X, via the FAA's Aviation Environment Design Tool (AEDT). The AEDT provides an integrated modeling capability of aircraft noise and emissions by integrating a set of legacy and new modeling tools such as the System for assessing Aviation's Global Emissions (SAGE), Emissions and Dispersion Modeling System (EDMS), and the Integrated Noise Model (INM) [30]. The AEDT also uses the Base of Aircraft DAta (BADA), a EUROCONTROL aircraft performance database used to model and characterize aircraft in trajectory simulation and air traffic management research [26].

The inability to model noise characteristics for future aircraft was identified as a critical capability gap for the present study. While the characterization of general flight performance parameters of notional future aircraft models is a manageable (albeit challenging) task, the equivalent characterization of noise-related performance demands significantly more data, both in amount and detail. Because this data did not exist at the time of this study, noise characterization of the future fleet with adequate technical rigor was not achievable. As a result the noise performance of the system was not included for its evolution in notional demand scenarios, but was included for the "frozen technology" case only where the aircraft models in the current fleet do not change over time.

Additional refinements of the problem scope included the definition of the baseline date, set to October 18^{th} 2005 based on previously acquired data by the researchers which was validated as a representative day of operations for that year. The airport set was scoped to the top 135 entries for passenger volume in the FAA Air Carrier Activity Information System (ACAIS) database [12], responsible for 97% of total enplanements for the baseline date. The 190 distinct aircraft models composing the fleet for the baseline date were consolidated into a set of 16 by aggregating aircraft models with less than 50 operations to the closest dominant model. For instance the 6 operations performed by B737-100 aircraft were aggregated to the 1,556 operations performed by B737-300 models. The technology pool for future scenarios included aircraft technologies which were modeled as anticipated industry response concepts and future aircraft concepts, shown in Figure 1, via BADA definitions. Additionally, Ultra-High Bypass (UHB) and Hybrid Laminar Flow Control (HLFC) technologies, of particular interest to research sponsors, were modeled separately via scaling factors in aircraft BADA definitions following established techniques for technology infusion [20] and assuming a 100% penetration rate for all new aircraft concepts produced after the technology introduction date.

Anticipated Industry Response	•Airbus 380 •Airbus 350	•Boeing 787 •Boeing 747-8
Future Technologies & Concepts	•Narrow-body Replacement •Wide-body Replacement •Blended Wing Body (BWB) •Ultra-High Bypass (UHB) •Hybrid Laminar Flow Control (HLFC)	

Fig. 1 Aircraft Technologies and Concepts

Operational technologies included Automatic Dependent Surveillance-Broadcast (ADS-B) which provides highly accurate air traffic displays and improves situational awareness, effectively allowing the safe reduction of aircraft separation [13]. The Wide Area Augmentation System (WAAS), which improves the accuracy and availability of ADS-B navigation [11], was also included. Both of these concepts were modeled in MEANS by adjusting the aircraft separation matrix, which details the separation minima between different weight-class aircraft. It was assumed that the minimum possible separation was dictated by wake-vortex margins under ideal visual conditions, meaning that ADS-B and WAAS separation reductions are only observed for marginal VFR and IFR conditions. CDA procedures maintain cruise altitude beyond beginning of descent in conventional procedures, effectively reducing noise exposure at ground level, followed by a continuous descent to the runway at near idle thrust settings, reducing fuel burn and emissions [4]. Low-fidelity CDA procedures were generated for the airport set and modeled accordingly in MEANS and AEDT. However CDA procedures contain an inherent uncertainty about the location of aircraft based on a number of operational factors [29] and were thus modeled to include increased aircraft separation margins.

4.2 Parametric Demand Growth Function

The parametric demand growth function was defined for passenger volume in terms of four key variables: the baseline date (previously established), the end year, the growth factor at the end year relative to the baseline date, and a profile shape parameter γ. In an effort to handle data in its most intuitive form, the function uses growth factors relative to the baseline year (e.g. 1.5X equivalent to 50% growth) rather than using absolute values. The shape parameter captures the growth rate of the demand profile, allowing the analyst to front-load, back-load, or linearize the profile as shown in Figure 2. Note that variations in γ result in changes for the growth factor in the evaluation year (2015).

