Evaluating the Flexible Deployment of an ADS/B Infrastructure in the Newark Terminal Area

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List of Acronyms

- AAR – Actual Arrival Rate
- ADS/B – Automatic Dependent Surveillance/Broadcast.
- ATM – Air Traffic Management
- CDTI – Cockpit Display of Traffic Information
- EWR – Newark International Airport.
- JPDO – Joint Program Development Office
- NAS – National Airspace System
- RPK – Revenue Passenger Kilometers

List of Mathematical Symbols

$s_1 \equiv$ Maximum service rate of CDTI-equipped traffic

$s_2 \equiv$ Maximum service rate of non-equipped traffic

$f(t) \equiv$ Service rate fraction for CDTI-equiiped traffic

$X \equiv$ Mean value of air traffic demand growth

$\eta \equiv$ Speed of reversion of air traffic demand growth

$\sigma \equiv$ Variation of demand of air traffic demand growth

$dz \equiv$ Weiner process increment

$e_t \equiv$ Standard Gaussian noise (i.e. N(0,1))

$\hat{T}(t) \equiv$ estimated deployment date at t

$T \equiv$ targeted deployment date

$S \equiv$ actual schedule slip

$\hat{S}(t) \equiv$ estimated schedule slip at time t

$\mathrm{S}_0 \equiv$ minimum estimated schedule slip

$e_s \equiv$ Standard Gaussian noise ~ N(0,1)

$y(t) \equiv$ demand at year t (RPK)

$y_0 \equiv$ initial demand (1985)

$r \equiv$ annual rate of growth

$a \equiv$ scale factor

$t \equiv$ year (year 0 = 1985)

$C_{ADSB} \equiv$ Effective capacity for ADS-B adopters

$C_{non-adopter} \equiv$ Effective capacity for non-adopters

$\Delta_{ADSB} \equiv$ Increased adopter throughput

$f \equiv$ Service fraction

$RPK_0 \equiv$ Initial year RPK
$RPK_i \equiv$ Year i RPK
$g_i \equiv$ Normalized NAS Demand Growth
$D_0 \equiv$ Initial Newark Terminal Area AAR (annual average)
$D_i \equiv$ Year i Newark Terminal Area AAR
$N_{RPK} \equiv$ Set of all nodes in the NAS demand growth lattice
$N_D \equiv$ Set of all nodes in the Newark Terminal Area demand growth lattice
$R_i \equiv$ Net revenue at node i
$c_{lf} \equiv$ Landing fee per arrival
$c_{delay} \equiv$ Delay cost per minute of delay per aircraft
$c_{fixed} \equiv$ Fixed costs of ADS-B terminal area infrastucture
$g_i \equiv$ Adoption fraction at node i
$D_i^{ADSB} \equiv$ Adopter delay minutes per aircraft at node i
$D_i^{non-adopter} \equiv$ Non-adopter delay minutes per aircraft at node i
$R_i^{nominal} \equiv$ Nominal revenue at node i
$R_i^{adjusted} \equiv$ Adjusted revenue at node i
$p \equiv$ Probability of demand growth increase in lattice
$V_i \equiv$ Terminal Area ADS-B Program Value at node i
$r_f \equiv$ Risk-free interest rate
$N_n \equiv$ Set of nodes in the last year of the lattice

Abstract

The deployment of an Automatic Dependent Surveillance/Broadcast (ADS/B) infrastructure in the Newark International Airport (EWR) terminal area via a differentiated service structure was analyzed in this project. Since users leverage ADS/B via Cockpit Display of Traffic Information (CDTI) equipage, this deployment strategy consists of appropriately allocating terminal area resources between technology (CDTI) adopters and non-adopters. This strategy contrasts with the usual strategy of equipage via mandate and relies upon the competitive advantage in equipping to motivate users to adopt. The value of using a flexible design in this deployment strategy was studied as a way to mitigate the various technical and economic sources of risks. Since a fixed architecture is often designed for a specific set of circumstances, the risks considered in this project were deemed synonymous with the sources of uncertainty in the project. Two major sources of uncertainty were specifically identified and developed: the growth rate in air traffic demand and the scheduled deployment date for the ADS/B infrastructure. The former was used in the comparison of two possible system concepts considered for deployment.

Decision Analysis was then used to establish the cost savings of deploying a flexible design over a fixed design when accounting for the uncertainty in terminal area demand. The flexibility in the former concept was achieved by allowing system operators to adjust the terminal area capacity after infrastructure deployment. The qualitative value of this flexibility resides in the ability to respond both to the actual evolution of terminal area demand and the CDTI equipage rate. Adjustment of the terminal area capacity was accomplished by specifying the ratio of terminal area capacity allocated to each category of user.

The model of uncertainty in air traffic demand was further developed for use in a more sophisticated decision analysis framework. Specifically, a binomial lattice describing the possible evolution of terminal area demand growth was constructed. This secondary analysis further bolstered the case for developing the ADS/B infrastructure by using a flexible design.

The motivation for this research and the contextual factors surrounding the proposed deployment strategy are detailed in Section 1. A detailed system description is provided in Section 2. Models for the two major sources of uncertainty are provided in Section 3. The details of a preliminary analysis conducted within a decision analysis framework is provided in Section 4 and is used to establish the cost benefit of incorporating flexibility into the deployment strategy. A binomial lattice of air traffic demand uncertainty is developed in Section 5. In Section 6, the binomial lattice is used in a more sophisticated decision analysis framework to establish the value added by incorporating flexibility into the deployment strategy. Conclusions, proposals for future extensions and comments regarding this project assignment are provided in Sections 7 and 8.

1 Introduction

As air traffic growth rebounds to pre-9/11 levels, capacity issues in the National Airspace System (NAS) are garnering increasing attention. Combining the current level of system performance with the forecast of airspace demand growth, there exists the possibility of choking potential growth unless the system performance improves. Thus modernization of the NAS infrastructure has become one of the air transportation industry's core areas of concern and research. One result of this research is the recognition of Automatic Dependent Surveillance/Broadcast (ADS/B) as a prime enabler of Air Traffic Management (ATM) applications that can offer substantial safety and capacity enhancement benefits. While many industry stakeholders recognize the potential benefits of ADS/B adoption, there is reasonable concern that ADS/B deployment may never transpire. This fear is predicated on the fact that a fair number of innovative products with the potential to benefit the air transportation system have been developed but ultimately unemployed. In particular, ADS/B, like any other infrastructure modernization product, requires a substantial amount of capital investment and government commitment. If history were an accurate indicator, it would seem that the only feasible implementation strategy would involve an equipage mandate in which users are required to adopt the technology by a certain date. In a time of unprecedented budget constraints on all industry stakeholders, the costs associated with an equipage mandate is an unattractive option.

Thus, the Joint Program and Development Office (JPDO) is currently researching innovative financial methods that could be used to implement ADS/B equipage. One proposal is to spur ADS/B adoption by offering it as a service to which air space users can subscribe. A prerequisite for subscription would entail equipage of the aircraft with Cockpit Display of Traffic Information (CDTI) hardware and software. This equipment increases the situational awareness of pilots and controllers and allows an increased traffic density in the terminal area without any sacrifice in safety. It effectively results in an increased terminal area capacity, making it attractive for airspace users, controllers and the airport authority. Under one particular scenario, NAS air space would be segregated into multiple service tiers, each of which are available to appropriately-equipped users. The hope is that the appropriate deployment of this system will spur the voluntary user adoption of ADS/B technology.

Thus, ADS/B deployment in the Newark Airport (EWR) terminal area as a service to which airspace users can subscribe is the topic that was researched in this project. It was assumed that the ADS/B infrastructure is deployed at present and that users can leverage ADS/B via CDTI equipage. In particular, this project attempted to value the flexibility of actively managing the terminal area airspace by adjusting the fraction of terminal area resources that are devoted to CDTI equippers and non-equippers.

