Risk Modeling of Sequential Decision-making in the National Airspace System and with Unmanned Aerial Systems

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Abstract

The National Airspace System (NAS) is expected to change dramatically over the next decade with the development of the Federal Aviation Administration's (FAA) NextGen initiative. One major challenge the FAA will be facing during this time is the projected increase of Unmanned Aircraft Systems (UAS) in domestic airspace, and the integration of these vehicles into the NAS without disrupting the current volume of manned aerial operations. As UAS technologies have matured over the last few years, a number of applications have become feasible, both for civil and military uses. The problem regulators are facing is that the introduction of UAS has the potential for such a wide range of impact on the already complex NAS, making exhaustive testing of all design options impossible. This, in turn, makes the identification and evaluation of risks difficult.

The FAA is also charged with making a large number of strategy decisions concerning the development of NextGen standards, procedures, and design choices in a short amount of time, many of which will not manifest themselves until several years from now. The challenge in making each of these decisions is being able to evaluate its impact not only on the project that the decision pertains to, but also on interdependent subsystems of the NAS. This thesis will develop a framework with which to evaluate the impacts of these current decisions on future options by making use of the shared state space among subsystems of the NAS, and will demonstrate the efficacy of this framework by focusing on a set of decisions pertaining to one NAS subsystem.

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Table of Contents

1 Introduction

1.1 Motivation

The Federal Aviation Administration's (FAA) NextGen program is a comprehensive overhaul of the National Airspace System (NAS), aimed at making air travel more efficient and dependable, while increasing the safety of its passengers and reducing its impact on the environment. NextGen marks the largest shift to date in an established transportation system, which would otherwise grow beyond its current capacity within a few years. The biggest change NextGen will bring to the NAS is an evolution from a ground-based system of air traffic control, using primarily RADAR technology, to an air traffic management approach using GPS technology (Burkle & Montgomery, 2008).

An important change to the NAS that is happening in conjunction with the development of NextGen over the coming years is the projected increase in use of unmanned aircraft systems (UAS), which consist of aircraft being controlled by pilots elsewhere, both for military and civilian use. Domestic civilian uses of UAS include tasks like remote sensing, crop dusting, tracking natural disasters, security, and transporting goods (DeGarmo & Nelson, 2004). One important challenge for the FAA will be to integrate these UAS into the airspace without causing disruption to existing manned aircraft operations, since fully-defined regulations concerning the manufacturing and operation of these vehicles do not currently exist, primarily because the risks associated with UAS operations are not fully understood (Dalamagkidis, Valavanis, & Piegl, 2008).

The NextGen project consists of three planning horizons: Alpha (through 2015), Bravo, (2016-2018), and Charlie (beyond 2018). Over the next few months, the FAA has to make 90+ strategy decisions, ranging from flight protocol standards and procedures to infrastructure design options, that will dictate the course by which the airspace evolves throughout the next decade. Although some of these strategy decisions affect only a single subsystem of the NAS, a number of the decisions have broader implications for the NAS system as a whole, and have a high chance of incurring programmatic risks if they are not made carefully.

1.2 Problem Statement and Scope

This thesis aims to accomplish two goals. The first goal is to identify the most important states and sources of risk that propagate throughout the National Airspace System as a whole, and on a smaller scale in the UAS subsystem. This set of states shared between subsystems represents the major interdependencies present within the NAS. The second goal of this thesis is to develop a framework with which to harmonize the large set of strategy decisions, so that their impacts on different subsystems and potential adverse consequences can be evaluated prior to making each decision. The framework will make use of existing decision-making methodologies, while building on the shared state space to add a focus on the interdependencies between subsystems. This framework needs to be flexible enough to make use of varying amounts of data present to the decisionmaker, and the results should be able to improve as more data becomes available. To show the efficacy of this approach, the framework will be used on a small set of decisions pertaining to a single subsystem of the NAS.

2 Background

This section discusses background for addressing the risks of UAS operations and the methodologies that exist to assist in risk analysis and management. Section 2.1 gives an overview of UAS and how their role has changed in recent years. Section 2.2 discusses literature relevant to the methods that will be developed and employed.

2.1 The Evolution of UAS

A UAS consists of an aircraft that can be flown without the presence of a pilot on board, the remotely located pilot that is operating the aircraft, and the infrastructure used by the pilot to communicate with the aircraft. In order to distinguish UAS from ballistic vehicles and missiles, the Department of Defense (DOD) uses the following definition: "A powered, aerial vehicle that does not carry a human operator, uses aerodynamic forces to provide vehicle lift, can fly autonomously or be piloted remotely, can be expendable or recoverable, and can carry a lethal or nonlethal payload" (2005). There exist many kinds of UAS, ranging in cost from a few hundred dollars to several million, and in size from under a pound to over 40,000 pounds. UAS can be fixed-wing, generating lift using the vehicle's airspeed and wing shape, or rotary-wing, generating lift using rotor blades revolving around a central mast.

UAS, like many ubiquitous technologies today, are a product of military research and funding. Their successes in military operations and recent technological advances to create cheaper and smaller systems have created a lot of interest in the civil sector, including private, commercial, and local government use, and for scientific research (DeGarmo, 2004). Although the demand for domestic UAS use is very high, regulatory restrictions, or rather the lack of fully-defined regulations, prevent the widespread use of UAS for anything but public (state-owned) use. Notably, the U.S. Customs and Border

Protection agency has used surveillance UAS to aid in the arrest of about 2000 illegal immigrants and the seizure of four tons of marijuana in the aircrafts' first half year of service (Karp & Pasztor, 2006).

The primary concern with integrating UAS into the airspace lies with the inherent safety risks that UAS pose over manned aircraft. One of the main risks, and the main consideration in the approval process of an operation, is the aircraft's see-and-avoid capability (DeGarmo, 2004). This capability, like its name suggests, constitutes the UAS' ability to detect structures and other aircraft and to perform maneuvers to evade them, without increasing the dangers to these other operators. The level and quality of see-and-avoid capability on a UAS also constitutes whether or not the vehicle must remain in the line-of-sight of the operator. Another challenge unique to UAS is the existence of a communications link between the vehicle and the pilot and flight crew. This link introduces some amount of latency between a given command and the vehicle's reaction, and the potential to disrupt the operational control of the vehicle through some vulnerability in the link. If the command link is lost, the pilot and air traffic controller may not know how the UAS will perform until the link is reestablished. Third, not having the pilot physically present in the vehicle makes it difficult for UAS to follow certain flight rules, such as avoiding flying into clouds, since the pilot cannot see directly out of the cockpit (Aviation Today, 2011).

Getting UAS to perform at an equivalent level of safety as comparable manned aircraft, including at the take-off and landing segments of flight, is the major challenge faced by manufacturers of UAS to have these systems fully integrated into the NAS.

2.2 Relevant Literature

This section discusses relevant literature for risk management, the sharing of state variables, and previous research. The literature and methodologies introduced here are discussed in a general scenario, with applications and extensions to UAS operations discussed in Section 0 below. The literature discussed here is organized into three sub-sections: risk assessment and management (Section 2.2.1), the concept of shared state variables in systems-of-systems (SoS) (Section 2.2.2), Multi-Objective Decision Tree analysis (Section 2.2.3), Event Tree analysis (Section 2.2.4), and previous research conducted in managing risks associated with UAS (Section 2.2.5).