A transformation from passenger volume to an operations data set, input to the M&S environ-

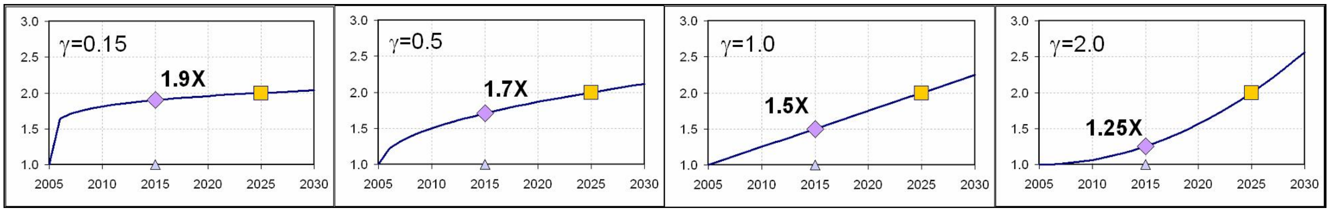


Fig. 2 Parametric Demand Growth Function for Four Values of Shape Parameter

ment, was facilitated by two assumptions. First, the relative volume between origin destination city pairs was assumed to remain constant over time, which carries implications about the uniformity of demand growth across routes and relative stability in the airline network topology. Second, values of load factor were uniformly implemented for all operations based on existing forecasts [7], effectively producing an estimate for the required available seats in each route. Finally, the combination of flight frequency and aircraft size used for each route by service providers was estimated by means of a simplified frequency-capacity split model [7]. The availability of aircraft models, retirement of units, and introduction of new models within each seat-class is captured through a retirements and replacement procedure that adjusts the operations set. The fleet age on the baseline year is used in conjunction with aircraft retirement curves to determine the survivability rate of aircraft models each year. If an aircraft is retired, the operations it performed on that year are modified to be executed by replacement aircraft in the following year. Additionally, because some growth in demand is expected, additional operations due to growth are assigned to new aircraft from one year to the next. The final result of this transformation series is a fully defined set of operations that captures key elements of airline behavior and fleet evolution within the prescribed scope.

4.3 Creation of Surrogate Models

For the creation of surrogate models a small study was performed to determine the type of surrogate that provided the best compromise between accuracy (i.e. low representation error) and number runs required in the fitting routine (i.e. low computational resources). It was determined that artificial neural networks offered the preferable alternative relative to response surface equations and Gaussian process models. Two sets of surrogates were developed. The first set was dedicated to the flight and environmental performance of the aircraft fleet, containing baseline and future models. The surrogates generated values for fuel burn, CO and NO_X as a function of mission stage length, aircraft performance attributes, and technology multipliers. The second set of surrogates was dedicated to capacity performance of the system, measured by arrival and departure delay as a function of demand growth factors, weather conditions, and availability of CDA procedures. All surrogates were verified by means of standard statistical tests and found to have good accuracy, featuring R^2 values above 0.95 and representation error means under 10% at all times. Standard deviation of error distributions varied among results, spanning from less than 1% to about 4% in some isolated cases.

4.4 Implementation of the Decision Support Tool

The data set for the reference day was adequately adjusted to the M&S scope (i.e. fleet, airport set), and used as direct input on the M&S environment to generate the baseline values. With this data and the surrogate models readily available a spreadsheet-based decision support environment was built. The construct of the support tool is based on key principles identified in previous sections: desired functionality, flexibility, transparency of results, and interactive visualization. These principles, identified as critical enablers for collaborative and dynamic decision making tasks, are embodied in the architecture of the support tool as well as in the set of features it contains. These are presented in detail along with sample results in the next section.

5 Results and Discussion

5.1 Inputs Dashboard

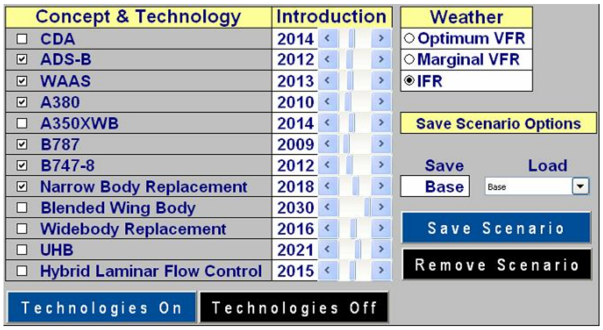
The formulation and understanding of an operational context in this research is of cardinal importance, and thus motivates the design of an input dashboard in the support tool. This part of the tool capitalizes on the parametric construct of the demand growth function and provides graphic control to instantaneously generate and modify demand inputs while displaying the demand profile for both passenger volume and the resulting operations. This display gives analysts a sense of how passenger volume quantitatively relates to operations, under the assumptions presented in previous sections, and indicates growth factors for the evaluation year and target year. Values for the three parameters of the function and the evaluation year are set via slide bars, as seen in Figure 3.