1.1 Contextual Factors

The growth in air transportation demand is one contextual factor addressed in this research since air traffic demand is the driver for modernization. Thus, if the flexible terminal area management strategy studied in this project improves the performance of the NAS (e.g. by decreasing the aggregate delay experienced by terminal area users), then real, sustained growth can be accommodated. This benefits airspace users by decreasing the operational costs associated with delays as well as the airport authority by increasing the terminal area and airport operating capacity. Incidentally, the latter benefit can also manifest itself via increased landing fee revenues.

Another contextual factor is regulatory. Redesigning airspace is subject to a substantial degree of regulatory hurdles. While ADS/B was successfully rolled-out in several trials (e.g. Alaska, Gulf of Mexico), segregated airspace operations, in which each tier requires a different level of service and set of operating rules, may be deemed too risky by the FAA. In addition, the ATM controller union has substantial bargaining leverage to prohibit adoption of this strategy if it remains unconvinced of the controller benefits.

2 System Description

In the terminal area, the minimum required separation standard between aircraft defines the maximum throughput that system operators can achieve. During nominal operations (e.g. periods of good weather during which pilots can use their vision to maintain approach separation), this throughput defines the capacity of the arrival flows in the terminal area. However, during periods of inclement weather, controllers increase the minimum separation between aircraft to account for the inability of pilots to maintain any separation via visual cues. The effect is that arrival flow capacity is markedly reduced. According to the EWR Benchmark Report, the capacity under these conditions is reduced, on average, from 90 flights per hour to 65 flights per hour [FAA, 2005a]. Thus, one major source of efficiency derived by servicing CDTI equipped aircraft in the terminal area is the ability to maintain visual-like separation during periods of inclement weather. Since the arrival flows into the terminal area depend on the required separation standards between aircraft, CDTI-equipped users can be serviced at a higher rate than non-equipped users because they can be sequenced closer together along a jetway (i.e. literally a “road” in the sky defined by waypoints that incoming traffic must use to enter the terminal area). Note however, that the mixing of CDTI-equipped and non-equipped aircraft should be minimized to decrease the burden on controllers. That is, if the two categories of users, each with different operational capabilities, were allowed to mix into the same arrival streams, then controller workload would unduly increase because the controllers now must mind whether every aircraft can maintain the reduced separation.

Thus, the system architecture used in this analysis was set-up such that each arrival flow into and within the terminal area is of homogenous composition. This design specification amounts to restricting a specific category of aircraft to a set of jetways leading into the airport. Segregating the arrival flow in such a way results in a binary service tier in which these two categories of aircraft can be serviced at the two different rates appropriate to their operational capabilities. By adopting CDTI technology and subscribing to the service, users can reap the operational savings of being processed quicker through the terminal area, especially during times of little or no spare capacity.

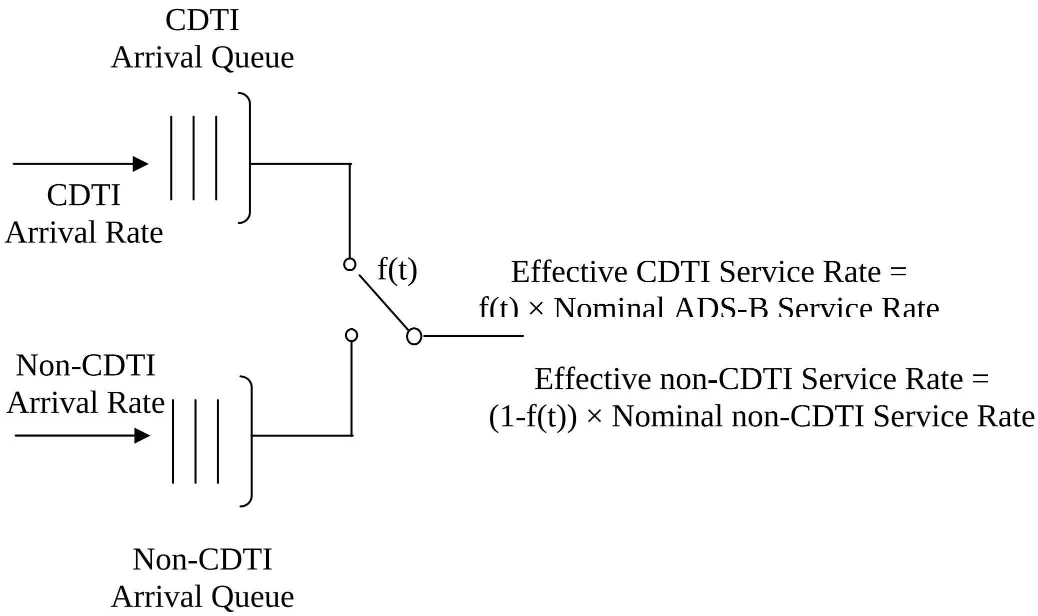

Figure 1. Proposed Terminal Area Architecture

A schematic of the proposed architecture is given in Figure 1. The model can be described by two input flows, representing the Actual Arrival Rate (AAR) of ADS-B equipped and non-equipped aircraft entering the terminal area at any given time. CDTI-equipped users can be processed at a maximum service rate s_1, while non-equipped users can be processed at a maximum service rate s_2. The fractional allocation of the arrival streams (i.e. the proportion of total arrival jetways devoted to CDTI-equipped traffic), expressed as $f(t)$, is a parameter that can be adjusted by the system operators and determines the service rate *effectively* experienced by each category of user of users. As illustrated in the figure, this allocation of airspace between these two categories of users can be thought of as a switch that is used to process each user queue at a time. The amount of airspace allocated to each type of user is analogous to the amount of time that the switch allows the processing of that user. Thus, the effective service rate for CDTI-equipped users is $s_1 \times f(t)$, while the effective service rate for non-users is $s_2 \times (1-f(t))$.

2.1 Characteristics Included in the System

The System Architecture included:

1. *A model of the arrival traffic in the Terminal Area composed of two distinct, segregated arrival flows: CDTI-equipped aircraft and non-equipped aircraft.* Modeling the arrival flows was used to assess the level of delays and costs as a function of terminal area demand and capacity. The details of how queueing theory and daily simulations of terminal area operations are used in the derivation of this model fall outside the scope of the project. Thus, it is useful to consider this component as a black box in which the inputs consist of the daily arrival (expressed by the annual average AAR) and capacity statistics and the outputs consist of the average delay experienced by each user type over the course of the

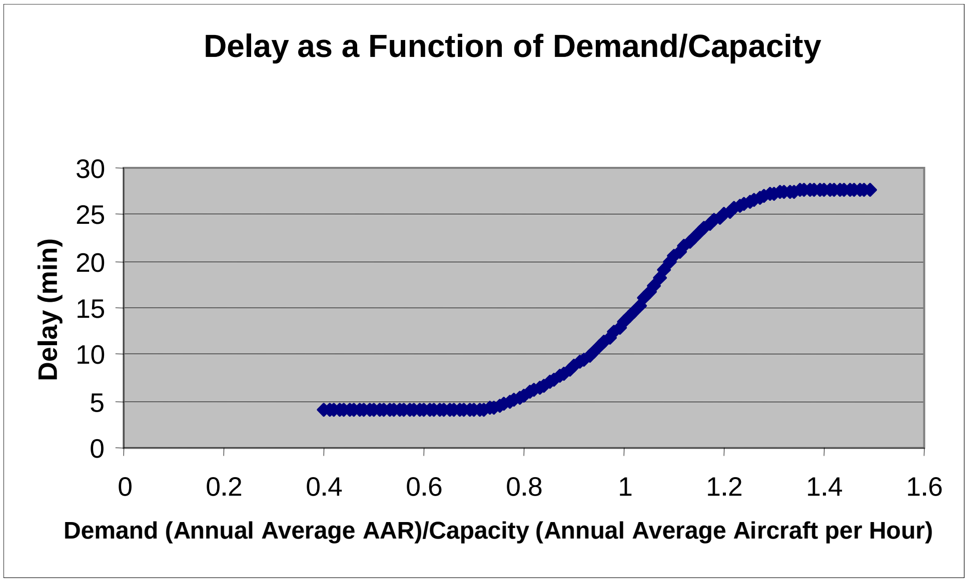

Figure 2. Terminal Area Demand as a Function of Demand and Capacity

year. Specifically, the ratio of demand (annual average AAR) to capacity (effective service rate), ρ, is used to determine the delay (in minutes) for each user type. The function describing this hypothetical black box is illustrated in Figure 2.