2.2.1 Risk Assessment and Management

The three fundamental risk assessment questions, as characterized by Kaplan and Garrick, are as follows: (1) What can go wrong? (2) What is the likelihood? and (3) What are the consequences? (1981). Haimes also adds a fourth important question: What is the time domain? Identifying and organizing the risks and objectives of a system is a very important task to answer the first question, especially when multiple competing objectives are involved. Because many technological and organizational systems are hierarchical in nature, Haimes (2009) and Keeney and Raiffa (1993) suggest that risks and objectives be organized in a hierarchical fashion as well. Haimes states that the hierarchical framework of organizing risks makes it easier to evaluate how risks apply to subsystems and how they contribute to the overarching system (2009). This leads to the development of hierarchical holographic modeling (HHM) and risk filtering, ranking, and management (RFRM) for identifying the most important risk factors to a system (Haimes, Kaplan, & Lambert, 2002).

HHM is the first phase of the RFRM process, and is an important step in the risk assessment process. The purpose of constructing an HHM is to attempt to identify and organize all possible risks to a system based on multiple possible perspectives and aspects of the system. This approach is useful for identifying and structuring the potential risk scenarios, inputs, and outputs of a system, especially for developing models of large-scale hierarchical systems, which the NAS is a good example of.

The remaining phases of the RFRM process consist of evaluating risks against a variety of criteria, likelihoods, and consequences, and serve to filter the risks down to those most crucial to system performance. At the conclusion of the RFRM process, a reduced set of risks to the system remains, constituting a group of scenarios that should be evaluated further in the risk assessment and management process (Haimes, Kaplan, & Lambert, 2002).

To build upon the risk assessment process, Haimes developed a second set of three questions: (1) What can be done and what options are available? (2) What are the associated trade-offs in terms of all relevant costs, benefits, and risks? and (3) What are the impacts of current management decisions on future options? (2009). These risk management questions, especially the third one, when addressed to the extent possible, are crucial to making a well-informed managerial decision. A decision cannot be considered optimal unless both the negative and positive effects of current decisions on future options are evaluated.

2.2.2 State Variables in Modeling and Shared State Variables

This section addresses the centrality of state variables in system modeling and the concept of shared state variables in a SoS. Haimes explains that before a meaningful mathematical model of a system can be developed, the state variables associated with that system must first be identified (2012). Once the state space describing the system has been established, the model of the system can be manipulated through decision, random, and exogenous variables, and unique outputs can be determined. The modeling process becomes more interesting and difficult when two or more systems are considered which share interacting components. Furthermore, system models can not only describe physical systems, but also organizational and social systems, all of which can share interdependencies. These systems, when considered together, can be described as subsystems of a larger SoS.

No single definition of a SoS exists, but Sage and Cuppan (2001) offer the following five properties, originally developed by Maier (1998):

1. *Operational Independence of the Individual Systems*. A SoS is composed of systems that are independent and useful in their own right.
2. *Managerial Independence of the Systems*. The component systems not only can operate independently, they generally do operate independently to achieve an intended purpose.
3. *Geographic Distribution*. Geographic dispersion of component systems is often large, and the systems can readily only exchange information and knowledge with one another.
4. *Emergent Behavior*. The SoS performs functions and carries out purposes that do not reside in any component system.
5. *Evolutionary Development*. A SoS is never fully formed or complete. Development of these systems is evolutionary over time.

One aspect unique to systems-of-systems is the occurrence of emergent forced changes, which connotes internal and external sources of risk to a SoS that can only be detected through modeling intra- and inter-dependencies between and among subsystems (Haimes, 2012). The model of a single subsystem will not highlight these emergent forced changes, which can affect multiple states of multiple subsystems, and thus the larger system as a whole. Another important aspect of many systems-of-systems is the existence of multiple competing objectives and stakeholders.

Haimes develops the idea of Phantom Systems Models (PSM) to address these challenges of modeling complex systems-of-systems. PSMs are largely an extension of HHMs, but make use of meta-modeling coordination and integration, which utilizes knowledge of the coordination and interdependencies of states between different subsystems in order to better inform the effects of inputs and outputs on various subsystems. The key idea is to build one or more representative models of the SoS under consideration using all possible direct and indirect sources of information. If a sub-model connotes a model of any particular subsystem, the meta-model represents the aggregation and integration of all available sub-models, as shown in Figure 1 (Haimes, 2012).

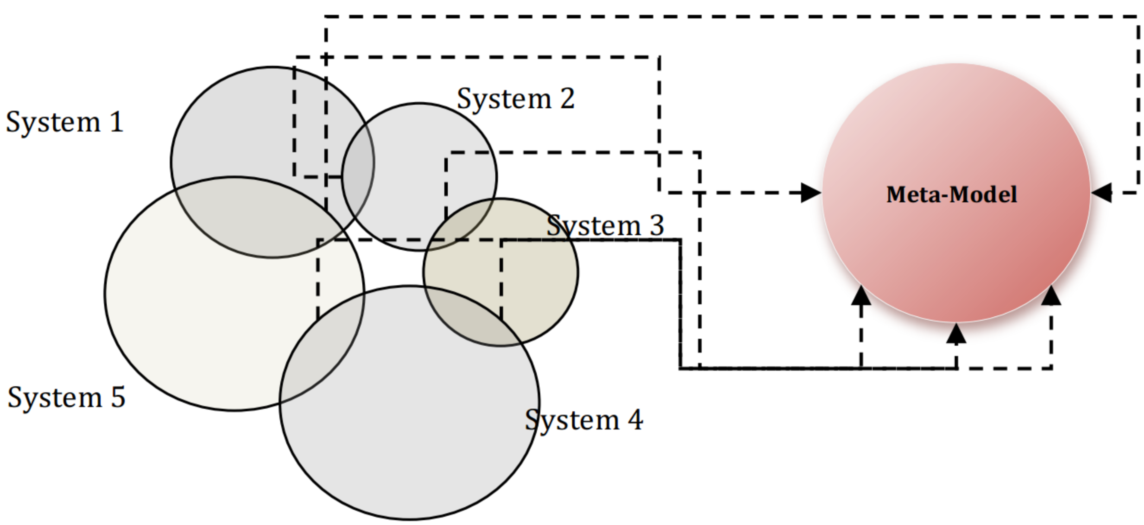

Figure 1. Sub-Model Coordination and Integration via System State Variables

Haimes continues that everything critical about any subsystem can be represented by a finite number of essential state variables. If two subsystems are part of the same

SoS, and if the system is defined properly, then they intrinsically must share at least one essential state variable and objective. Exploring how these shared state variables are affected through the variation of inputs to multiple subsystems leads to an increased understanding of the interdependencies associated with these subsystems and allows system managers to foresee potential emergent forced changes (Haimes, 2012). This is particularly useful when more data exists to describe one subsystem over another, and allows the modeler to make extra use of this data in ways that did not previously seem feasible.