Scenario Setup

Evaluation Year	2020
Target Year	2025
Year 2025 Growth Factor	2
Shape Parameter γ	1.6

Fig. 3 Parametric Demand Growth Function Display and Controls

Similarly, all technologies and concepts are displayed in the inputs section and can be independently turned on and off, while their introduction year can be adjusted via control slide bars as shown in Figure 4. Also shown in this figure are selection buttons for weather conditions, which offer alternatives for optimum visibility (Visual Flight Rules (VFR)), marginal VFR and Instrument Flight Rules (IFR). As mentioned in section 2 a parametric operational scenario framework provides flexibility beyond static scenarios without eliminating their potential use. Because some scenarios may be of particular interest to the analyst the support tool can save any series of input settings as a user-defined scenario that can be called upon at a later time. Control buttons for this functionality are shown on the bottom right of Figure 4.



Concept & Technology	Introduction
☐ CDA	2014
☑ ADS-B	2012
☑ WAAS	2013
☑ A380	2010
☐ A350XWB	2014
☑ B787	2009
☑ B747-8	2012
☑ Narrow Body Replacement	2018
☐ Blended Wing Body	2030
☐ Widebody Replacement	2016
☐ UHB	2021
☐ Hybrid Laminar Flow Control	2015

Weather
○ Optimum VFR
○ Marginal VFR
● IFR

Save Scenario Options
Save: Base
Load: Base

Fig. 4 Technology, Weather and Scenario Controls

5.2 Emissions Outputs

As part of the outputs, emissions are visualized in a flexible construct that allows the analyst to select the metric of interest (fuel burn, NO_X, or CO), the regime (total flight or LTO), and the region (one of the 135 study airports or the total system). These alternatives are chosen in the pull-down menus shown in Figure 5. Once selected, emissions results are presented visually in comparison with operations growth. This comparison provides insight about the sensitivity of system environmental metrics to increases in aviation activity, thus addressing an important part of the research questions for this project. Results are also compared with a notional "do-nothing" baseline scenario representative of a frozen technology level, providing comparative insight for the technology portfolio under consideration and helping answer the question "how much improvement is attained with this portfolio?".