2. *A model of the growth in terminal area traffic, specifically the annual average AAR.* It is assumed that the expected growth rate of Terminal Area traffic follows the expected growth rate of NAS traffic.
3. *A model of the CDTI uptake rate for EWR traffic based upon an analysis conducted by the ADS/B Program Office* [FAA, 2005b]. The uptake data from the ADS/B Program Office is represented as the annual fraction of fleet CDTI equipage and is defined by the curve in Figure 3. For example, an equipage ratio of 0.5 represents the notion that 50% of the NAS fleet is equipped and using CDTI. The S-curve is typical of the technology diffusion process. In this case, adoption accelerates only after a critical mass of adopters causes enough competitive pressure on the unequipped users to adopt. Specifically, non-equipped users will notice that the early adopters are lowering their operating and delay costs by adopting CDTI. Note that in absence of an equipage study specific to the EWR terminal area, it is reasonably assumed that the equipage rate for aircraft operating in the EWR terminal area follows the NAS equipage rate.

2.2 Characteristics Omitted from the System

The system architecture did not include:

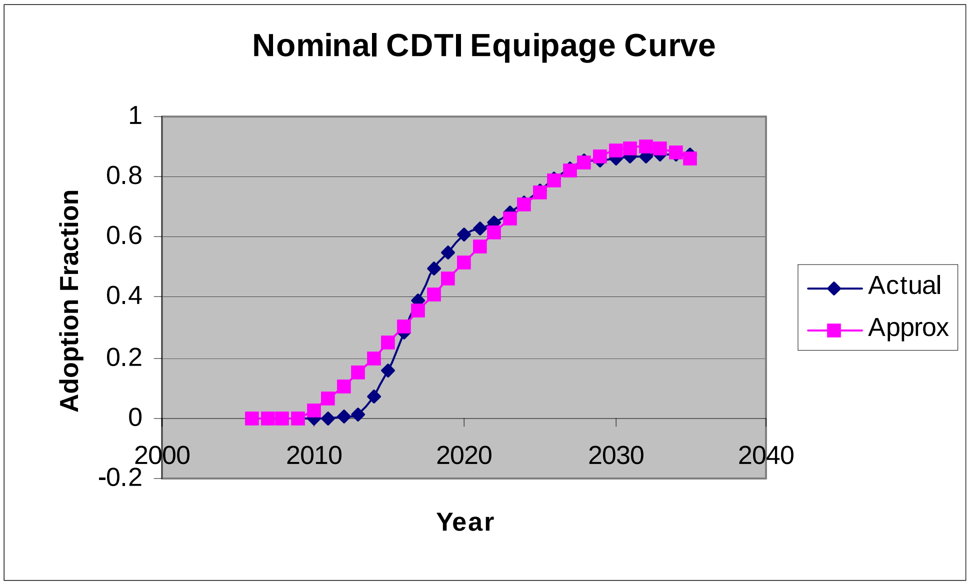

Figure 3. CDTI Equipage Curve [Source: ADS/B Program Office]

1. *Modeling of the departure flows.* While arrival and departure traffic is highly segregated for safety and controller workload reasons, coupling between the two flows does exist. The most overt example of this coupling is at the runway, where the sequencing of departure and arrival traffic has an impact on the servicing rate of both flows in the terminal area. In contrast with the arrival traffic, the effect of terminal area delays on the departure traffic is more difficult to model and measure because the remaining stages of the flight must be considered and forecast. For example, some of the delay incurred by departing traffic may be mitigated during the en route stage.
2. *The consideration of any increased safety benefits derived from ADS/B user adoption.* Whereas the delay can be readily transformed into a useful metric such as the ensuing financial cost, there is no simple manner in which to translate safety benefits into costs.

2.3 System Levers

The levers available in the system architecture included:

1. *Adjustment of the service rate fraction.* The amount of the total arrival stream dedicated to CDTI equipped users can be adjusted. In practice, this would amount to allocating a fraction of the available jetways to CDTI-equipped aircraft exclusively.
2. *Maximum allowable delay difference.* A greater difference in the effective service level between the two categories of users results in a faster technology adoption at the expense of a reduced capacity and increased delays for the non-user base.
3. *Equipage mandate.* As previously noted, the typical deployment of NAS technologies has consisted of equipage fiats by a certain date. Thus, it is reasonable that system operators maintain this leverage in the case that the ensuing equipage and terminal area efficiency are deemed inadequate.

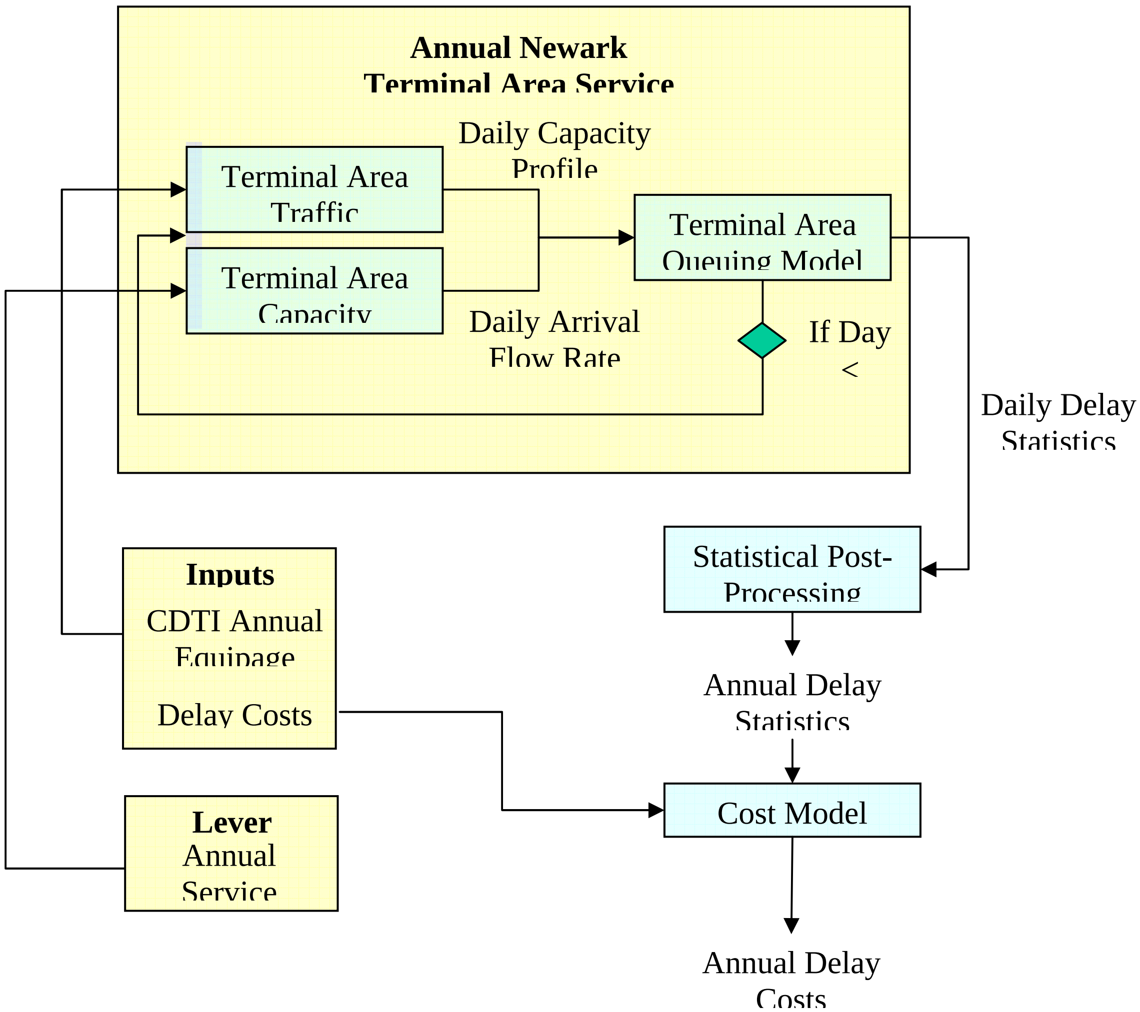

Figure 4. System Architecture Blueprint

2.4 System Tensions

Given the levers described above, it is worth defining the tensions that drive how the levers are used. On one hand, the earlier adoption of CDTI allows the airport authority to capture additional revenue via the increased arrival rate made possible by the CDTI-equipped aircraft. In addition, adopters would also benefit from a decrease in the delay experienced in the terminal area. These factors favor the allocation of arrival resources on behalf of the equipped traffic. On the other hand, an overly aggressive allocation of the arrival capacity that favors the adopters could result in severe and costly delays for non-adopters. This factor favors the allocation of arrival resources on behalf of the unequipped aircraft.