2.2.3 Multi-Objective Decision-Tree Analysis

Decision-tree analysis is a useful tool in decision-making processes and can be employed in a variety of situations. Traditionally, decision trees have dealt with optimizing a single objective function, which in most real-world cases does not represent the true goal of the analyst or the decisionmaker; multi-objective decision trees (MODT) are an extension of these decision trees that simultaneously allow the optimization of multiple, noncommensurate objectives (Haimes, 2009). The results from an MODT analysis present the decisionmaker with a Pareto-optimal frontier of decision paths over time.

Decision trees consist of decision nodes, usually portrayed as squares, and chance nodes, portrayed as circles, as shown in Figure 2 (Haimes, 2009). At a decision node, several branches emanate towards the right, each representing one action a_i the decisionmaker can make from a finite set of alternatives $\{a_1, a_2, \dots, a_m\}$. Each set of alternatives is also labeled with a superscript $\{0,1,\dots,n\}$ representing the stage in the decision tree at which the decision can be made. Thus, the set of alternatives available at the first decision node are labeled $\{a_1^0, a_2^0, \dots, a_m^0\}$. At each subsequent stage of the decision tree, the superscript is incremented by one. Each branch leads to another decision node, a chance node, or a terminal point. Terminal points represent the end of the decision-making process along a path (Haimes, 2009).

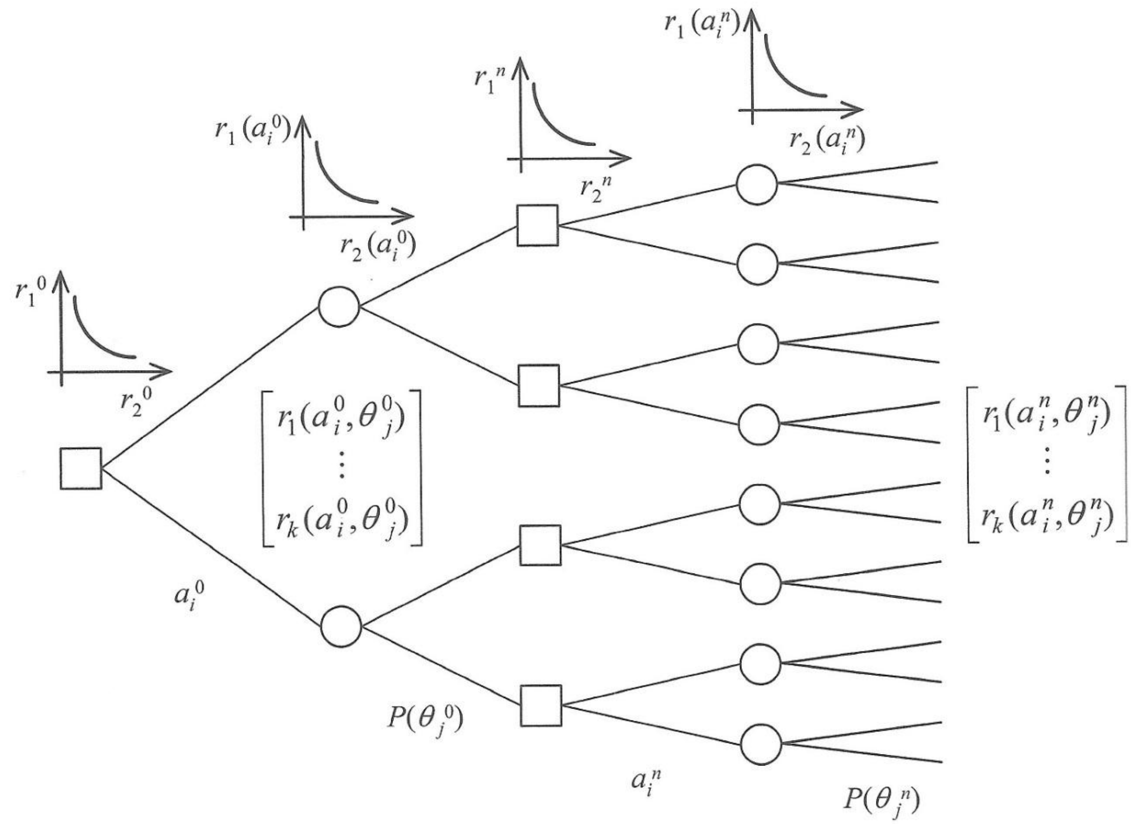

Figure 2. Structure of MODT

At a chance node, an event θ_j occurs that is outside the decisionmaker's control. This event can be discrete or continuous in nature, and branches representing the different possibilities of this event emanate towards the right. Once again, a superscript is added to each event label to denote at which stage in the decision tree the event can occur at. The discrete probabilities $P(\theta_j)$ of an event state occurring are written alongside the branch representing that event state, or a probability density function can be used. After a chance node, each branch leads to a decision node, another chance node, or a terminal point (Haimes, 2009).

At each terminal point, a vector $\left(a_i^n, \theta_j^n\right)$ associated with alternative a_i and state of nature θ_j in period n is calculated, representing the measured performance objectives $\{r_1, r_2, \dots, r_k\}$:

$$r\left(a_i^n, \theta_j^n\right) = \left[r_1\left(a_i^n, \theta_j^n\right), r_2\left(a_i^n, \theta_j^n\right), \dots, r_k\left(a_i^n, \theta_j^n\right)\right]'$$

This can be done by either directly assigning values for the objectives to the entire path that culminates at that terminal point, or by evaluating the objectives along each branch, starting at $r\left(a_i^0, \theta_j^0\right)$, and sequentially combining them at the terminal point using an appropriate operator for each objective (Haimes, 2009).

Once all terminal points are populated with objective vectors, the MODT can be folded back towards the initial decision node in order to find the set of noninferior decision paths. This is done by starting at the right side of the tree, and evaluating the vector of expected value (or some other "risk" measure) of the performance objectives at each chance node, using the probabilities assigned to the chance nodes' branches. For example, assume that one decision branch in the final stage of the decision tree leads to a chance node *C1*, with two states of nature of probabilities 0.7 and 0.3, producing objective values as indicated in Figure 3.

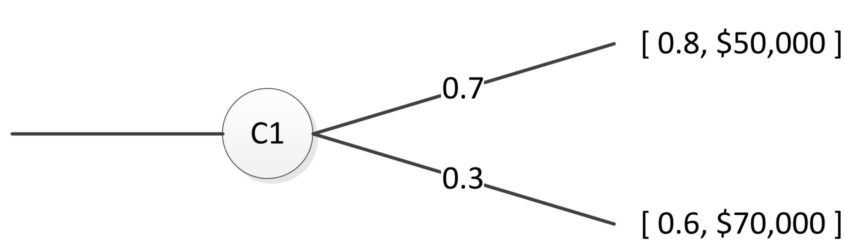

Figure 3. Averaging out at Chance Node C1

In this simple case, the expected value at chance node *C1* would be calculated as follows:

$$r = \begin{bmatrix} (0.7 \times 0.8) + (0.3 \times 0.6) \\ (0.7 \times \$50{,}000) + (0.3 \times \$70{,}000) \end{bmatrix} = \begin{bmatrix} 0.74 \\ \$56{,}000 \end{bmatrix}$$

If a decision node leads to multiple chance nodes, one of which performs worse in every objective than another chance node, then this decision is dominated and should not be regarded by the decisionmaker. If, for example, decision node *D4* leads to chance nodes *C1* and *C2* with the objective values shown in Figure 4, then *Choice 1* is dominated for every objective by *Choice 2* (assuming minimization of both objectives).