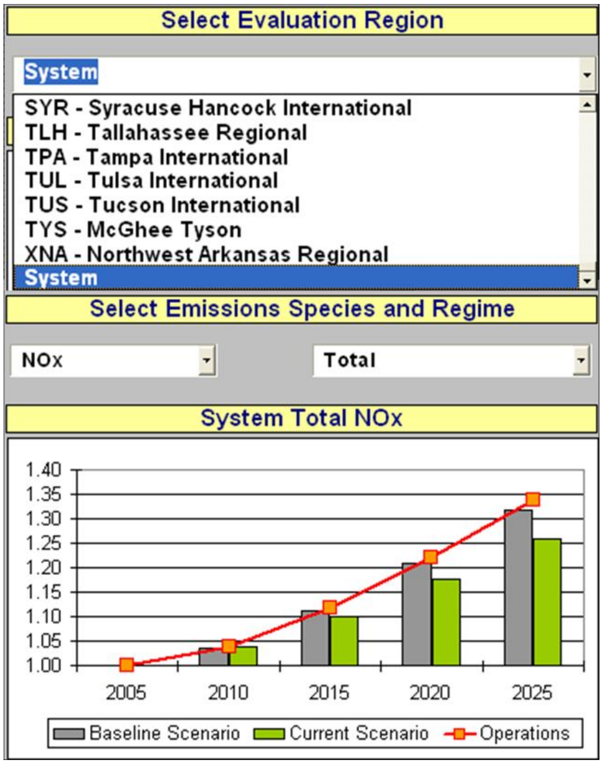


Fig. 5 Emissions Evaluation Display and Controls

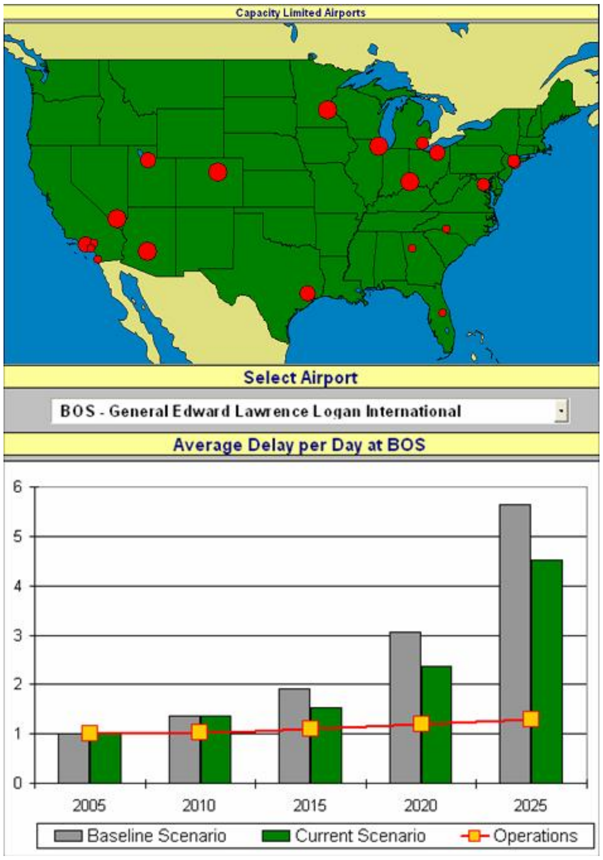
The example shown in Figure 5 is for system-wide NO_X emissions. In this example it is apparent that NO_X in a frozen technology setting grows almost at the same rate as operations, reaching a 30% increase relative to the reference year. The data shown in green for the technology portfolio under consideration, in this case reflecting the inclusion of anticipated industry response vehicles (i.e. A380, A350, B787, B747-8) and a narrow-body replacement vehicle, suggests a mitigation of this increase, reaching a 25% value relative to the baseline year.

5.3 Capacity Outputs

Airport and terminal area capacity results are presented in a number of ways. First, the top 20 capacity constrained airports are listed for the analyst and plotted on a U.S. map where the size of the bubble is indicative of the degree of relative capacity deficiency experienced at that airport, as shown in Figure 6. A plot of average delay per day shows the evolution of this metric over time for a user-selected airport, both for the frozen technology scenario and for the current technology portfolio under consideration. Additionally a trend line of operations growth is included, thus revealing the sensitivity of delay to technologies and activity growth at the selected airport. The example shown in Figure 6 shows the delay increase at Logan International Airport under IFR conditions. The baseline scenario data indicates a sharp increase in average delay past 2015, suggesting that a critical limit in airport capacity is surpassed beyond this point. This hypothesis is additionally supported when noting a six-fold increase in delay by 2025, whereas operations count has only increased by 35% (1.35X) relative to the reference state. The data plotted in green corresponds to a technology portfolio comprised of ADS-B and WAAS, with assumed entry dates of 2012 and 2014 respectively. The reader will note that the evolution of delay through 2010 is the same for baseline and current scenario given the prescribed entry dates. Though not providing sufficient increase in capacity for this operational growth level, these technologies offer measurable improvements. Most importantly, this type of result informs analysts about system sensitivity of operational capacity relative to activity growth, as well as relative improvement of operational concepts in the portfolio. Analogous analyses on other airports may reveal different sensitivities altogether due to runway configuration and potential for addressing operational growth at each location.

5.4 Noise Outputs

As mentioned in section 4.1 one of the major limitations in this research is the present lack of noise performance characterization for aircraft in the future fleet, whether they be part of the expected industry response or notional advanced



Select Airport

BOS - General Edward Lawrence Logan International

Fig. 6 Capacity Evaluation Display and Controls

concepts. This gap in the available data impeded the implementation of noise assessments at study airports for notional future scenarios, and clearly represents an area of improvement and future work. Efforts are currently underway for the development of a methodology that will produce such noise characterizations with proper analytical rigor. However capabilities for noise exposure calculation and generation of contours are currently available, and demonstrated for a frozen technology case whose fleet does not include new aircraft models. Noise contours for the baseline and evaluation years at a representative airport are plotted in the outputs section of the support tool, as shown in Figure 7, where the user can select the different decibel (dB) thresholds to be visualized. As can be seen the contour for each dB value grows over time, reflecting the increase in operations. When adequate noise performance for future aircraft concepts become available and are included in the assessment the resulting contours are expected to grow at a slower rate or even decrease in size.

