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Risk-Benefit Analysis of Advanced Air Transportation System Technologies Using Logic Gate Models

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***Abstract*—Risk-benefit analysis of new systems for use in the Next Generation Air Transportation System (NextGen) is complicated by the large number of alternatives that must be analyzed. The alternatives are generated by combinations of system design options, CONOPS variations and changing assumptions about the evolving state of the NextGen environment. We present here a demonstration of the use of Logic Gate Models (LGMs) to represent and perform a risk-benefit analysis for an advanced ATS technology in NextGen. An LGM is a generalization of a class of hierarchical models that includes event, fault and decision trees. Solution of the LGM yields a set of scenarios; each one is a unique combination of initial conditions, system specifications and ATS environment. An important aspect of our LGM implementation is the ability to perform path wise calculation of risk-benefit metrics for each scenario. Path wise metric calculation allows for a consistent and practical treatment of solution dependencies that are difficult or cumbersome to treat with less general LGMs.**

A systems model for Airborne Precision Spacing (APS).was developed to demonstrate the application of LGMs to aviation systems analysis. APS is a NASA-developed technology for Flight Deck Merging and Spacing. Models for risk and benefit metrics are presented. The risk model combines accident scenarios obtained from the LGM with historical data for operational incidents and human error rate estimates. The benefit model uses reduction in arrival bank delay time and the increase in airport arrival rate to evaluate changes in system performance. Risk-benefit calculations for each scenario are performed during solution of the LGM. The analysis showed that APS-based merging and spacing operations exhibit significantly lower risk and improved benefit relative to current practice over a range of demand states and system design variations. The interaction of APS with a second, advanced technology and the extension of the approach to larger systems models are discussed

Keywords-systems analysis, risk-benefit, logic gate models, merging and spacing

I. INTRODUCTION

Systems analysis is the evaluation of alternatives using a set of specific metrics. The number of alternatives – the combination of design options, operational variations, technology insertions and environment projections may be very large. The need to consider a large number of alternatives is seen in the analysis of future, advanced, complex systems. Such systems by definition are based on new technologies that replace existing ones completely or in part and must be integrated with current technologies that continue in use. Concepts of Operation (CONOPS) may appear relatively unchanged but in fact will strongly affect the interface requirements with other parts of the system. The environment in which the prospective technology or system will operate may be quite different from what exists today and in fact projected changes in the environment may be driving technology development.

Systems analysis of advanced technologies for the Next Generation Air Transportation System (NextGen ATS) requires the evaluation of a large set of alternatives. In addition to the factors mentioned above, NextGen will be an evolutionary system with more or less continuous introduction of new technologies and processes over decades. The ATS must perform at an acceptable level at all times during the system transformation. System acceptability is assessed using a set of metrics whose values can be calculated within a system model. Although many sub-metrics may be evaluated, in the final analysis they will be expressed in terms of a risk-benefit-cost triplet. To be of value the computation of the risk-benefit-cost metrics must be done consistently over the set of alternatives so that relative changes can be assessed fairly. In addition, metric estimates for future system configurations must have a known relationship to the existing system state so that resource allocation options can be assessed.

In this paper we present an approach to systems analysis of advanced technologies for the ATS using Logic Gate Models (LGMs). An LGM is a hierarchical, tree-like structure where a specific set of alternatives is represented using an OR-type logic gate and combinations of alternatives are represented via an AND-type logic gate. The specific LGM methodology used here is Logic Evolved Decision Analysis (LED), developed at Los Alamos National Laboratory [1]. LED extends the use of LGMs to allow for the consistent calculation of system metrics and rank ordering of alternatives. To demonstrate the application of LGMs to systems analysis of advanced technologies for NextGen, we developed an LED model for Airborne Precision Spacing (APS). APS is a Flight Deck Merging and Spacing (FDMS) tool developed by NASA to allow aircraft to maintain consistent inter-aircraft spacing intervals at the runway threshold. We show how APS alternatives are represented using the LGM formalism, compute risk-benefit metrics for the alternatives and compare them to the performance of current Merging and Spacing (M&S) processes for near-term (NT) and NextGen (NG) ATS environments. Finally we consider the interaction of technologies by modeling the interaction of a second advanced technology with APS.

II. Background: Logic Gate Models for Systems Analysis

The most frequently encountered LGMs in safety analysis are event trees and fault trees [2]. An event tree is inductive; it starts with some initial event and delineates the paths to all possible end states via a series of branching points. Logic gates on an event tree do not appear because each branch point is an OR gate. A fault tree is deductive; it begins with a final state, the failure of the system and finds all of the unique combinations of failures, referred to as cut sets that produce the failed state. A fault tree is actually a directed graph and not a tree and is characterized by a combination of OR and AND logic gates.

For both types of LGM, the primary output of the model is the assignment of a probability to an event path or to a failure cut set. A well-known issue in the probability calculations is one of dependency on other events or failures. If for example, a branching probability is dependent upon one or more of the previous branchings then every dependency must be accounted for. This applies for every transition where a dependency occurs. For very large event tree dependency management is a difficult task. A similar problem arises in fault tree analysis where the probability of failure for two or more elements in a cut set may be dependent.

An LGM in LED is a more generalized logic structure. The top node in the model can be a specific system state, a system or a process. In the first case the LGM is causal – similar to the top node in a fault tree, or resultant – similar to the initial event in an event tree. An LED LGM that describes a system or process can be causal, resultant or a hybrid where the perspective shifts from inductive to deductive as appropriate. The output from an LED LGM is a set of scenarios. These scenarios are similar to the paths in an event tree. The scenarios are obtained using a process similar to the solution of a fault tree with the important exception that the entire solutions, not just the cut sets are retained.