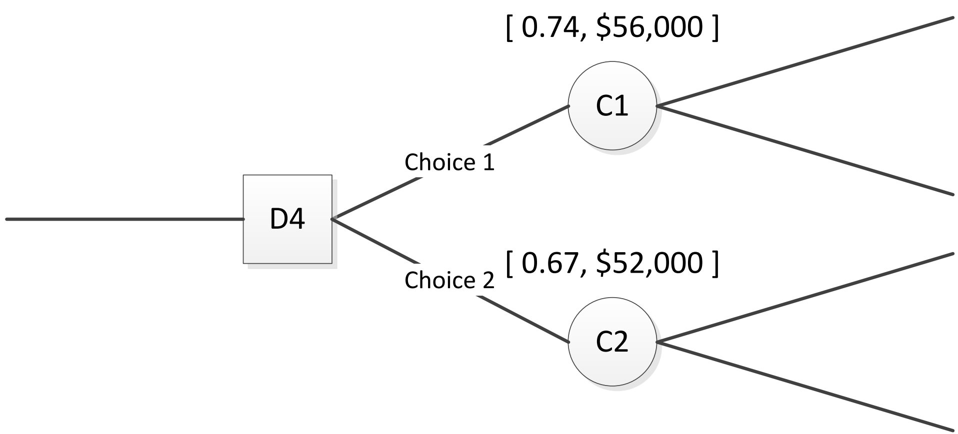

Figure 4. Comparing Objective Values

Note that each decision node can be associated with more than one noninferior solution vector, and thus it may be possible that more than one decision branch remains as a viable choice during the folding-back process. This process is continued until the initial decision node is reached, at which point the decisionmaker is left with a set of Pareto-optimal decision paths for any type of chance event that is considered in the MODT (Haimes, 2009).

Once all these Pareto-optimal decision paths are identified, the decisionmaker can weigh the trade-offs in the decision space. For example, if the two objectives are to minimize risk and minimize cost, the Pareto-optimal decision space may look like the one depicted in Figure 5. In this example, there are seven decision paths that are not dominated in both objectives by another decision path, represented by the seven points along the Pareto-optimal frontier line shown.

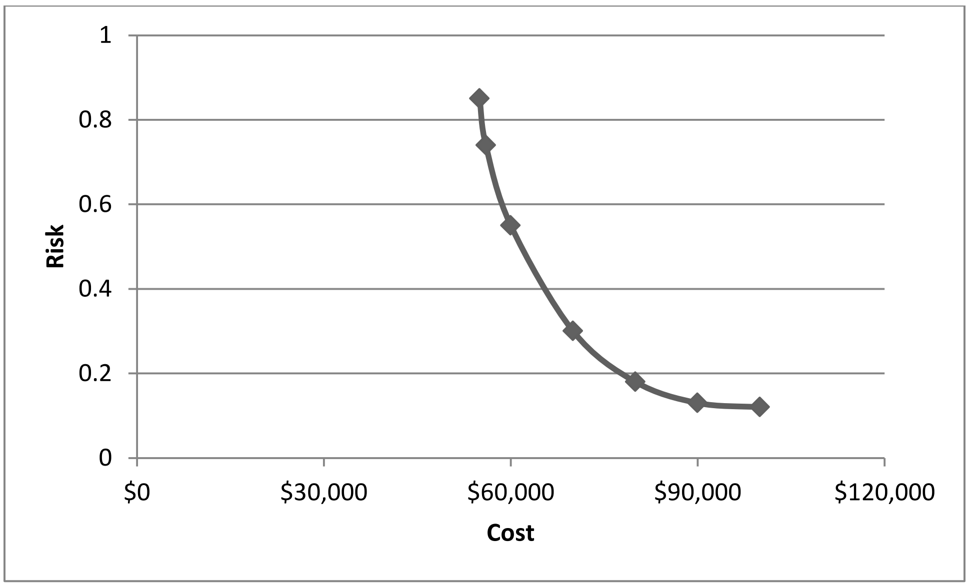

Figure 5. Pareto-Optimal Decision Space

2.2.4 Event Tree Analysis

Event trees differ from decision trees in that there is no element of human control involved. Instead, typical event trees begin with some kind of initiating event *I*, often a system failure or disruption, and further events pertaining to the initiating event are assessed in sequential order. Subsequent events are usually related to the safety systems in place to mitigate the initiating event, and consist of at least two states (success *S* and failure *F*), though more states can exist (e.g., partial success or partial failure). The initiating event is represented by a horizontal line, and each state of a subsequent event is represented by a branching of this line towards the right, as depicted in Figure 6 (McCormick, 1981).

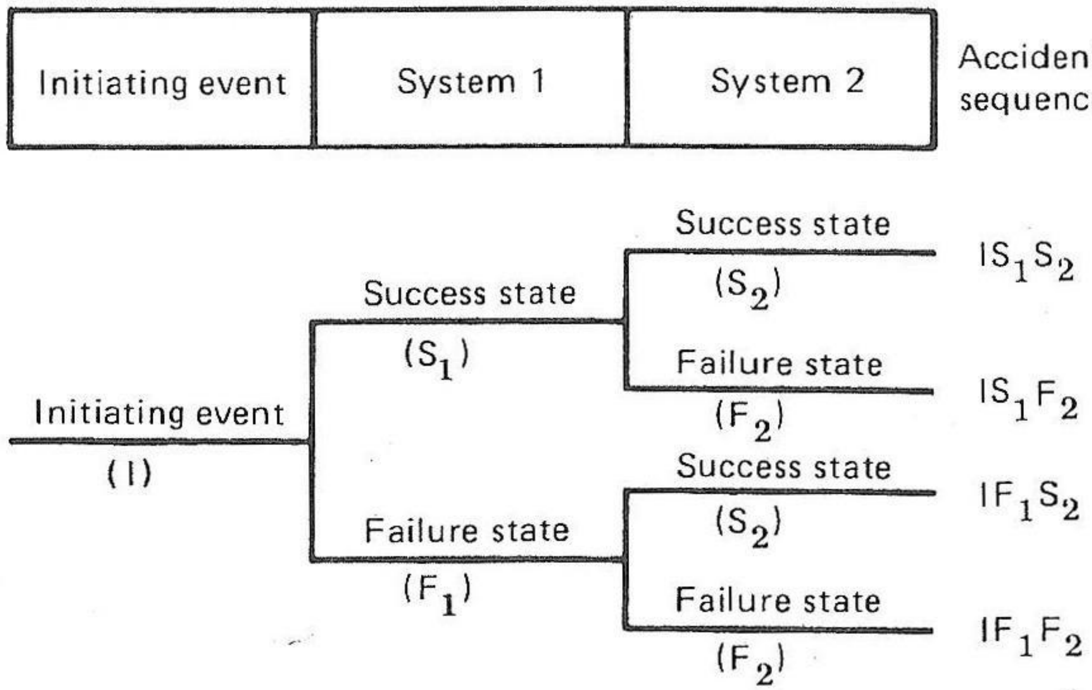

Figure 6. Event Tree Branching

This process is continued until all pertinent systems' states are enumerated—in the case of safety systems, this refers to all existing states of the systems in place to mitigate the initiating event. In the above example, two safety systems exist, each with a success and failure state, for a total of four event sequences. At every stage in the event tree, a probability $P(state)$ is assigned to each branch, in which all states connected to a previous branch must add up to one (McCormick, 1981). This gives us three equations for this example:

Under the *System 1* heading: $P(S_1|I) + P(F_1|I) = 1$
Under the *System 2* heading: $P(S_2|S_1) + P(F_2|S_1) = 1$
$P(S_2|F_1) + P(F_2|F_1) = 1$

It is important to note that each state must be defined on the condition that the initiating event and any previous system states along that branch have already occurred, or in other words, that the states on a certain branch are not independent of previous branches. This means that the probabilities of the two S_2 success states in the above example must not necessarily be equal (McCormick, 1981).

The total probability associated with each event sequence is then calculated by multiplying the probabilities along the branches leading to that outcome (McCormick, 1981). For this example, the four accident sequences shown would have the following probabilities:

$$P(Sequence\ IS_1S_2) = P(S_2|S_1) \times P(S_1|I) \times P(I)$$
$$P(Sequence\ IS_1F_2) = P(F_2|S_1) \times P(S_1|I) \times P(I)$$
$$P(Sequence\ IF_1S_2) = P(S_2|F_1) \times P(F_1|I) \times P(I)$$
$$P(Sequence\ IF_1F_2) = P(F_2|F_1) \times P(F_1|I) \times P(I)$$

An event tree analysis such as this can be used to determine which safety systems need to be made more resilient by improving their reliability or increasing redundancy.

2.2.5 Previous Research on UAS Risks

Several researchers of UAS have noted the importance of treating UAS separately from conventional human-controlled aircraft when evaluating risks associated with them. Clothier, et al., explains that safety regulators cannot simply adapt an existing human-piloted risk management framework to UAS operations, since UAS exhibit several unique aspects that must be considered. These include differences in technology (communication links, automation), performance and capability, and human-machine interfacing (2007). The two major categories of risk involved with UAS are mid-air collisions and ground collisions (Weibel & Hansman, 2005). Despite the differences in technology between unmanned and manned aerial vehicles, the majority of today's mid-air collisions occur in clear daylight, which points to human failings to see and avoid other aircraft as a major contribution (DeGarmo, 2004). Since human elements are integral to both manned and unmanned operations, and are a major source of risk in both cases, it is not infeasible to inform these sorts of risks of UAS from manned operations. There are also issues unique to UAS, such as flying in patterns or tracking an object as opposed to point-to-point operations, and a vehicle's sense of situational awareness, that can still benefit from studies of manned aerial operations although there do not exist direct counterparts to them (DeGarmo & Nelson, 2004).

3 Technical Approach

This section outlines the technical approach to accomplishing the goals listed in Section 1.2. Section 3.1 discusses shared states within NextGen and the NAS, the challenges of the 90 strategy decisions the FAA has to make to standardize the procedures and infrastructure of NextGen, and the development of the Modified MODT (M-MODT) to deal with these challenges. Section 3.2 discusses the shared states within UAS operations, and the sources of risk associated with transitioning from UAS accommodation to integration into the airspace.

3.1 Shared States in NextGen and NAS

In order to tractably examine the state space of the NAS, the system-of-systems is first divided into several overarching subsystems: a single airport, the airspace, and a single flight operation. These subsystems are then further divided into five headtopics, each constituting one of the four objectives of NextGen (*safety, efficiency, capacity*, and the *environment*), and the fifth for UAS integration into the airspace. For each subsystem, two tables are populated, one with the NAS state variables affecting that subsystem, the other with inputs, constraints, and decisions affecting that subsystem. Table 1 and Table 2 show the states and inputs, respectively, for the airspace subsystem. In these tables, some states (# 4, 6, 15, 17, 19-22) and inputs (c, e, g, h, l, m) are not present since they are not part of the airspace subsystem, but they exist in, and are shared between, other subsystems. States and inputs for the other subsystems, and an overarching one for NextGen can be found in Appendix A: NextGen States and Inputs.

Table 1. Airspace (FAA) State Variables

Efficiency	Safety	UAS Mission	Capacity	Environment
1. Technological Capabilities	1. Technological Capabilities	1. Technological Capabilities	1. Technological Capabilities	
2. Corridor Spacing			2. Corridor Spacing	
3. Personnel Quality	3. Personnel Quality	3. Personnel Quality	3. Personnel Quality	
5. Situational Awareness	5. Situational Awareness	5. Situational Awareness		
7. Culture	7. Culture	7. Culture	7. Culture	
8. Budget			8. Budget	
9. Reliability (6 Sigma)	9. Reliability (6 Sigma)	9. Reliability (6 Sigma)	9. Reliability (6 Sigma)	9. Reliability (6 Sigma)
10. Trust	10. Trust	10. Trust	10. Trust	
11. Standardization		11. Standardization		
12. Congestion	12. Congestion			
13. Routing Flexibility				
14. Flight Path Flexibility		14. Flight Path Flexibility		
16. Personnel Scheduling	16. Personnel Scheduling	16. Personnel Scheduling	16. Personnel Scheduling	
	18. Digital/Voice Comm.	18. Digital/Voice Comm.	18. Digital/Voice Comm.	
				23. Fuel Usage

Table 2. Airspace (FAA) Inputs/Constraints/Decisions

Efficiency	Safety	UAS Mission	Capacity	Environment
a. New Technology	a. New Technology	a. New Technology		
b. Flight Path		b. Flight Path	b. Flight Path	b. Flight Path
d. Collaboration		d. Collaboration		
f. Training	f. Training	f. Training	f. Training	
i. Policies & Procedures	i. Policies & Procedures	i. Policies & Procedures	i. Policies & Procedures	i. Policies & Procedures
j. Number of Airplanes		j. Number of Airplanes		
k. Schedule		k. Schedule	k. Schedule	
		n. Airspace Accessibility		
o. Demand		o. Demand	o. Demand	

3.1.1 The Significance of Shared States

The states and inputs in Table 1 and Table 2 represent potential sources of risk to NextGen and the NAS, and the more times each state or input shows up, both within each subsystem and across subsystems, the higher this risk is permeated throughout the SoS. These tables were used to identify the states which pose the greatest source of risk to NextGen. To demonstrate the significance of the shared states in the context of this project, this section will discuss the state and input variables that were found to be most important in the risk analysis process, through examining these tables and input from subject matter experts (SMEs) at The MITRE Corporation (MITRE). The full list of state and input definitions can be found in Appendix B: NextGen State and Input Definitions.