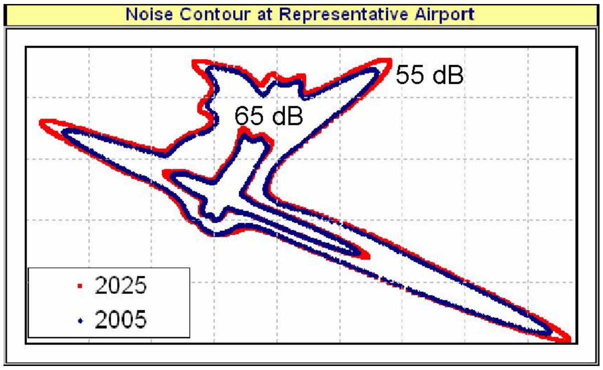
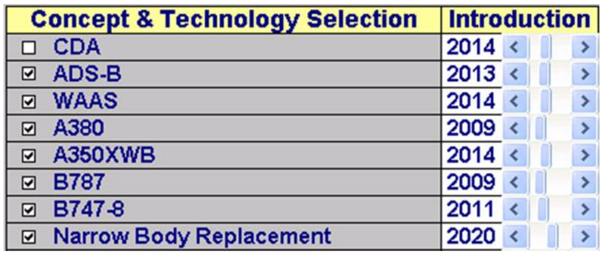


Fig. 7 Noise Evaluation Display and Controls

5.5 Technology Assessment and Rankings

Information from the input and output displays described in the previous sections collectively provide decision makers with information where valuable insight is revealed. Consider for instance the evaluation of the technology set described in Figure 8. Assuming a 3.5% average yearly growth in passenger volume consistent with current forecasts [14], the resulting growth factor is 2X for a target date 20 years from the baseline. The effect of these technologies on system performance can be studied for a variety of growth profiles by front-loading or back-loading the growth curve via the shape parameter γ. Figure 9 shows the system-wide LTO fuel burn and local capacity improvements at LAX for representative profiles. Note for instance that delay is much more sensitive to operations growth than fuel burn. Also, significant delay reductions are observed only after the introduction dates of ADS-B and WAAS, particularly for the front-loaded profile, thus revealing the local capacity sensitivity to those operational technologies for different growth profiles. Similarly reductions in system-wide fuel burn are more pronounced for higher operational activity and in particular after the introduction date of the B787.

Technology rankings calculated by the tool complement insight gained from data visualiza-



Concept & Technology Selection	Introduction
☐ CDA	2014
☑ ADS-B	2013
☑ WAAS	2014
☑ A380	2009
☑ A350XWB	2014
☑ B787	2009
☑ B747-8	2011
☑ Narrow Body Replacement	2020

Fig. 8 Technology Set for Sample Assessment

tion and further support decision makers in the assessment of portfolios. A multi-attribute decision making scheme combines quantitative data generated by the surrogate models, qualitative mappings provided *a priori* by analysts, and user-defined weightings on system-level attributes to produce the rankings. Figure 10-a illustrates an approximately even weighting across capacity and environmental attributes and the resulting technology ranking. The sensitivity of operational technologies to preference weightings is revealed by increasing the relative importance of system delay as shown in Figure 10-b, which shifts ADS-B and WAAS higher in the ranking lists as expected. This trend can be concurrently traded with the system sensitivity to the introduction date of a narrow-body replacement, whose primary effect is the reduction of fuel burn and emissions. Figure 10-c shows that, even while weightings are shifted from an even profile to an emphasis on delay, introducing the aforementioned aircraft concept just two years earlier (2018) has a significant impact on the system and thus on the rankings.

6 Summary and Concluding Remarks

The definition of a technology portfolio that supports capacity enhancement and environmental viability of the air transportation system is a complex but highly relevant endeavor. A characterization of this problem and the identification of key analytical needs enabled the development of a methodological approach whose process and final capabilities address research questions identified in the opening section. The definition of a problem scope and an adequate M&S environment addressed the internal system attributes and external forces that need to be considered in the formulation of a solution to the problem at hand. The parametric demand function and surrogate models are key enablers, whose integration into a visually interactive tool represents the use of state of the art methods and techniques in support of decision makers. The sensitivities of system performance to the external and internal elements under consideration are thus readily revealed by capitalizing on the different display and control features of the support tool. While suggesting multiple areas of improvement and avenues of future work, the capabilities demonstrated represent a contribution to the field that serve as a basis for ongoing and future research efforts.