The computational capabilities of an LGM in LED are expanded relative to the standard LGM in several ways. First, calculation of other attributes beside probability is enabled. In the case of a system or process other metrics can be estimated for each scenario. Secondly, the solver in LED automatically computes attribute dependencies during the solution process. A dependency in LED can be much more complex than in an event tree and can be a function not only of previous events, but other parameters associated with system, process or environment inputs. This provides for an efficient solution of an n-step Markov model. A comparison of the features of event, fault and LED LGMs is given in Table I. The specific features of an LED LGM will be discussed in Section IV.

LED has been applied to a wide range of system and decision analysis problems including the development of scientific complexes [3], programming planning for advanced technology development [4], safety analysis of nuclear waste storage [5], and the evaluation of research technology to reduce the risk of terrorist attacks against the ATS [6].

TABLE I. Comparison of Logic Gate Model types

LGM Type	Model Characteristic		
	Top node	***Computed attributes***	***Dependency handling***
Event tree - resultant	Initial event	Path-dependent probability only	Must be defined explicitly at each branch point
Fault tree - causal	System failure	Cut set probability only	Resolved during post processing
LED LGM - hybrid	Event, System or Process	Numerical or string attributes; combined attribute and subroutine calculation	Path dependent resolution during solution using generalized rule base structure

III. Overview of Airborne precision Spacing

The sequencing of aircraft for arrival at a large hub airport is a critical process in NAS Traffic Flow Management (TFM). The sequencing process consists of two basic steps:

- *Merging aircraft*, that is placing them in a specific order. A pair of aircraft that have merged have a leader/follower relationship and are on a common path to an arrival runway. The standard terminology to describe this pair is from the perspective of the follower, identified as Own Aircraft (OA) with its leader identified as the Traffic to Follow (TTF). An arrival sequence has many pairs of such aircraft. The location at which a pair acquires a physical TTF/OA relationship is called the merge point.
- *Spacing aircraft*, that is controlling the inter-aircraft spacing. Spacing is an operational measure and is distinct from maintaining separation. The spacing may be specified using distance or time. For NAS TFM in the near-term and certainly for NextGen it is accepted that time-based spacing is a superior metric. The datum for spacing is the runway threshold crossing time. That is, the Spacing Interval (SI) is the interval in seconds between the TTF/OA pair at the runway threshold.

There are a number of approaches to Merging and Spacing (M&S). Current M&S practice is for an Approach Controller at the TRACON to merge and space aircraft by providing vectors to individual aircraft, hereafter referred to as manual control. This is a ground-based approach. There are concerns that manual control of arrival sequences with greater densities, that is, with aircraft spaced closer together than at present will be difficult. We will consider the sources for these concerns in Section V.

An alternative to ground-based M&S is to use automation tools on board the aircraft. NASA has developed the Distributed Air-Ground Traffic Management (DAG/TM) concept that incorporates FDMS as one design alternative to assign some of the workload to aircraft. The FDMS concept was first considered in the 1980s [7]. Serious consideration of FDMS at NASA and elsewhere began after the emergence of two key technologies: Global Positioning System (GPS) and Automatic Dependent Surveillance - Broadcast (ADS-B). On board GPS provides the necessary position accuracy for the TTF and OA to compute their distance from each other and to the runway along specified paths. ADS-B provides the data link so that the automation tool on OA can calculate the speed profile to merge and space as required. NASA research has included development of speed control laws [8], fast time studies of arrival sequence behavior [9], human in-the-loop simulations [10] and flight testing of FDMS hardware in actual spacing tests with three aircraft [11].

Following extensive testing, a commercial application of FDMS has been approved by the FAA for UPS night air cargo operations at Louisville International Airport (SDF). UPS has equipped a significant fraction of its Boeing 757 fleet with FDMS and will conduct late night operations at SDF, primarily involving West Coast arrivals using the cockpit-based system. The primary advantage of FDMS-based arrivals is fuel savings. The fuel savings are realized by the use of Continuous Descent Approaches (CDAs) rather than Area Navigation Standard Arrival Routes (RNAV STARs) that are characterized by a series of descents linked by level flight. A second potential benefit from APS-based M&S is a more stable and predictable arrival stream. APS can be viewed from this perspective as an enabling technology for the 4-D trajectory-based operations needed in NextGen.

Fig. 1 shows an operational view of a TTF/OA pair performing an APS-based arrival. The two aircraft depart from different airports as shown at the left. Aircraft A will be the TTF and Aircraft B, OA. Aircraft B will be merging and spacing behind Aircraft A. Aircraft A may be equipped with an FDMS and be spacing on another aircraft in the arrival stream. In any case Aircraft A is ADS-B equipped. The ordering of the arrival stream has been determined earlier. Once the aircraft are in ADS-B range, Aircraft B begins to follow speed commands provided by the system. Speed commands are generated to allow Aircraft B to merge behind Aircraft A and then to provide proper spacing. Both aircraft are now following the same trajectory to the airport. This common path, needed to allow the FDMS on Aircraft B to perform the spacing calculations to achieve the commanded SI is expected to be an RNAV STAR. At the Final Approach Fix each aircraft slows to the Final Approach Speed.