2.5 Benefits

The benefits resulting from the deployment of this multi-tiered service concept can be measured using a combination of any of the following metrics:

1. Increased traffic/passenger throughput
2. Decreased delay and delay costs
3. Increased revenue from air traffic service

In this project, the second and third benefits were used in the course of the analysis given that they could be readily transformed into monetary terms.

2.6 Inputs

The necessary inputs included:

1. CDTI Equipage Curve [FAA 2005b]
2. F&E Cost Numbers [FAA 2005b]
3. Landing Fees
4. Subscription Fees
5. Service Fraction Adjustment Strategy

2.7 System Architecture Blueprint

Given the complexity of the system architecture outlined above, it is instructive to view the system in terms of the schematic in Figure 4.

3 Identifying and Modeling Sources of Uncertainty

Two sources of uncertainty were considered in this project. The first source of uncertainty was due to the evolution of the terminal airspace demand. The relevance of this factor was expounded on briefly in the Introduction. The second source of uncertainty was the deployment date of ADS/B service in the terminal area. The relevance of this factor is predicated on the history of delays in the actual deployment date of previous and future NAS modernization products.

3.1 Uncertainty in Terminal Airspace Demand

The main source of uncertainty considered in this research is the demand in the terminal area, represented as the amount of arrival traffic. In many ways, this factor drives many of the dynamics in the model of the differentiated service system. Consider that a greater number of airspace users for a given amount of capacity will degrade performance of the system, manifested as the resultant magnitude of delays and added costs incurred in the terminal area. As previously noted, it is assumed that the growth in the EWR terminal area is assumed to match the growth in the NAS.

Revenue Passenger Kilometers (RPKs) or Number of Operations are the metrics typically used in characterizing demand. Thus, annual growth is simply the change in either of these metrics over the course of a year, expressed as a percentage. The demand for air transportation has been previously modeled as a mean-reverting process of the form [Miller and Clarke, 2005]:

$$dx = \eta\left(X - x\right)dt + \sigma dz$$

where:

$X \equiv$ Mean value of growth

$\eta \equiv$ Speed of reversion

$\sigma \equiv$ Variation of demand

$dz \equiv$ Weiner process increment

This mean-reverting process was used to model how demand, expressed as the number of flights in the terminal area, grows annually in the terminal area. The parameter values X, η, and σ were derived from a forecast of air transportation demand growth in North America. The source of this forecast is the Boeing 2004 20-year Outlook Report, and is expressed in following table as the historical and forecast percentage increase in NAS demand growth [Boeing, 2005]:

Table I: NAS Demand Statistics			
Year	Demand	Total Growth	Annual Growth
-	RPK	%	%
1985	470.63	-	-
1990	589.06	25.16	5.03
1995	670.74	13.82	2.76
2000	857.47	27.89	5.58
2001	812.76	-5.21	-5.21
2002	783.48	-3.6	-3.6
2003	828.27	5.72	5.72
2004	925.18	11.7	11.7
2014	1273.26	37.62	3.76
2024	1856.81	45.83	4.58

Based on these values, X = 3.5%. The other two parameters, η and σ were derived by performing a linear regression on the maximum likelihood functions for each parameter according to the following regression equation [Dixit and Pindyck, 1994]:

$$X_t - X_{t-1} = a + bX_{t-1} + e_t$$

where:

$e_t \equiv$ Standard Gaussian noise (i.e. N(0,1))

Performing this regression resulted in η and σ:

$$\eta = -\frac{a}{b}$$

$$\sigma = \sqrt{\frac{2\ln\left(1+b\right)}{\left(1+b\right)^2 - 1}}$$

The results from the regression were found to be η=0.380 and σ=0.496, thus completing the description of the mean reverting process for demand growth.

3.2 Uncertainty in ADS-B Implementation Date

Another source of uncertainty is the schedule slip in the installation date of the ADS/B ground infrastructure that is necessary to service the CDTI equipped users. The schedule slip is modeled by taking into account the current estimated schedule slip of 12 existing modernization programs under development/deployment. The source for both the list of these programs and their estimated schedule slip is the FAA's 2004 Capital Investment Plan (CIP) report [GAO, 2005] and the distribution of these statistics are listed in the following table:

Table II: Schedule Slip Histogram for NAS Modernization Programs	
Schedule Slip	Number of Program Slips
Years	-
0	4
1	0
2	2
3	0
4	1
5	0
6	1
7	1
8	1
9	0
10	2

This distribution was described by a mean of 4.08 years of schedule slip and a standard deviation of 0.5 years.

Note that the estimated schedule slip is a factor that users consider when deciding whether to adopt the ADS/B technology (e.g. CDTI). For example, the existence of a substantial amount of schedule slip at a given time would offset part of the incentive that users have to adopt the technology. Therefore, in addition to using the expected value to simulate the schedule slip of ADS/B it is also necessary to define a process of how the estimated schedule slip evolves from the perspective of potential ADS/B adopters. A literature review failed to turn up a stochastic process model for schedule slip, thus a simple one was derived from first-principles and intuition. The primary intuition that needed to be captured was that the estimate of the schedule slip could be characterized as the actual schedule slip corrupted by uncertainty, or “noise.” In addition, it is reasonable to assume that this uncertainty decreases as the actual deployment date nears. That is, as the technology nears deployment it is more mature and the possible variance in the final deployment date decreases. These considerations resulted in the following stochastic process for the estimated deployment date:

$$\hat{T}(t) = \max\left[(T+S)+(T+S-t)\left(e_s\right), S_0 + t\right]$$
$$\hat{S}(t) = \hat{T}(t) - T$$
$$where:$$
$$\hat{T}(t) = \text{estimated deployment date at t}$$
$$T = \text{targeted deployment date}$$
$$S = \text{actual schedule slip}$$
$$\hat{S}(t) = \text{estimated schedule slip at time t}$$
$$\text{S}_0 = \text{minimum estimated schedule slip}$$
$$e_s = \text{Standard Gaussian noise} \sim \text{N(0,1)}$$

In this stochastic process, the difference between the estimated and actual target deployment dates decreases non-monotonically until a minimum slip value S_0 is achieved. This feature captures how the uncertainty is resolved over time until some time approaching the target deployment date. Beyond that date a static schedule slip is assumed because any remaining uncertainty is likely to remain unresolved with users believing that any delays will be shortly resolved. The evolution of this stochastic process over time is illustrated in Figure 5 for a targeted deployment date of 6 years, mean schedule slip of 4.08 and $S_0=0$.

4 Alternative System Designs

As a first step to recognizing the value of incorporating flexibility into the system design, a decision analysis framework was used to compare the value and efficacy of different system concepts. Two concepts were considered. One concept represents the base case architecture in which system operators do not have the ability to change design parameters in response to the terminal area demand that is actually realized (i.e. in lieu of the anticipated or forecast demand). The second concept represents the flexible case architecture in which system operators do have the ability to change the terminal area capacity in response to the terminal area demand that is actually realized.