The first state, *technological capabilities*, is understandably present throughout the majority of the NAS system. This state represents the ability to deliver capability-based services for flights and airport operations, and is affected most notably by the *new technology* input, which represents the delta in the technological capabilities between two points in time. The *technological capabilities* state can be broken down to a more specific definition depending on the NAS subsystem in question. For example, in the M-MODT for surface operations in the FAA strategy decision space discussed later in Section 3.1.4, the state refers to the ability and accuracy of delivering moving surface maps of ground vehicles to remote locations. Each decision alternative discussed in that example provides a different *new technology* delta. This capability, in turn, determines the level of performance objectives that can be achieved by the alternatives, such as percent surface visibility and excess taxi time.

The second state, *personnel quality*, represents the proficiency and consistency in delivering expected services and performing tasks. This state is most affected by the *collaboration* input, joint decision-making in real-time resource contention resolution, and *training*, improvements to personnel quality. The *personnel quality* state refers to the total quality of service delivery, and may thus be improved or worsened by changing the total number of personnel responsible for a task. Aside from affecting the efficiency of nearly all operations in the NAS, the *personnel quality* is also important when making decisions that determine the role of personnel or when introducing new technologies. In the surface operations M-MODT, some alternatives would require air traffic control staff to be trained to use new technologies and make decisions based on their understanding of these technologies. The training would have an effect on both the implementation time of the alternative and on the safety and efficiency that could be achieved by the alternative.

The third state, *reliability*, represents the service delivery process and Minimum Equipage List designed defect rates. The state is most affected by *standards* input and by the technology available. This state is especially important when introducing new technologies, or mandating operators to equip a set of technologies, to make sure that they work as expected in the vast majority of cases and have appropriate redundancies and fail safes in place when they do not work as expected. Since the NextGen project aims to redefine the airspace and the way flight operations are handled, largely through the introduction of new technologies, this state permeates throughout every aspect of the NAS. For surface operations, *reliability* largely refers to the combined accuracy of the surface moving maps, and to the cockpit services designed for low-visibility operations.

The fourth state, *route flexibility*, represents the options available to air traffic managers to resolve congestion. This state is affected by a number of inputs, such as *new technology*, *routing/flight path*, *airspace accessibility*, which refers to the level of services available to less-equipped operations, and *demand*, the mixture of fleet and types of operations required. The *route flexibility* has a large impact on the both the total number of aircraft that the NAS can support at a time and on the resources lost by planes being stuck in long holding patterns and ground delays. With greater route flexibility, controllers could better optimize the runway use so as to minimize these adverse effects. For surface operations, the state mostly serves as a constraint to the maximum taxi efficiency that can be achieved by an alternative.

Worth mentioning are also the two most critical inputs, *budget* and *policies and procedures*. *Budget* is especially important to the NextGen project because it provides a limit on the level of technologies that can be introduced, and thus resources have to be allocated carefully so that the performance goals can still be achieved within this limit. This is one of the main reasons for the M-MODT approach for the FAA strategy decisions that will be discussed later, so that resources are not wasted on an alternative that will cause implementation delays and budget overruns later on. The *policies and procedures* input deals with the rules and regulations of services provided, which must be considered carefully in a project like NextGen where these regulations are changed over time with the introduction of new technologies and the changing of procedures as decisions are implemented.

3.1.2 FAA's 90 Strategy Decisions

The FAA is faced with making a large number of strategy decisions over the next few months and years, dubbed the "90 decisions," that will establish standardized protocols, procedures, infrastructure, and technological capabilities of NextGen. Because a number of these decisions will impact the same subsystems of the NAS, and will take effect at different times during the NextGen overhaul, it is important that these decisions be made in an order that does not cause problems down the line or overly constrain the solution space of future decisions. It may be the case that the majority of these strategy decisions are trivial and do not have a large impact on other decisions, but if the small number of high-impact decisions are not made carefully, it could mean large budget overruns and project delays over the next decade.

The analysis of the NextGen system-of-systems through the use of subsystems was critical in uncovering the most important states that are shared throughout the system, and thus pose the greatest potential risk to the system as a whole, as explained in Section 3.1.1. These states are used to help identify the smaller set of high-impact decisions that could most constrain the future solution space of NextGen over a period of time.

Moreover, by its nature, risk analysis addresses future probabilistic events with adverse consequences. Any approach employed to deal with this problem must be able to incorporate uncertainty into the decision-making process, not only because many of the strategy decisions will have impacts that take several years to fully materialize, but also because of the potential that some decisions have to alter the design space of NextGen, as explained above.

3.1.2.1 90 Decision Impact on Shared States

The first step to organizing the strategy decisions so that a systematic approach can be used to assess them is to cluster the decisions into groups based on the major infrastructure subsystem that they affect. There were 18 major subsystems identified in this process:

Air Traffic Operations Facility	Flight Data Management	Safety Ops Approval and Certification
Airport Surface Guidance	Flight Plan Support	Surface Separation
Airspace Management	Government/Agency Support	Surface Traffic Management
En Route Advisory – Weather	Monitoring and Maintenance	Tactical Management of Flow in the En Route for Arrivals/Departures
En Route Navigation	Oceanic Separation	Terminal Advisory – Weather
En Route Separation	Precision Approach, Landing and Departure	Terminal Separation

At this point, every decision is rated on the likely impact that it will have on each of six critical states that are shared between numerous subsystems of NextGen and the NAS, discussed in detail in Section 3.1.1. These states include *technology*, *personnel*, *reliability*, *route flexibility*, *procedures*, and *budget*. The states were identified as potential sources of risk in a relatively high number of NAS subsystems, and thus must be considered when evaluating any strategy decision. The possible ratings for each state are *low*, *high*, or *very high*, and the rubric to make these assessments can be found in Appendix C: Strategy Decision State Impact Rubric.

Using these ratings, a number of decisions can be identified in each subsystem that have potentially high adverse consequences if they are not examined in detail. More specifically, some decisions have the ability to constrain the solution space for future infrastructure and equipage options that may cost stakeholders a lot of time and money in the long run. For example, choosing an alternative of one decision that increases a performance objective by a small amount at a low cost, may force the use of a much more expensive alternative of another decision to increase that performance objective to an acceptable level. In order to evaluate high-risk decisions that depend on a certain decision-making sequence, a Modified MODT approach will be developed in Section

3.1.3. For the airport surface operations subsystem, three decisions were identified as high-risk candidates, and these decisions will be evaluated using the M-MODT approach in Section 3.1.4.

3.1.2.2 Needs and Challenges of Proper Data Collection

It is important to know what to look for when evaluating possible decisions. For example, assessing the impact of Decision A on a new infrastructure system B would mean examining the impact on any or all of the requirements, specifications, design, prototyping, and ultimately construction of System B. Thus, ideally, input would be gathered from everyone involved in the planning and implementation of System B, as well as from managers and systems architects who know how System B will impact and interact with the rest of the airspace. Since an elaborate data collection effort like this is usually not feasible in a timely manner, it is often necessary to rely on the inputs of a smaller set of SMEs to estimate the likely effects of a decision on a subsystem and on a larger system-of-systems. The contributions of MITRE's experts and inputs from the FAA team are imperative for populating the proposed roadmap and for its ultimate effectiveness and use by the FAA. What must be remembered, though, is that the cost of such an elaborate modeling effort is likely to constitute an insignificant fraction of the likely adverse consequences to the entire NextGen project resulting from wrong or misguided decisions uncovered by not performing such modeling and analyses.