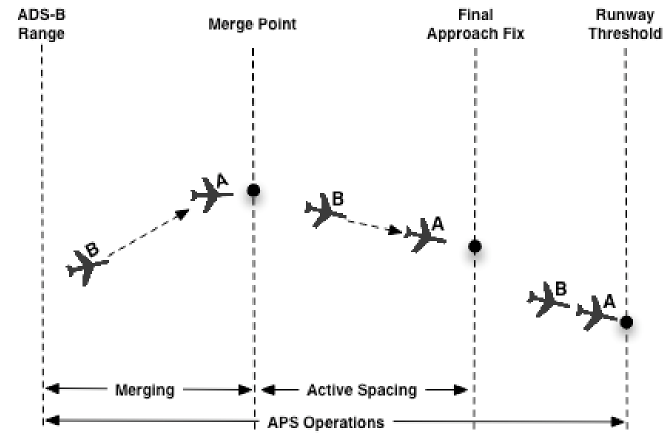

Figure 1. APS Merging and Spacing Process

IV. SYSTEM LOGIC GATE MODEL FOR APS

The systems model for APS can be represented functionally in block diagram form as shown in Fig. 2. The middle three blocks represent the actual M&S process. The first block shows the need to define the set of assumptions associated with the environment. This is part of the analysis process and allows for the specification of use cases. The last block is also associated with the analysis process and represents the assignment of the computed metrics associated with each use case/scenario analyzed.

This block diagram is the starting point for the LED Systems Logic Gate Model (SLGM) for APS. Fig.3 is a top level view of the SLGM, simplified somewhat for presentation here. Each of the blocks is translated into a series of logic gates with multiple inputs. The Initial Conditions node is decomposed into architecture, M&S operation type, description of the M&S environment, airport acceptance rate (AAR) assumptions that define the demand state, and short term dynamic conditions that specify the possible disruptions to APS from external events and the meteorological conditions in which APS is occurring.

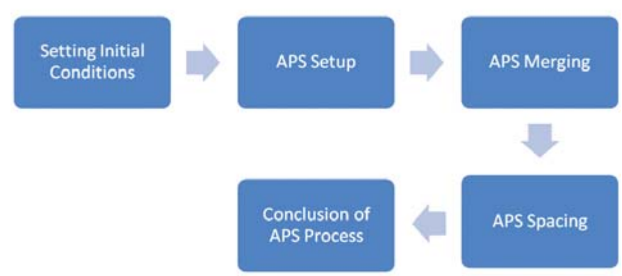

Figure 2. Block diagram for APS systems model

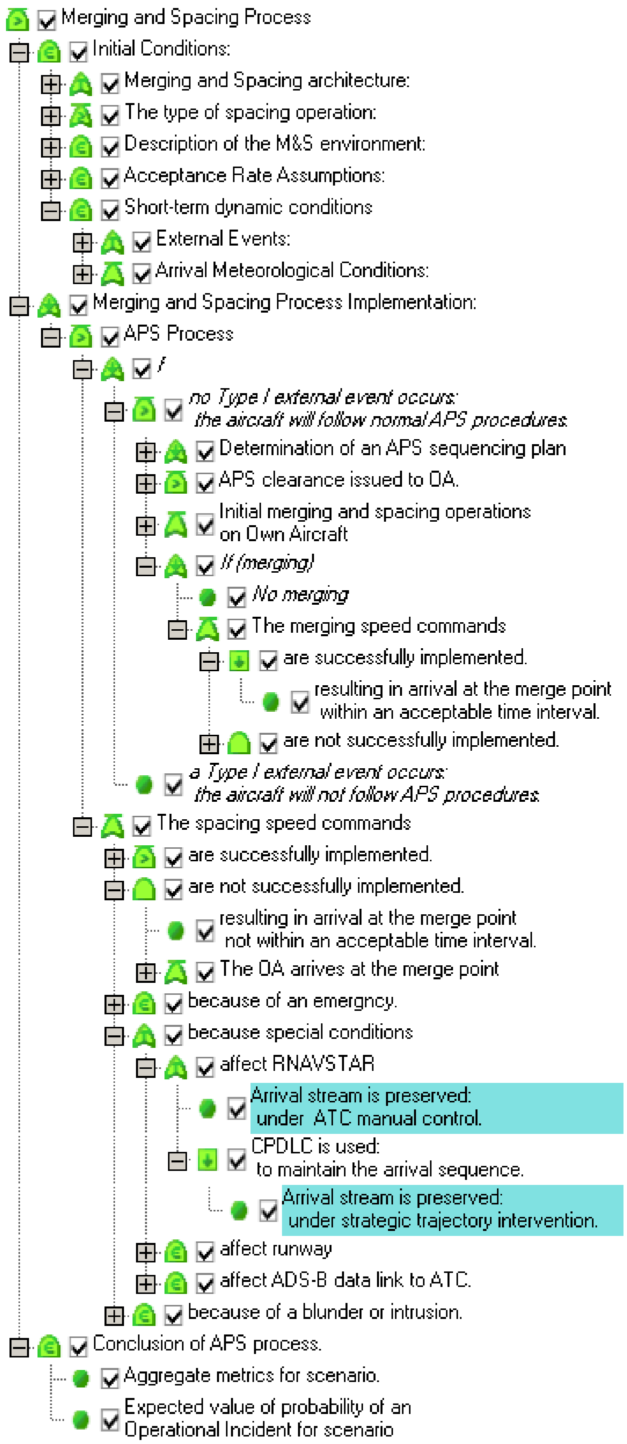

Figure 3. Translation of APS block diagram to an LGM

The logic gate for this node is an ELEMENT gate, an AND-type gate. Using this gate type implies that each input to the gate is considered an integral part of the initial conditions. Inputs to the *Initial Conditions* node are either again an ELEMENT gate or a TAXONOMY gate – a specialized form of an EXCLUSIVE OR gate. A plus sign indicates that the gate inputs are presently hidden. The LED software has a large selection of logic gate types including CAUSAL, CYCLE and a set of connectors (CONTINUE, GO) that facilitate model development.