4.1 Defining Alternative Designs

The first system concept that was analyzed is identified as the “base” design case and represents the scenario where a mandated equipage date is specified. This case represents the usual means by which the FAA introduces new infrastructure procedures and operations. According to the ADS/B Program Management Office, a mandated equipage date of 2020 is one option that is being considered. To better understand the potential drawbacks of this strategy, it is instructive to consider the case of HDTV adoption in the United States. In order to spur manufacturer development of cheaper units and consumer adoption, the FAA originally set a date of 2006 when all broadcasts would cease analog transmission and switch over to digital transmission. However, the FCC has recently

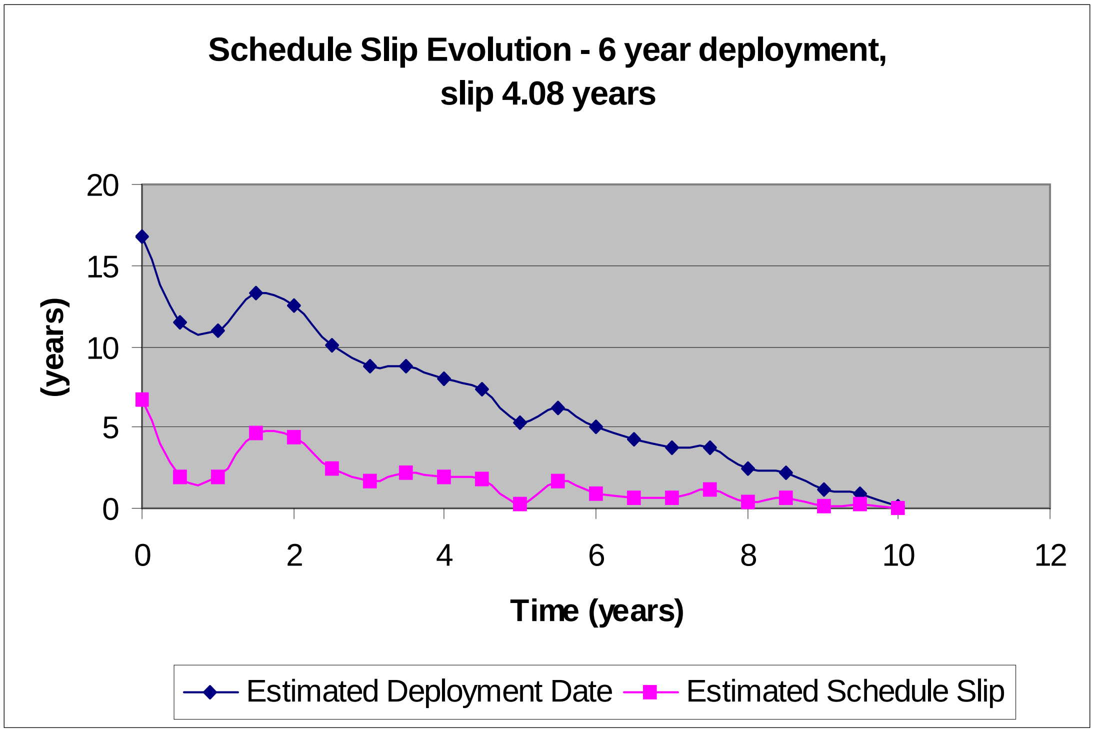

Figure 5. Example Schedule Slip Evolution

pushed back the date because of the lack of uptake in HDTV units. Note that in contrast to the HDTV case, the implications for non-adoption in the technology means that all non-CDTI equipped aircraft arriving into the terminal area will be processed only if sufficient terminal area capacity is available. If no excess capacity beyond that which is being allocated to the CDTI adopters is available, then the non-adopters will be delayed until they can be serviced. Essentially, delays may increase substantially for non-CDTI arrivals in the terminal area, while some fraction of adopter capacity remains unused. In this concept, it is assumed that the service rate fraction is set to 0.5 for the 2005-2020 period. Doing so allocates the terminal area capacity evenly between CDTI-adopters and non-adopters.

An alternative system concept is identified as the "flexible" design and represents the scenario where the service rate fraction is adjusted in response to the actual equipage that takes place. Specifically, the service rate fraction is adjusted by considering the magnitude of delays experienced between CDTI adopters and non-adopters in the terminal area. The idea behind this strategy is to allocate the necessary amount of adopter capacity so that all remaining terminal area capacity can be allocated to non-adopters, thereby mitigating the effect of delays on the latter. In the ensuing analysis, it is assumed that system designers have two opportunities to re-set the service rate fraction. One opportunity takes place in 2005 and the other opportunity takes place in 2012.

It is assumed that the terminal area annual demand growth can take three distinct values, low (1%), nominal (3.5%) and high (5%), in the periods of 2005-2012 and 2012-2020. For example, one possible trajectory is nominal growth in the 2005-2012 period and high growth in the 2012-2020 period. Furthermore, it is assumed that the three possibilities are equally likely and independent:

$$p(per.1 = high) = p(per.1 = nominal) = p(per.1 = low) = 0.333$$
$$p(per.2 = high \mid per.1 = i) = p(per.2 = nominal \mid per.1 = i)$$
$$= p(per.2 = low \mid per.1 = i) = 0.333, \forall i \in \{high, nominal, low\}$$

4.2 Preliminary Analysis of Alternative Designs

The two system concepts are illustrated in Figure 6 within the context of a decision analysis framework. System designers have two opportunities, one in 2005 and another in 2012, to adjust the amount of capacity allocated to the two categories of terminal area users. The metric used to analyze each potential state is the cumulative NPV of the net annual cash flows for the 2005-2020 period, expressed in 2005 Dollars. These cash flows are comprised of the total annual landing fee revenues less the annual cumulative delay costs incurred by users less the recurring infrastructure costs (facilities, equipment, operating and maintenance costs). For example, for the fixed architecture, in which system users do not modify the service fraction, the NPV of this system concept, expressed in 2005 Dollars, is given by

- -$5.61B for the case of 5% growth during 2005-2020
- -$4.93B for the case of 5% growth during 2005-2012 and 3.5% growth during 2012-2020
- -$4.21B for the case of 5% growth during 2005-2012 and 1% growth during 2012-2020

Note that the values are all negative due to inclusion of the aggregate delay costs. This cost is not externalized given that cost is being used as a proxy for system throughput and capacity.

As illustrated in Figure 6, there are 36 possible end states in 2020. The fixed system concept is defined by all trajectories that traverse through the graph edges labeled as "fixed". The flexible system concept is defined by all trajectories that traverse through the graph edges labeled as "flexible." Note that the decision lattice actually incorporates more possibilities than these two concepts. For example, a fixed-flexible hybrid concept in which the service rate adjustment is deferred to the 2012-2020 period is also described in the lattice.

Only the values for the two system concepts specified are needed in this analysis. These two trajectories are illustrated in Figure 6. The fixed system concept results in a total cost of -$6.09B while the flexible system concept results in a total cost of -$1.90B. Thus, it behooves system managers to incorporate the flexibility to adjust the service rate fraction during the CDTI deployment period. Doing so results in a cost savings of ($6.09B-$1.90B)=$4.19B in 2005 Dollars.