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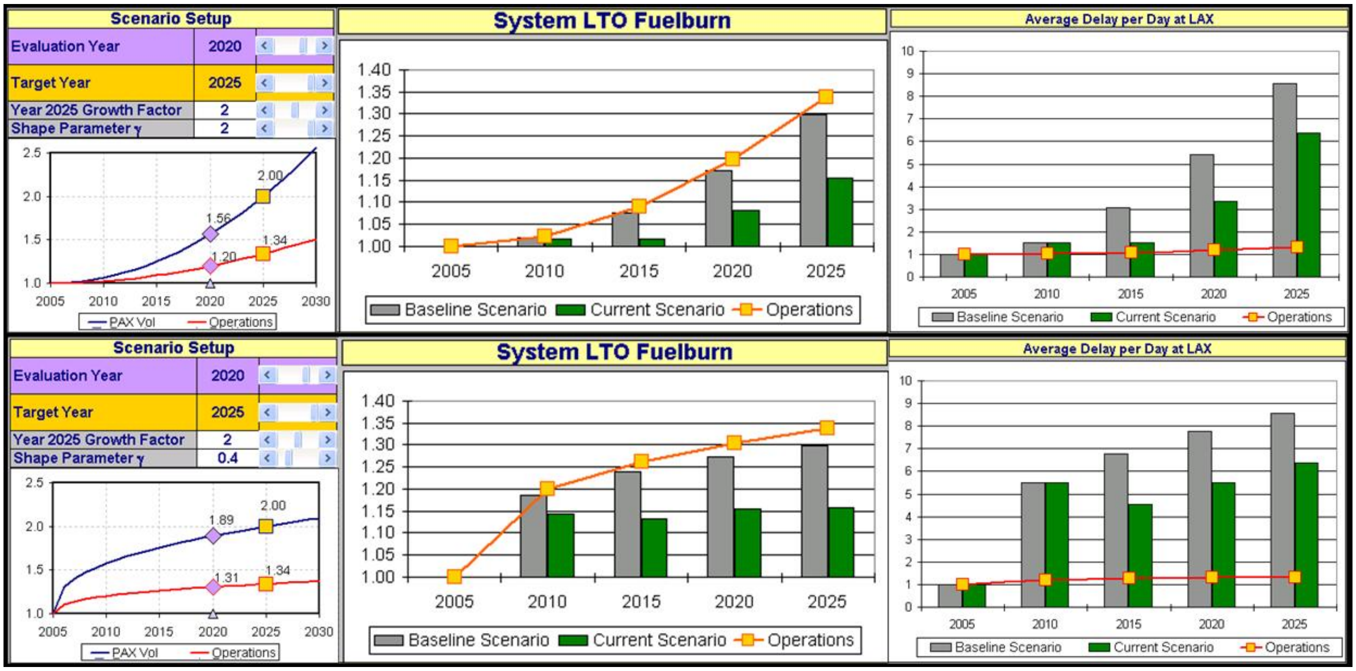
8 Copyright Statement