Solution of the Initial Conditions sub-model generates different combinations of initial conditions. For the SLGM as configured there are 108 initial condition scenarios. The number of combinations depends on how many different options are considered. One solution, edited here for brevity is:

Initial Conditions: Merging and Spacing architecture: .. APS … Central Facility Manager for APS operations The type of spacing operation: … Merging of an aircraft pair ,,, followed by in-trail spacing … common runway Description of the M&S environment: … Flight crew input to FDMS via: MCDU using the keypad FDMS output: Automatically via aircraft data bus linked to the FADEC. Drag Device required alerting : available Insufficient Achieved Speed: alerting available, FDMS failure to pair with TTF. : annunciated Basis for FDMS Profile Speed Commands: RNAV STAR speed profile. M&S begins: during.Initial approach. APS information sent: via data link…Acceptance Rate Assumptions: … 1X - Short-term dynamic conditions External Events: Aircraft emergency: Ownship emergency…Arrival Meteorological Conditions: Visual Meteorological Conditions.

The three underlined elements, Acceptance Rate Assumptions …1X, weather conditions (VMC) and external event (OA emergency) lead to different estimates for the risk-benefit metrics. A specific choice of initial conditions defines an analysis use case.

Three process blocks that describe the operation of APS appear in the middle of the SLGM. Note also that other process steps not necessarily assigned to APS appear as well e.g. determination of an APS sequencing plan that defines an arrival stream and therefore a set of TTF/OA pairs. The appearances of these external processes define interfaces with other parts of the ATS. Finally, the analysis step associated with assigning the risk-benefit metrics appears as the last node in the SLGM. The risk and benefit models implemented in the SLGM are discussed in Section V.

The main M&S process begins with the node *APS process*. Directly below this node is an EXCLUSIVE OR with two inputs. If no Type I external event appears in the scenario, then OA enters the APS process. A Type I external event is one that precludes an aircraft from performing APS-based M&S. In the scenario above, an OA emergency precludes participation in M&S. The progression of the scenario along one or the other inputs is controlled by a logic switch that is set when the external event appears in the scenario. Logic switches allow for path-wise treatment of dependencies. Additional logic switches are used to flag whether a merge operation is needed and to eliminate inconsistencies that appear when incompatible combinations of nodes would appear together in a scenario. Logic switch filtering occurs during the solution of the SLGM. Probabilities are assigned to input nodes of OR-type gates where the inputs are treated as random variables. For example in the scenario above, VMC has been assigned a probability of 0.7. All scenarios that include this node contain this probability.

Four classes of scenarios appear in the solution:

- Success scenarios where the system functions without error, with OA crossing the threshold within an acceptable interval about the SI;

- Recovery scenarios where one or more errors occur but automatic or human intervention allows the scenario to proceed to an acceptable conclusion;
- APS fault scenarios that lead to a consequence, and
- External event upsets that result in a failure to enter or finish M&S.

The first two classes have no adverse consequence, therefore no risk and maximize the benefits associated with APS for a particular use case. Scenarios in the last two classes have some degree of risk and will have reduced benefits. An example of a scenario where a reduction in benefit may occur is the node *Arrival stream is preserved: under ATC manual control* that is shaded in blue in Fig. 3. A delay time calculation is performed for scenarios that contain this node. The amount of delay is dependent upon the weather conditions and the assumed spacing interval set in the *Initial Conditions* sub-model. The shading indicates that this node, actually a one node sub-model is a replicant, a sub-model used multiple times in the SLGM. The appearance of the external event scenario class in the SLGM is important. The total risk-benefit for APS is strongly affected by the presence of external events and they must be taken into account when comparing APS to CMS. Summation over all of the scenarios in all classes gives the aggregate risk and expected benefit metrics for a use case.

V. Risk-Benefit Metrics for APS

A prerequisite for the introduction of an advanced technology into the ATS is that it results in a positive improvement to the system. The two classic metrics used to evaluate the utility of an overall systems improvement are cost-benefit and risk-benefit ratios. Our analysis is directed at specifying metrics for risk and benefit and then estimating them for APS for a number of different assumptions about the NAS. We also compare risk-benefit for the APS use cases to the performance of CMS for the same initial conditions. An important constraint for NextGen systems is that an equivalent level of safety must be maintained. This is interpreted to mean that no increase in risk be chargeable to the advanced system's introduction

A. Risk Metric Model

Risk is defined as the expected value of the loss function [12]. Here "expected" has the natural language meaning of likely, a measure of outcome uncertainty. The loss function specifies the consequences to be considered in the risk estimation and how they are to be combined. In aviation risk analysis, the standard consequences are hull loss and passenger casualties. Probabilistic Risk Analysis (PRA) uses probability to represent likelihood. The probability of interest is for an entire sequence of events culminating in a hull loss. Such an event sequence in safety analysis is referred to as an accident scenario. The probability of an accident scenario, *j* is normally written as the product of an initiating event (e.g. an engine failure) p_I and the product of a set of enabling event probabilities p_E that describe the likelihood that the initiating event results in the consequence. The risk associated with scenario *j* is then

$$R_s^j = \left(p_i^j \prod_k p_{Ek}^j \right) C \quad (1)$$

where *k* denotes the sequence of enabling events associated with scenario *j*. To get the total risk it is necessary to sum over all of the scenarios of interest.