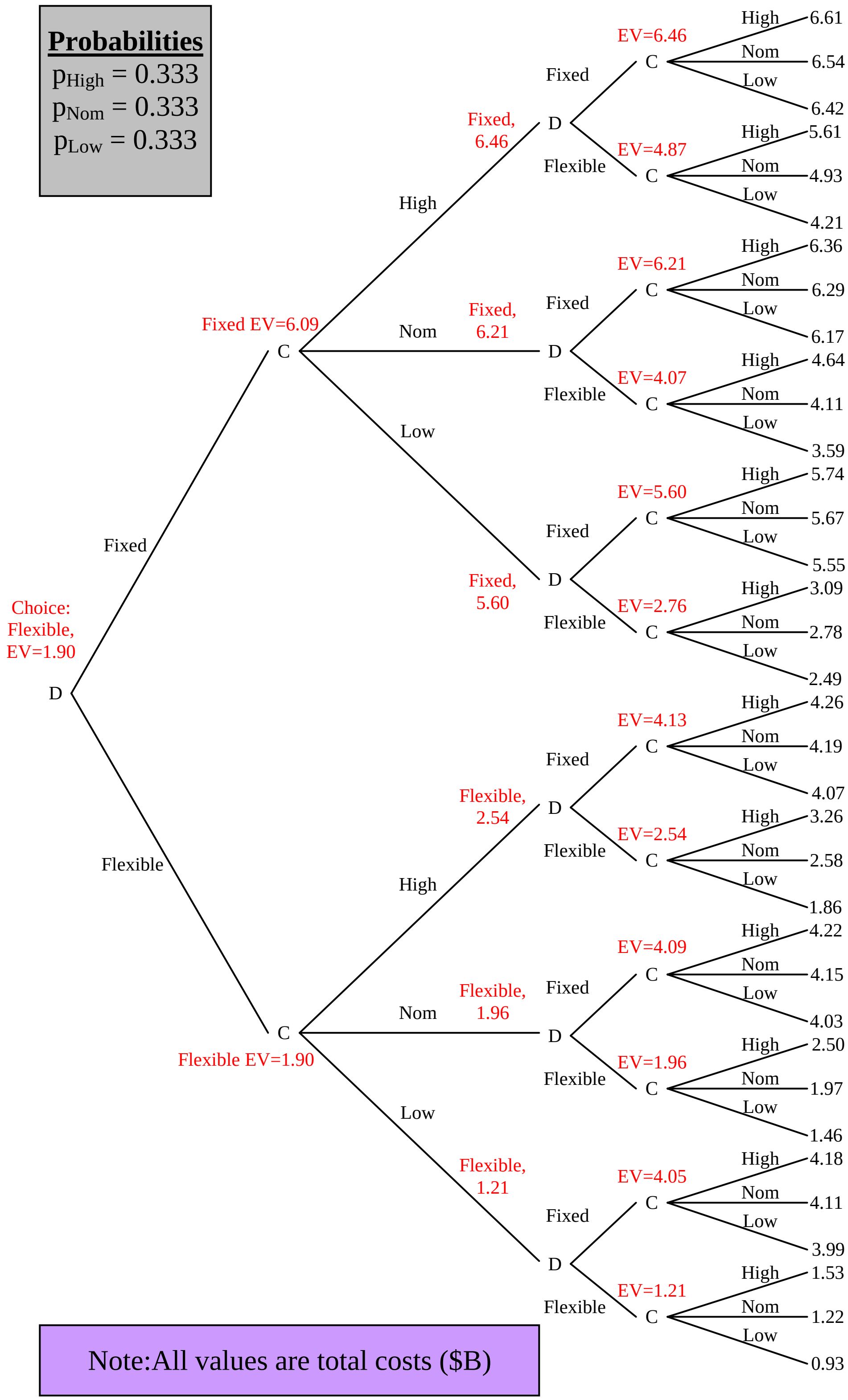

Figure 6. Decision Analysis Framework for System Concepts

5 Modeling the Evolution of Uncertainty

In order to perform a more sophisticated analysis of the flexible design concept, the sources of uncertainty were recast within the context of a binomial lattice. Doing so allowed for a richer representation of how the uncertainty evolves beyond simply assuming three distinct realizations as was done in the preliminary analysis (e.g. high demand, nominal demand, and low demand). In the limited scope of this project, only one source of uncertainty was considered in the modeling of the lattice and the subsequent analysis. Terminal area demand growth was deemed a good choice for development given that it was previously modeled as a mean-reverting process and the necessary parameters used to define the lattice could be readily deduced.

5.1 Defining the Demand Growth Trend

The following forecast for demand growth was assumed:

$$
\begin{aligned}
&y(t) = y_0 a e^{rt}, \textit{where}: \\
&y(t) = \text{demand at year t (RPK)} \\
&y_0 = \text{initial demand (1985)} \\
&r = \text{annual rate of growth} \\
&a = \text{scale factor} \\
&t = \text{year (year 0 = 1985)}
\end{aligned}
$$

Taking the log of the forecast resulted in the following linear expression:

$$\ln y = \ln A + rt$$

The parameters of this last expression were determined via linear regression, resulting in the following values:

$$
\begin{aligned}
&\ln A = 6.125 \\
&r = 0.0288 / \textit{year}
\end{aligned}
$$

The demand growth of the assumed model is contrasted with the actual trend in Figure 7 and is shown to be a good fit.

Transformation back to the original form resulted in the following growth forecast model:

$$
\begin{aligned}
&y(t) = 470.63\left[0.97144 e^{(0.028821/\textit{year})t}\right], \textit{where}: \\
&t_0 = 0 \text{ at } 1985
\end{aligned}
$$

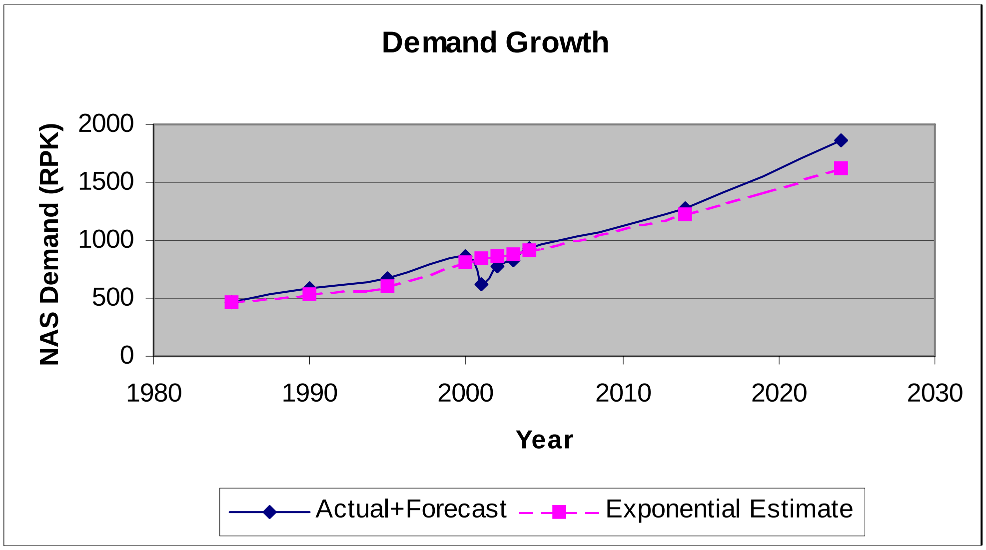

Figure 7. Exponential Curve Fit to NAS Demand Growth

5.2 Defining the Demand Growth Volatility

The demand forecast had previously been modeled as a mean reversion process and a special regression analysis specifically defined for the mean reversion model and using the demand data cited above was shown to yield the standard deviation in the annual demand growth. This value was determined to be 0.1542/year.

5.3 Developing the Lattice

With the mean and standard deviation values for the annual rate of demand growth specified, the binomial model parameters were derived:

$$u = e^{\sigma\sqrt{\Delta t}} = e^{0.02882/year\sqrt{1year}=1.167}$$

$$d = e^{-\sigma\sqrt{\Delta t}} = e^{-0.02882/year\sqrt{1year}=0.857}$$

$$p = 0.5 + 0.5\left({}^{v}\!/_{d}\right)\sqrt{\Delta t} = 0.5 + 0.5\left({}^{0.02882}\!/_{0.1542}\right)\sqrt{1year}$$

Using 2004 as the current time, the outcome lattice over the next 5 years was given by

2004	2005	2006	2007	2008	2009			
0	1	2	3	4	5	Step	(u/d)^(step)	outcome/lowest
925.18	1079.43	1259.397	1469.369	1714.348	2000.172	5	4.674	4.674
	792.9723	925.18	1079.43	1259.397	1469.369	4	3.434	3.434
		679.657	792.9723	925.18	1079.43	3	2.522	2.522
			582.5344	679.657	792.9723	2	1.853	1.853
				499.2906	582.5344	1	1.361	1.361
					427.9423	0	1.000	1.000

The probability lattice was given by

	2004	2005	2006	2007	2008	2009
	0	**1**	**2**	**3**	**4**	**5**
	1	0.593452	0.352186	0.209005	0.124035	0.073609
		0.406548	0.482533	0.429541	0.339883	0.25213
			0.165281	0.294259	0.349258	0.345446
				0.067195	0.159507	0.23665
					0.027318	0.081059
						0.011106
sum	1	1	1	1	1	1

Finally, the distribution for the overall NAS demand at year 5 (2009) is illustrated in the Figure 8.