Another important challenge is to develop appropriate metrics with which to evaluate the collected data and define success of the subsystem in question and the NAS system-of-systems. The efforts made in identifying shared states, inputs, and decisions associated with the objectives of NextGen and within its subsystems are a crucial step in developing these metrics.

3.1.3 Modified MODT Analysis

In order to address the challenge of assessing the 90 NextGen strategy decisions, a Modified MODT approach was developed which combines useful aspects of both MODTs and event trees. The main difference between the MODT and the M-MODT developed here is that the primary objective is not to find the Pareto-optimal decision-making sequence(s), but to assess each path in the tree for the purpose of discovering potential precursors to poor strategy choices over time. In effect, the M-MODT allows the analyst to trace the effects of current strategy decisions on future options, and to discover potential adverse consequences arising from the interactions between these decisions over time.

Assume that there exist three decisions in a set of interdependent strategy decisions, labeled A, B, C. The M-MODT begins with an initial decision node, such as Decision A, which represents making Decision A first. Emanating from this decision node are a set of branches, one for each alternative of Decision A, labeled $\{A_1, A_2, \ldots\}$. Each alternative branch is split into two additional branches that culminate in decision nodes, one for each of the remaining decisions B and C.

At these decision nodes, a branch emanates for each alternative of that decision, labeled $\{B_1, B_2, \ldots\}$, and $\{C_1, C_2, \ldots\}$. Each of these Alternative branches is finally split into four additional branches, which culminate in chance nodes that represent the effect of a particular alternative of Decision A on one of the four particular performance objective of another decision:

- Implementation schedule
- Cost/budget
- Safety objective
- Efficiency objective

For example, the branch denoted by {[A] → A_1 → [B] → B_2 → (Safety)} represents the effect of Decision A's first alternative on the safety objective of Decision B's second alternative. At this point, the following question is asked:

"In a reasonable worst-case scenario, to what degree will Alternative A1 adversely affect Alternative B2 in achieving the safety objective of the system?"

This assessment is made by eliciting expert knowledge on the interdependencies and relationships between the decisions in question. This *safety* chance node is labeled with the result of the assessment, either with a calculated numeric metric or with rank such as *high, medium,* or *low*, depending on the data available. This chance node then leads to another decision node for Decision C, the only decision left after A and B.

This process is repeated for the other three performance objectives, and for the other decision and alternative branches, until all alternatives and performance objectives are assessed. An expanded view of the upper part of this M-MODT is shown in Figure 7, with dotted lines and darkly shaded nodes indicating the undeveloped parts of the tree. For clarity purposes in the notation, the alternative set $\{a_1^k, a_2^k, a_3^k, \dots, a_9^k\}$ established in the MODT background Section 2.2.3 has been replaced with $\{A_1^k, A_2^k, A_3^k, B_1^k, B_2^k, B_3^k, C_1^k, C_2^k, C_3^k\}$ in the figures, where $k = \{0,1,2\}$ indicates the time period that the decision is made in.

In order to keep this approach from becoming too overwhelming and intractable, the only paths fully assessed in the "first cut" of the methodology are ones that rank *high* for potential adverse consequences during each stage. Any paths in the M-MODT that contain only *high* branches should be regarded as "critical paths" or "red flags," and should be avoided before further analysis can be conducted, as depicted in the truncated

M-MODT shown in Figure 8. In this figure, paths that rank *low* or *medium* lead to empty decision nodes, indicating that the path will not be further assessed here.