$$R = \sum_j R_j = \sum_j p_j C_j \quad .(2)$$

The use of risk of hull loss, R_{hl} directly as the metric to evaluate whether an equivalent level of safety is achieved in APS-based operations is problematic. Calculating the probability of a hull loss chargeable to a new technology in an environment where the CONOPS are still largely unspecified is impractical. In the case of M&S, a model for the terminal air space with a much higher density of aircraft executing 4-D trajectories with a mix of manual and automated control would be needed. The development of such a model would be a major task in itself and could not be justified by risk-benefit studies for individual technologies at this time. Direct extrapolation from existing hull loss occurrences would be problematic not only for these same reasons but more importantly because no hull loss event in the available historical data could be associated with M&S. For these reasons a different safety risk metric is needed. This risk metric must be clearly related to R_{hl}. For our APS safety risk estimates we used safety-related incidents as the consequence. The incidents of concern are:

- Loss of Separation (LOS)
- Near Mid-air (NMA), and
- Traffic Collision Avoidance System resolution advisory (TCAS-RA)

Each of these incidents is a potential precursor to a hull loss and/or fatalities. More importantly, occurrences of these events do appear in the historical data and specific records can be associated with M&S as discussed below. For these consequences the PRA expression for risk RI is the expected probability of an incident per flight. By taking into account the number of operations per unit time the risk could also be expressed as a frequency, e.g. the expected number of incidents per hour or per arrival bank.

1) Risk Model for APS-based M&S

Each incident scenario is of the form

[InitiatingEvent] ^ [EnablingEvent] ^ [IncidentOccurrence]

An example from the SLGM is shown in Fig. 4 for the sub-model associated with setting up the APS system after a clearance to perform APS-based M&S has been received. The two initiating events are associated with selecting the TTF and the SI. Both of these errors are actions associated with the Pilot Not Flying (PNF). The opportunity for recovery occurs when the Pilot Flying (PF) confirms the selections after reference to the clearance. Note that both the initiating event and the non-recovery alternative are associated with human error. Both of these opportunities for error are eliminated when a data link is used to upload the clearance information into the FDMS. Events in an enabling event sequence are mainly failures of human operators to arrest the developing incident sequence. The probability of the failure to recover is conditional on both the initiating event and prior events in the enabling event sequence.

The initiating event probability values used in the SLGM were populated with a mixture of surrogate data, standard data and expert judgment. A more difficult problem is encountered when estimating the probabilities for the enabling event sequence for a scenario. This type of estimate is generally more difficult because the enabling event sequence is a complex string of events including a mixture of human errors of omission, slips, incorrect actions and errors in diagnosis. Fortunately, the historical estimates for CMS scenario risk supplemented by standard human error rate estimates provides a good source for these probabilities as will be explained below. Multiplying the initiating event and enabling sequence probabilities produces the overall probability of occurrence for each incident scenario.

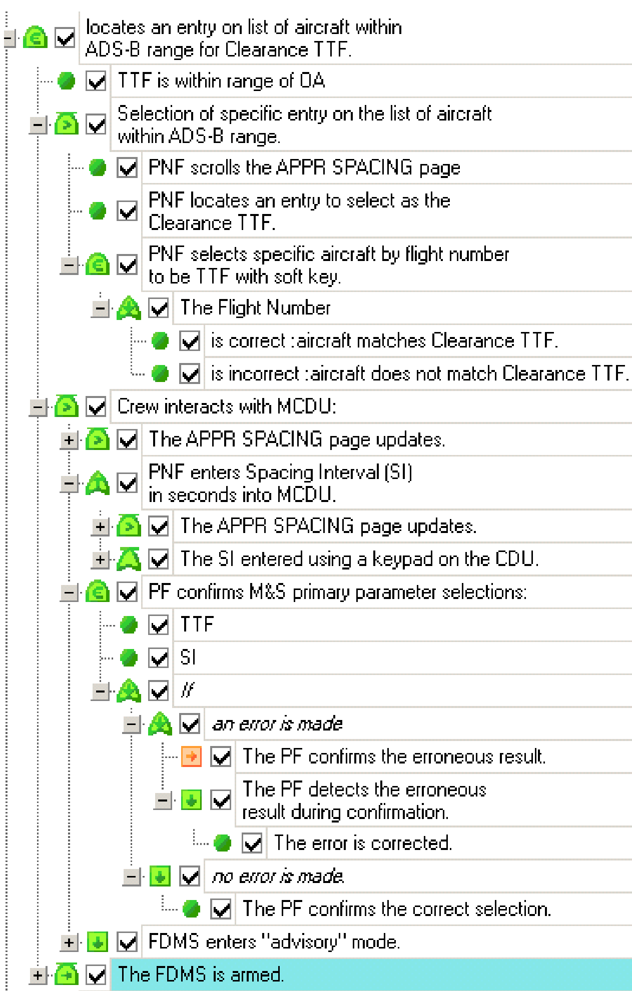

Figure 4. Sub-model for APS setup showing the start of an incident sequence

Four classes of incident sequences appeared in the SLGM:

- Manual Spacing Error (MS): incorrect spacing as a direct result of errors made by ATC or aircrews when M&S is performed under manual control via ATC vectors.
- Single Aircraft Re-sequencing Error (SR): an error arising during vectoring of a single aircraft to return it to the arrival stream after an initiating event e.g. a missed approach.
- Bank Re-sequencing Error (BR): an error that occurs following an event that requires ATC to re-sequence a portion of an entire arrival bank of aircraft e.g. a runway closure.
- Automatic re-sequencing errors (AR): an error that occurs as a direct result of an initiating event during APS-based M&S e.g. selection of an incorrect aircraft as TTF. After the initiating event, the incident sequence is similar to what happens in an MS scenario with CMS.