6 Decision Analysis via Lattice Design

The ability to allocate terminal area capacity between ADS/B adopters and non-adopters was previously identified as a system lever that could be leveraged to enhance the system performance. As was previously detailed, given an average terminal area capacity of C aircraft per hour, the service fraction f could be used to allocate terminal area resources as follows:

$$C_{ADSB} = f\Delta_{ADSB}C$$
$$C_{non-adopter} = (1-f)C$$
$$\Delta_{ADSB} = 5/3,$$

where:

$C_{ADSB} \equiv$ Effective capacity for ADS-B adopters

$C_{non-adopter} \equiv$ Effective capacity for non-adopters

$\Delta_{ADSB} \equiv$ Increased adopter throughput

$f \equiv$ Service fraction

The factor Δ_{ADSB} represents the increased throughput of adopter airspace given the closer spacing allowed for CDTI equipped aircraft (i.e. from 5 nm to 3 nm of separation). The factor also illustrates the primary source of positive "tension" in the system: by increasingly accommodating the CDTI equipped aircraft, a greater throughput can be achieved, airport capacity is effectively augmented and the airport authority can collect more revenue via landing fees. The primary source of "negative" tension is the decreased fraction of overall capacity allocated to non-adopters, leading to a decreased non-adopter service rate in the terminal area and increased non-adopter delays and operating costs. This negative tension can become especially costly if the growth forecast in terminal area demand occurs in the absence of any meaningful CDTI adoption.

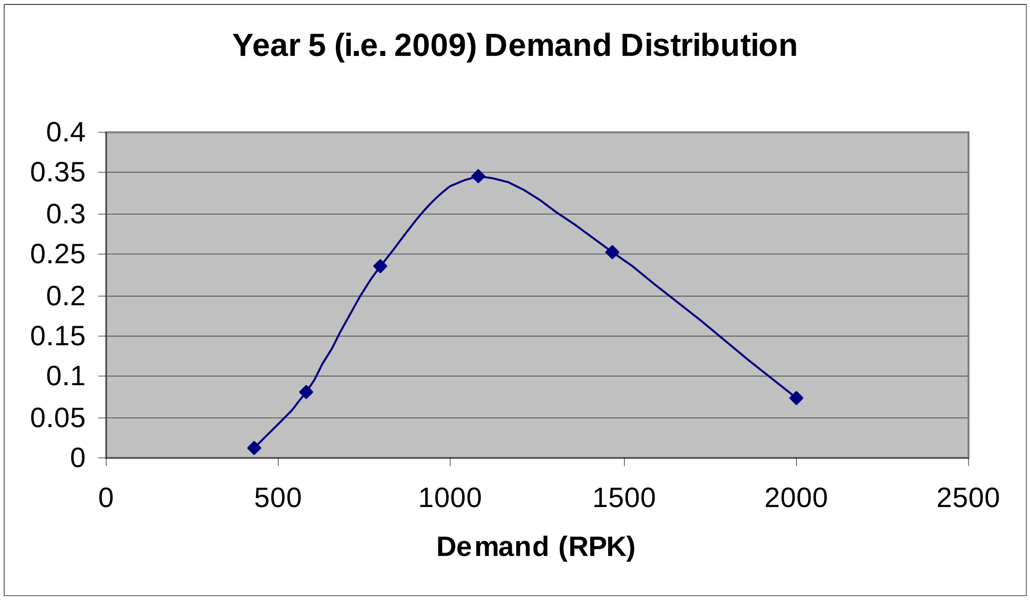

Figure 8. NAS Demand Distribution at Year 5 (2009)

A source of flexibility proposed and previously explored in the preliminary analysis consisted of the ability to change the service fraction at any point in the future to increase the system performance while remaining mindful of these sources of tension. Thus, this analysis was concerned with the option to change the service fraction at any year in the future. The analysis was carried out within the context of the diffusion lattice of terminal area demand growth that was previously developed.

6.1 Defining the Revenue Lattice

The transformation of each node value in the demand growth lattice to a revenue amount is detailed in the section. Each node in the demand growth lattice represents the total number of RPKs in the NAS. Thus, the first step involved the transformation of these node values to average AARs in the Newark Terminal Area:

$$g_i = RPK_i / RPK_0, \forall i \in N_{RPK}$$

$$D_i = g_i D_0, \forall i \in N_D$$

where:

$RPK_0 \equiv$ Initial year RPK

$RPK_i \equiv$ Year i RPK

$g_i \equiv$ Normalized NAS Demand Growth

$D_0 \equiv$ Initial Newark Terminal Area AAR (annual average)

$D_i \equiv$ Year i Newark Terminal Area AAR

$N_{RPK} \equiv$ Set of all nodes in the NAS demand growth lattice

$N_D \equiv$ Set of all nodes in the Newark Terminal Area demand growth lattice

With the capacity (for a given *f*) and demand defined for both types of traffic, the next step was to determine the average delay experienced by each aircraft over the course of a year. As previously detailed, the ratio of demand to capacity, ρ, was used to determine the delay (in minutes) for each aircraft type. Having established the delays experienced by both categories of users, the delay costs were then derived by using a value of $47.64 per each minute of delay per aircraft [Melconian, 2001]. This value is an estimate accounting for the cost to the entire NAS (i.e. beyond the fuel and operational costs) and can be thought of as being analogous to the variable costs.

The fixed costs are comprised of Facilities & Equipment (F&E) costs and Operational & Maintenance (O&M) costs. These cost figures are given in Table A1 in the Appendix and were culled from the ADS/B cost benefit analysis produced by the ADS/B Program Office [FAA, 2005b].

Finally, the revenue source from this project was assumed to originate solely from the landing fees that the Newark Airport Authority assesses to each arrival and was assumed to be $1000 per aircraft [FAA, 2005a].

Thus, the net revenue for each node was defined as:

$$R_i = c_{lf} \times D_i - c_{delay} \times \left[g_i \times D_i^{ADSB} + \left(1 - g_i\right) D_i^{non-adopter} \right] \times 365 - c_{fixed}, \forall i \in N_D,$$

$$j \in \left\{ adopter, non-adopter \right\}$$

where:

$R_i \equiv$ Net revenue at node i

$c_{lf} \equiv$ Landing fee per arrival

$c_{delay} \equiv$ Delay cost per minute of delay per aircraft

$c_{fixed} \equiv$ Fixed costs of ADS-B terminal area infrastucture

$g_i \equiv$ Adoption fraction at node i

$D_i^{ADSB} \equiv$ Adopter delay minutes per aircraft at node i

$D_i^{non-adopter} \equiv$ Non-adopter delay minutes per aircraft at node i

6.2 Service Fraction Adjustment Strategy

The flexibility in the system is achieved by changing the service fraction to better account for both AAR growth and CDTI adoption. For example, in the case of higher AAR growth and slow adoption, the service fraction should be relaxed to transfer the excess adopter capacity to non-adopter capacity. Doing so mitigates the non-adopter delay without affecting the adopter delay. On the other hand, if adoption is brisk, the fraction should be increased to mitigate the adopter delay. The strategy is defined by the maximum allowable delay difference, Δ_{max}, which is another system lever. This lever can was used as follows:

Step 1. $d_i^{non-ADSB} = d_i^{ADSB} + \Delta_{max}$

Step 2. $\rho_{new} = h^{-1}\left(d_i^{non-ADSB}\right)$

Step 3. $C_{i_{new}}^{non-ADSB} = \dfrac{D_i^{non-ADSB}}{\rho_{new}}$

Step 4. $C_{i_{new}}^{non-ADSB} = \left(1 - f_{new_1}\right)C_i \Rightarrow f_{new_1} = 1 - \dfrac{C_{i_{new}}^{non-ADSB}}{C_i}$

Step 5. $f_{new_2} = \dfrac{D_i^{ADSB}}{C_i}$

Step 6. $f_{new} = \max\left(f_{new_1}, f_{new_2}\right)$

where:

$d_i^{ADSB} \equiv$ Minutes of delay per aircraft for adopter traffic at node i

$d_i^{non-ADSB} \equiv$ Minutes of delay per aircraft for non-adopter traffic at node i

$\rho_{new} \equiv$ Non-adopter demand to capacity fraction satsifying max allowable delay difference

$f_{new_1} \equiv$ Service fraction satisfying max allowable delay difference

$f_{new_2} \equiv$ Service fraction satisfying adopter traffic

$f_{new} \equiv$ Adjusted service fraction

This strategy was applied at each node in the revenue lattice, resulting in an adjusted revenue lattice as described above that was used when performing the decision analysis.