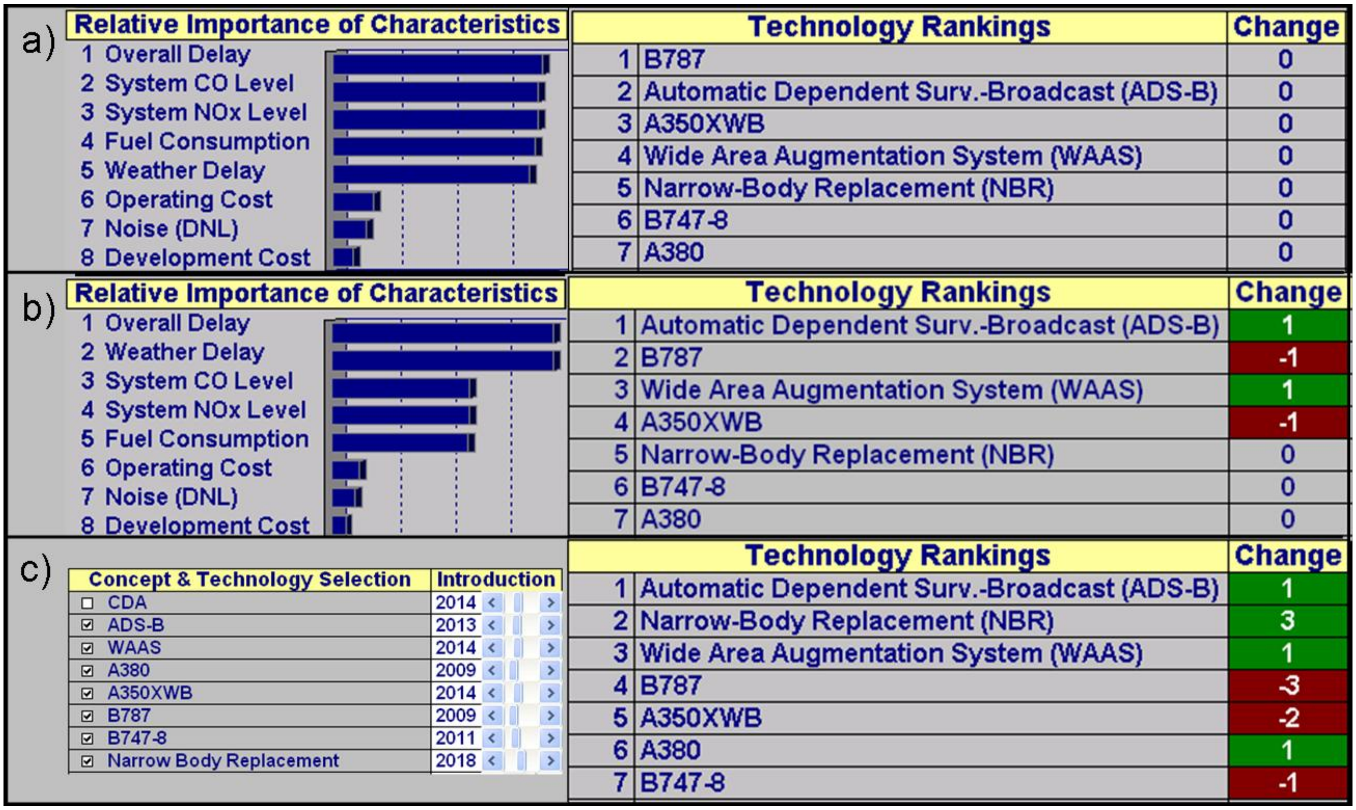
Scenario Setup

Evaluation Year	2020
Target Year	2025
Year 2025 Growth Factor	2
Shape Parameter γ	2

Scenario Setup

Evaluation Year	2020
Target Year	2025
Year 2025 Growth Factor	2
Shape Parameter γ	0.4

Fig. 9 Selected Decision Support Tool Displays for Sample Assessment



a)

Relative Importance of Characteristics

1 Overall Delay
2 System CO Level
3 System NOx Level
4 Fuel Consumption
5 Weather Delay
6 Operating Cost
7 Noise (DNL)
8 Development Cost

	Technology Rankings	Change
1	B787	0
2	Automatic Dependent Surv.-Broadcast (ADS-B)	0
3	A350XWB	0
4	Wide Area Augmentation System (WAAS)	0
5	Narrow-Body Replacement (NBR)	0
6	B747-8	0
7	A380	0

b)

Relative Importance of Characteristics

1 Overall Delay
2 Weather Delay
3 System CO Level
4 System NOx Level
5 Fuel Consumption
6 Operating Cost
7 Noise (DNL)
8 Development Cost

	Technology Rankings	Change
1	Automatic Dependent Surv.-Broadcast (ADS-B)	1
2	B787	-1
3	Wide Area Augmentation System (WAAS)	1
4	A350XWB	-1
5	Narrow-Body Replacement (NBR)	0
6	B747-8	0
7	A380	0

c)

Concept & Technology Selection	Introduction
☐ CDA	2014
☑ ADS-B	2013
☑ WAAS	2014
☑ A380	2009
☑ A350XWB	2014
☑ B787	2009
☑ B747-8	2011
☑ Narrow Body Replacement	2018

	Technology Rankings	Change
1	Automatic Dependent Surv.-Broadcast (ADS-B)	1
2	Narrow-Body Replacement (NBR)	3
3	Wide Area Augmentation System (WAAS)	1
4	B787	-3
5	A350XWB	-2
6	A380	1
7	B747-8	-1

Fig. 10 Technology Rankings in Sample Assessment

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