The risk expressions for the different classes of incident scenarios include adjustments to account for differences in aircraft density and workload stress between APS and CMS and among the various APS use cases. The aircraft density factor is inversely proportional to the SI for AS, SR and MS scenarios. For BR scenarios the density factor is inversely proportional to the square of the spacing interval. Workload stress factors for the different scenario classes were derived using human reliability analysis [13]. The stress factors are based on an evaluation of ATC and aircrew workloads and their familiarity with the upset scenarios encountered with CMS and APS-based operations. The stress factors vary according to the type of incident scenario. In general, the ATC workload is predicted to be lower with APS than with CMS because much of the M&S is performed with automation. However the familiarity with manual control procedures required during APS upsets may be lower than for current operation because of lack of practice. For example, during a BR scenario ATC must manually vector a number of aircraft as in CMS with a similar workload factor and possibly less experience with the operation.. Thus while lower workload tends to reduce error rates during an MS, AS or SR sequence, this improvement is at least partially offset by less familiarity with manual control procedures.

2) Risk for CMS

In order to evaluate whether APS-based M&S provides an equivalent level of safety, a direct comparison to the risk chargeable to M&S using CMS is needed. The incident risk of CMS for Part 121 aircraft was derived from an FAA data base of incident records for the period 1988-2003. These data include short descriptions of each incident, providing sufficient detail in most cases to allow determination of the sequence of events that led to each incident. The FAA data also provided the event data needed for a maximum likelihood estimate of probability of occurrence per arrival [14]. Records in the data base could be associated with the MS, SR and BR incident scenarios in the SLGM. Risk estimates for these scenario classes are shown in Table II. Note that no occurrence of a BR

TABLE II. INCIDENT RISK ESTIMATES FOR CMS

Incident Scenario Class	Population	Occur-rences	Mean	Lower 5% CB	Upper 5% CB
MS	1.48×10^{8}	10	6.75×10^{-8}	3.66×10^{-8}	1.15×10^{-7}
SR	1.48×10^{8}	1	6.75×10^{-9}	3.46×10^{-10}	3.20×10^{-8}
BR	1.48×10^{8}	0	4.68×10^{-9}	0	2.02×10^{-8}

error for the time interval covered appeared in the database. AS type errors are associated with APS-based operations only.

B. Benefit Metric Model

Spacing between aircraft must increase in IMC to meet separation standards for CMS. This reduces the actual acceptance rate resulting in delay. Aircraft using APS-based spacing procedures in IMC self-separate as if in VMC. This is defined as Equivalent Visual Conditions -- the spacing under IMC will be the same as under VMC. The capability to operate in EVC is a significant factor in reducing delay.

Reduction in delay time and the increase in actual AAR are the benefit metrics for comparing APS with CMS. Alternatives for arrival runway demand are expressed either in terms of the SI or arrivals per hour. We considered three demand states: 1X, 1.5X and 2X corresponding to SIs at the runway threshold of 120, 90 and 60 s respectively. The SI for CMS is either 90 or 120 s depending upon whether operating in VMC or IMC. An SI = 60 s for the 2X demand state is a lower bound on spacing based on minimum runway occupancy time. The equivalent runway capacity is 60 arrivals per hour. This is an upper bound for capacity as it does not take into account increases in SI to account for wake separation, runway conditions and limitations imposed by ground operations. It does provide a serious challenge to APS-based operations because of arrival delays generated from system upsets. Table III summarizes the three demand state characteristics.

The acceptance rates in Table III do not take into account the delays generated by APS faults and loss of capacity associated with external events. An analytical delay time model

TABLE III. DEMAND, SPACING INTERVAL AND ACCEPTANCE RATE PARAMETERS

ATS State	Use Case	Demand Designation	Spacing Interval VMC/IMC (seconds)	Runway Acceptance Rate VMC/IMC (aircraft/hour)
Current with CMS	CMS	1X	90/120	40/30
Near-term with APS	NT	1.5X	90/90	40/40
NextGen with APS	NG	2X	60/60	60/60

is incorporated into the SLGM to allow for estimation of these effects. If the arrival stream is modeled as a continuous stream of aircraft spaced at the minimum interval, then a delay to any aircraft will propagate upstream as a continuity wave affecting all subsequent arrivals. This is unrealistic; gaps in the arrival stream accommodate some delay. A gap that occurs at regular intervals at many large hub airports is generated by bank operations with alternating arrival and departure banks. Delay model parameters are the number of aircraft in the bank, the bank duration and the interval between arrival banks as parameters..

The model is an idealization of the time distribution of arrivals at the Detroit Municipal Airport (DTW) discussed by Ater [14]. The delay time per aircraft or per bank assigned to a scenario depends upon the type of upset and the bank length, inversely proportional to the SI. The upset types are the incident scenario types discussed above. The bank delay depends upon the location in the arrival sequence where the upset is generated and the number of aircraft that have to be re-sequenced. The bank delay is proportional to the number of aircraft in the bank, N when only a single aircraft requires re-sequencing and N2 when an entire bank must be re-sequenced. More accurate delay time estimates could be generated using simulations to model the upset and recovery scenarios developed in the SLGM

VI. RESULTS

Preliminary analysis provided data on sensitivity and importance to allow for the design of a set of use cases. The principal use cases for the APS risk-benefit study are shown in Table IV. They were defined to cover a range of variations in the application of APS to different time frames and with different levels of capability. NT Hi, a near-term application of APS with a high degree of automation and fault annunciation is considered the base case.