6.3 Decision Rule Definition

Finally, the decision rule was defined for each node in the revenue lattice as follows:

$$E\left[R_i^{nominal}\right] = p \times R_i^u + (1-p)R_i^d, \forall i \in \{N_R - N_n\}$$

$$E\left[R_i^{adjusted}\right] = p \times R_i^u + (1-p)R_i^d, \forall i \in \{N_R - N_n\}$$

$$V_i = \frac{max\left(R_{i+1}^{nominal}, R_{i+1}^{adjusted}\right)}{\left(1+r_f\right)} + R_i^{nominal}, \forall i \in \{N_R - N_n\}$$

where:

$R_i^{nominal} \equiv$ Nominal revenue at node i

$R_i^{adjusted} \equiv$ Adjusted revenue at node i

$p \equiv$ Probability of demand growth increase in lattice

$V_i \equiv$ Terminal Area ADS-B Program Value at node i

$r_f \equiv$ Risk-free interest rate

$N_n \equiv$ Set of nodes in the last year of the lattice

6.4 Results

Assuming *f*=0.5, the revenue lattice for the first 5 years was given by:

Total Net Revenue Lattice

year	0	1	2	3	4	5	6
	$116,552,851	$77,404,509	$76,723,092	$83,537,152	$98,972,866	$117,141,972	$136,029,699
		$136,402,687	$116,142,092	$73,195,846	$74,097,557	$88,570,711	$102,932,449
			$132,422,442	$132,194,025	$113,516,557	$78,176,959	$79,462,266
				$111,955,173	$129,796,908	$138,915,546	$148,713,079
					$97,293,445	$116,936,286	$136,680,949
						$85,725,268	$100,266,298
							$73,515,317

Combining these results with the probability lattice yielded an inflexible strategy NPV of $421,437,373.

The possible alternative service fraction for each node was given by:

Alternative Service Fraction

year	0	1	2	3	4	5	6
	0.5075	0.4256	0.3300	0.2185	0.0883	0.0046	0.0122
		0.5780	0.5078	0.4259	0.3302	0.2209	0.1711
			0.6384	0.5783	0.5080	0.4277	0.3911
				0.6902	0.6385	0.5795	0.5527
					0.7345	0.6911	0.6714
						0.7731	0.7586
							0.8226

The alternative revenue lattice for this set of alternative service fractions was given by:

Alternative Total Net Revenue Lattice

year	0	1	2	3	4	5	6
	$(993,086)	$(992,682)	$(992,174)	$(991,542)	$63,938,489	$48,165,693	$59,614,965
		$(992,789)	$(992,416)	$(991,952)	$100,365,942	$91,881,474	$92,218,906
			$(992,594)	$(992,253)	$102,118,024	$107,109,362	$116,996,493
				$(992,474)	$89,908,944	$99,979,557	$112,461,508
					$73,656,418	$84,856,990	$96,859,495
						$68,413,078	$78,775,910
							$61,917,628

Finally, the value and decision lattices was given by:

Value Lattice

Year	0	1	2	3	4	5
	$632,732,948	$518,209,835	$411,307,610	$327,075,967	$281,492,952	$214,691,734
		$602,093,898	$504,473,334	$366,177,963	$257,626,227	$193,755,394
			$492,523,311	$452,663,490	$342,254,572	$197,259,055
				$357,223,977	$343,249,982	$269,813,249
					$247,101,199	$215,554,460
						$155,419,839

Decision Lattice

Year	0	1	2	3	4	5
	No change	no change	no change	no change	change	change
		no change	no change	no change	no change	change
			no change	no change	no change	no change
				no change	no change	no change
					no change	no change
						no change

Thus, the first desirable opportunity to change occurs at the end of year 4, and the resulting value of this flexibility (i.e. the option value) was given by:

Option Value = \$632,732,948 - \$421,437,373 = \$211,295,575

Clearly, it behooves system designers to include this flexibility in the system design. Note that the limited scope of this project specified the definition of a binomial lattice for only 5 periods (i.e. the 5 first years of the deployment schedule). The reason that only three future states within the first 5 years of deployment benefited from the flexible strategy was due to the fact that CDTI adoption did not reach critical mass until beyond year 5. That is, the initial service fraction was pre-set to a value that could accommodate the initial wave of adopters (approximately 50% of the fleet).

7 Conclusions & Future Work

The value of incorporating flexibility into the design of an ADS/B deployment strategy at EWR was established in this project. This flexibility was designed into the system as the ability for system managers to actively manage the terminal area capacity in response to the uncertain evolution of terminal area demand and an assumed CDTI adoption schedule. The value of this flexibility was shown to originate from the ability to allocate the available resources between the CDTI-adopters and non-adopters so as to minimize unused capacity and thus, minimize the amount of delay and delay costs experienced by system users. This flexibility could be alternatively couched in the context of a real option, whereby system managers have the right, but not the obligation to reallocate terminal area resources in order to cash in on the additional revenue realized by optimizing the system throughput.

The next step in the development of this research should entail the modeling and integration of the feedback mechanism detailing how the delay experienced by non-adopters drives equipage. In addition, the uncertainty in the actual deployment date of the ADS/B infrastructure should be incorporated into the analysis, specifically in the uptake dynamics as well.

8 Reflections

I believe that the approach of incorporating and valuing flexibility into the NAS modernization initiative is a necessary ingredient for its success. The most significant barriers to the successful deployment of these programs are political and financial. These capital-intensive programs entail substantial and sustained investment over a period of years. Given the constant flux of the political environment, future funds are all but guaranteed. These factors explain the seemingly irrational risk aversion exhibited by the FAA apropos technically sound products that can improve the NAS infrastructure. In short, a flexible deployment that can be downscaled or cancelled with little effect upon the NAS seems to be a requisite in the current environment. Thus, the proper valuation of these programs is crucial and should be established within a real options context.

The invaluable lesson that I have learned as a result of working on this project is that a real option analysis of system design does not need to be derived from a financial options perspective. The difficulties I experienced in the embryonic stages of this research were often rooted in the inability to confidently leverage tools from the mathematically sophisticated analysis and derivations from financial options theory. I have learned that there are other, more intuitive and useful tools (e.g. Decision Analysis on a Binary Lattice) that are more appropriate for use in system design and engineering. In addition, I also appreciate the pedagogical value of these latter approaches when presenting the substance of this work to both my research advisor and research sponsor.

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Appendix

Table A1: Annual EWR F&E and O&M Costs	
Year	Future Costs
2007	$ 473,350.00
2008	$ 1,445,568.75
2009	$ 884,109.38
2010	$ 5,654,231.25
2011	$ 3,509,643.75
2012	$ 673,118.75
2013	$ 536,790.63

2014	$ 462,015.63
2015	$ 425,556.25
2016	$ -
2017	$ 993,086.33
2018	$ 993,086.33
2019	$ 993,086.33
2020	$ 993,086.33
2021	$ 993,086.33
2022	$ 993,086.33
2023	$ 993,086.33
2024	$ 993,086.33
2025	$ 993,086.33
2026	$ 993,086.33
2027	$ 993,086.33
2028	$ 993,086.33
2029	$ 993,086.33
2030	$ 993,086.33
2031	$ 993,086.33
2032	$ 993,086.33
2033	$ 993,086.33
2034	$ 993,086.33
2035	$ 993,086.33
2036	$ 993,086.33
2037	$ 993,086.33
2038	$ 993,086.33
2039	$ 993,086.33
2040	$ 993,086.33