A. Incident Risk

The incident risk per aircraft for CMS (Demand state 1X) and the APS use cases NT Hi and NT Lo (capacity 1.5X) and NG Hi (capacity 2X) are shown in Fig. 5. The contributions to the risk from the different scenario classes can be seen. Introduction of APS into the near-term NAS environment results in a significant decrease in the incident risk associated with M&S. The primary difference is the decrease in MS scenario risk. The fraction of total risk associated with BS scenarios increases with APS and is a function of arrival stream density. A small but significant reduction in risk in the near-term environment is seen with increased automation and fault annunciation (High-end APS) in comparison to an implementation with greater direct aircrew involvement (low-end APS). Note that all of the APS use cases exhibit a significantly lower risk per aircraft than for CMS.

B. Acceptance Rate

The expected arrival bank delay time is the measure in the SLGM used to estimate benefit Fig. 6 shows the delay time per aircraft for CMS and the principal APS use cases. Delay time

TABLE IV. SLGM USE CASES FOR APS

Use Case	Description
NT Hi	Near –term APS application with data-link, auto throttles and APS fault alerting. Also called High-end. This is the base case.
NT Al	Near–term APS application with voice communications, manual throttles, and APS fault alerting.
NT Lo	Near–term APS application with voice communications, manual throttles, and limited APS fault alerting.
NG Hi	Same as UC1 but with capacity conditions 2X
NG Lo	Same as UC4 but with capacity conditions 2X
NG ST	Same as UC5 but with insertion of NASA Integrated Intelligent Flight Deck program Strategic Trajectories technology

can be converted to arrival capacity, a standard form of the benefit metric by dividing the number of aircraft in the bank by the time required to land the bank taking into account any delays. The arrival capacities for the near-term APS (NT Hi) and NextGen APS (NG Hi) are compared to the arrival capacity with CMS for the same demand conditions in Figure 7.

VII. DISCUSSION OF RESULTS

The analysis shows that APS-based M&S can potentially result in improved performance while maintaining an equivalent level of safety. Figure 8 shows incident risk per hour versus arrival capacity. Increases in capacity are seen for all use cases while the risk remains below that associated with CMS. The increase in capacity from CMS to NT Hi is about 7%. This is a useful improvement. It is somewhat less than other estimates for capacity improvement resulting from APS in the near-term. However these estimates take into account the overall capacity improvement for the airport with APS-based

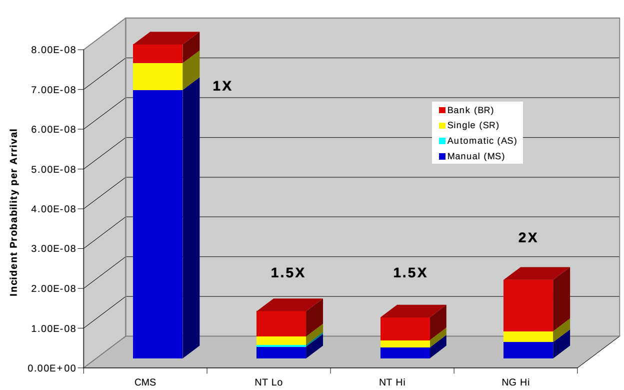

Figure 5. Incident Risk per Arrival for CMS and APS Applications

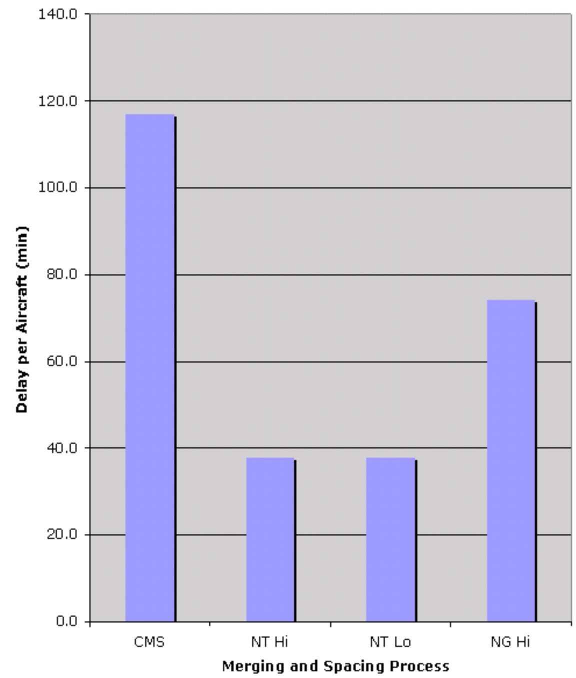

Figure 6. Delay Time per aircraft for CMS and APS for Near-term and NextGen Demand States

operations in place. We would expect the estimate here to be somewhat lower as it only considers the direct benefit of APS but fully accounts for the effect of external events. In addition the delay time model implemented in the SLGM is conservative with respect to the benefit estimate. When system capability is held constant, and demand increases, the risk-benefit relationship worsens. This is expected as incident risk is inversely correlated with the benefit, reduction in delay. A trend to the upper right is typical for a system when performance is falling below demand. This can be clearly seen

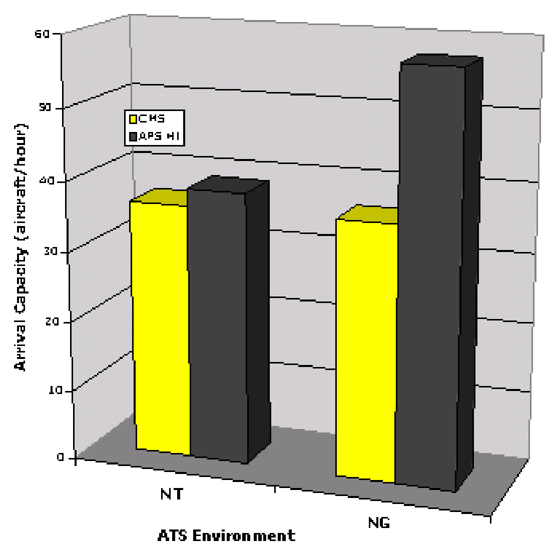

Figure 7. Arrival Capacity for CMS and APS for Near-term and NextGen Demand States

for the two use cases NT Hi and NG Hi connected by the red line in the Fig. 8. Note also that an equivalent level of safety is not maintained across this transition.

When system demand is held constant but system technology improves, then the risk-benefit metric improves. This is shown in Fig. 8 by the blue lines connecting the pairs (CMS, NT Hi) and (NG Hi, NG ST). The first pair represents the expected transition from CMS to APS in the near-term. The second data pair represents the effect of the insertion of the Strategic Trajectories technology [15] into the APS system in the NextGen environment. The benefit analysis showed that a large fraction of the delay in the NG Hi use case was associated with external events that forced an aircraft to deviate from an RNAV STAR. Once an aircraft has been vectored off the known path to the runway it is no longer possible to compute the threshold crossing time with sufficient accuracy to achieve an SI with an acceptable error margin. This results in an SR re-sequencing event and the generation of delay. Strategic Trajectories provides a mechanism for generating a known 4-D trajectory to either return to the RNAV STAR or fly a different approach with the information needed to calculate the threshold crossing time. The insertion of the Strategic Trajectories technology appears in the SLGM as shown in Fig. 3 at the node *The arrival stream is preserved under strategic trajectories intervention*. Other technologies, alternative system interfaces and CONOPS can be studied using this approach.

VIII. CONCLUSIONS

The analysis showed an improvement in risk-benefit for all of the APS use cases when compared to CMS at increased demand levels. APS-based M&S operations also maintain an equivalent level of safety. These conclusions are insensitive to the details of the APS implementation. This conclusion from the risk analysis suggests that the emphasis in future systems analysis should be on better benefit estimation and that cost-benefit analysis should take priority over additional risk-benefit studies.

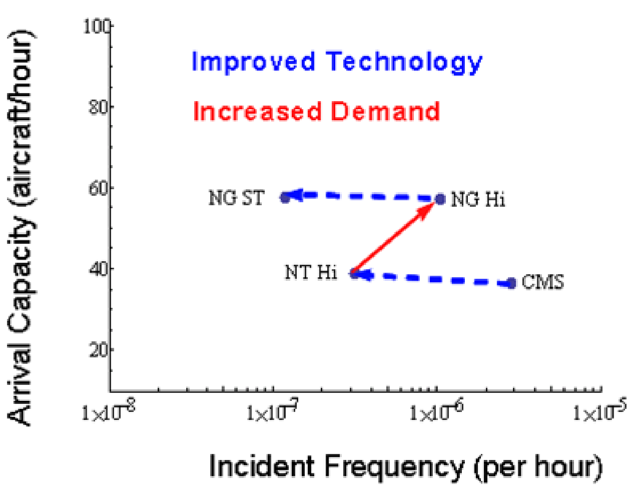

Figure 8. Effect of Increased Demand and Improved Technology on Risk-Benefit

The risk metric used for the analysis is the probability of an operational incident per arrival. It is based on a consequence – the occurrence of one of three operational incidents that are potential precursors to a mid-air instead of the standard consequences – hull loss and on-board fatalities. The use of this metric has a number of advantages. These include:

- The ability to estimate risk for CMS using historical data. The aggregate CMS risk estimate can be decomposed to assign risk to distinct classes of accident scenarios. By making a few defensible approximations, a quantitative comparison between CMS and APS safety risk was developed.

- The risk model developed here allows for internally consistent comparisons of APS systems options across the range of initial conditions and changes in the NAS environment. These relative changes are more accurate than the absolute risk estimates.

The risk estimates in the analysis are specific to APS-related accident sequences. No conclusions about the aggregate risk in the NextGen environment can be drawn from this analysis. The estimates for risk and benefit in NextGen are based upon a spacing interval, SI = 60 s. In reality the average SI will be significantly greater to take into account wake separation, aircraft stopping distances and many factors associated with the efficiency of ground operations. The benefit estimates can be considered as optimistic for APS-based M&S considered as a standalone system. The overall improvement in runway or airport capacity with APS-enabled operations will require a larger systems model.

Improved estimates of the risk are possible. These would require collection of better data on specific events such as the frequency of missed approaches. Simulation of terminal air space operations at increased aircraft densities associated with higher demand states would also be useful for scaling the data to the NextGen NAS. The path forward to better benefit estimates are simulations of APS-based arrival operations that take into account the dominant upsets identified in the SLGM.

The analysis of APS-based merging and spacing operations successfully demonstrated the capability of Logic Evolved Decision analysis to model an advanced aviation system for risk-benefit analysis. The SLGM represents a very large combination of initial conditions, APS system variations and alternative process outcomes, including accident scenarios in a compact form. The ability to insert other new technologies into the SLGM of interest is an important step in the integration of advanced systems into NextGen. The SLGM also provides a framework for linking systems analyses of multiple proposed NAS changes.

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