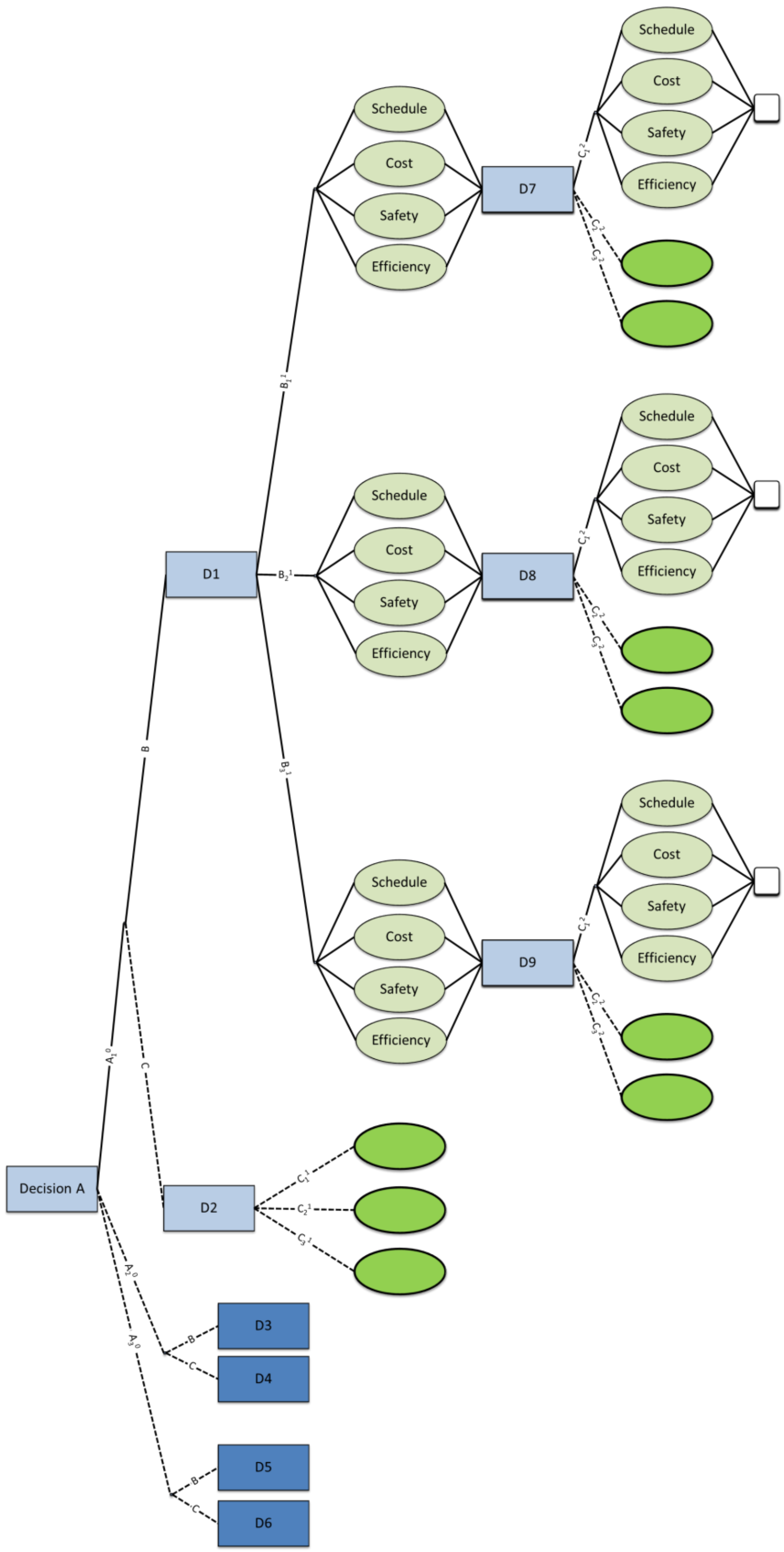

Figure 7. Expanded M-MODT Example

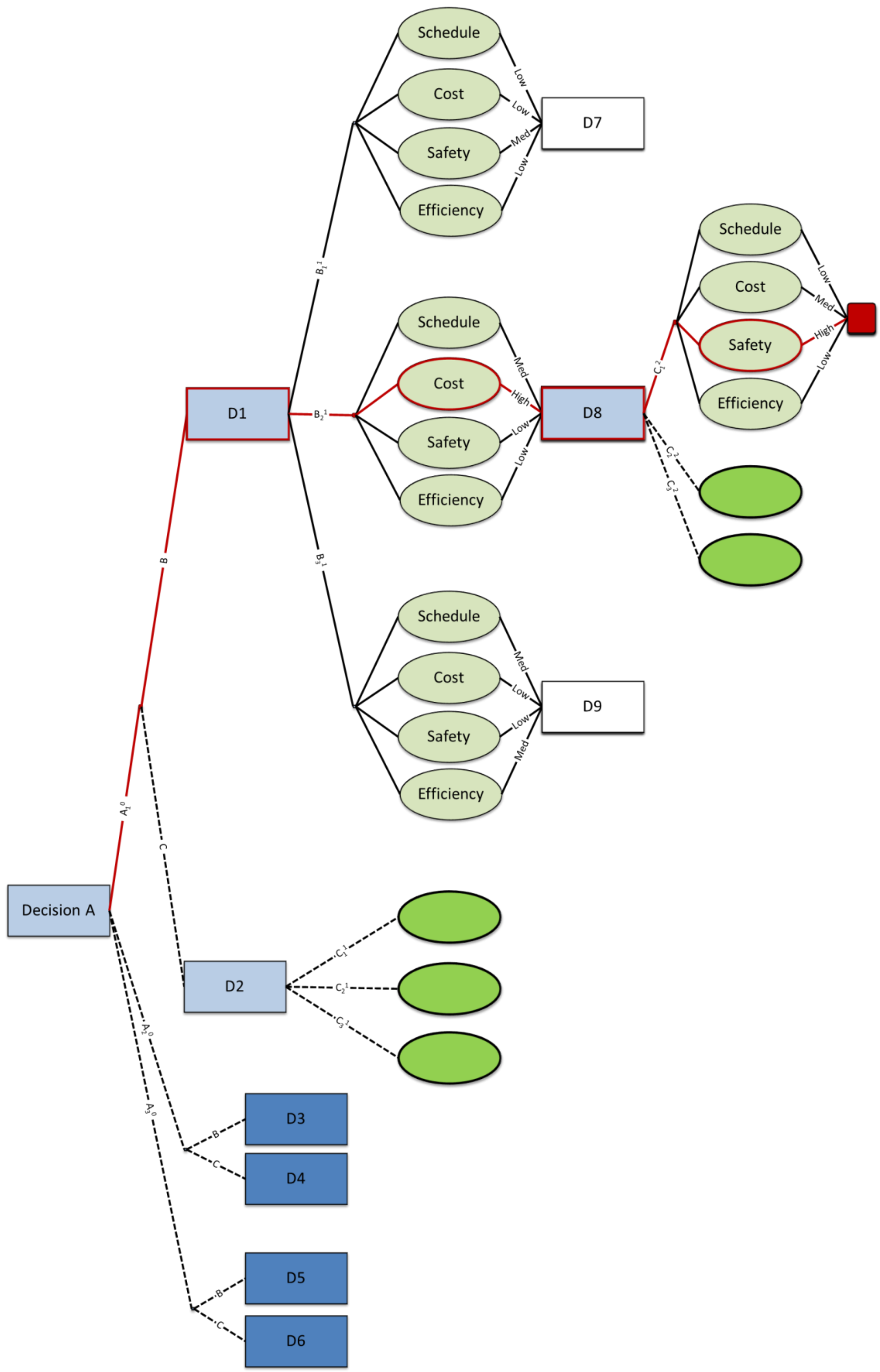

Figure 8. Truncated M-MODT Example

Once the M-MODT is completed starting with Decision A, the approach is repeated starting with one of the other interdependent decisions, through all permutations of decision sequences, and with respect to the four objectives at each stage.

This M-MODT approach constitutes a roadmap with which to navigate through the combinatorial problem faced in assessing the impacts of one decision in one time period on all other current and future decisions. This roadmap is a flexible process that allows a decisionmaker to more easily examine a problem like this with multiple objectives in mind, without being overwhelmed by the total number of choices available.

3.1.4 M-MODT Case Study for NextGen Strategy Decisions

As a case study, a subset of the 90 NextGen strategy decisions will be examined using the M-MODT. This subset consists of decisions related to surface operations, and will influence the nature of future surface surveillance and air traffic control decision support tools. There are three pairs of decisions that will shape the architectural alternative space of the airport surface capabilities subsystem, and thus each decision may impose constraints on the feasibility of future decisions affecting this subsystem. The three decision pairs are as follows:

A. (i) Business continuity services concept [691], (ii) Strategy for integration of certain ACTC functions [692]
B. (i) Policy for beacon/transponders [598], (ii) Surface moving maps [599] in airport surface vehicles
C. (i) Enhanced low visibility operations [792], (ii) Cockpit surface navigation [243]

The numbers in brackets are the decision numbers from the FAA Enterprise Architecture (FAA, 2012).

3.1.4.1 Strategy Decisions and Alternatives

In order to evaluate the alternatives, the state space of each alternative is defined in terms of its inputs and the effect on critical subsystem shared states and outputs. Inputs for each alternative are characterized by a combination of

(i) *technology,*
(ii) *information,*
(iii) *policy,*
(iv) *procedures,* and
(v) *airport surface.*

Similarly, the critical states and outputs are characterized by a combination of

(i) *safety,*
(ii) *efficiency,*
(iii) *capacity,*
(iv) *trust,*
(v) *budget*, and
(vi) *degraded modes* in case of a failure due to a catastrophic event.

Each of the three decisions has three potential goal alternatives, which are summarized below, and a full list of inputs and outputs can be found in Appendix D: Surface Decisions Inputs and Outputs, provided by Andy Anderegg at MITRE.

Decision A addresses the implementation of a remote air traffic control tower. The first alternative (A_1) focuses on maximizing resilience in case of the catastrophic loss of an air traffic control tower by employing a backup facility. The second alternative (A_2) focuses on cost efficiency and budget savings by manning fewer low-traffic volume towers with dedicated staff. The third alternative (A_3) focuses on safety and capacity at one-in/one-out airports by providing a remote controller with a surface view of the airport.

Decision B addresses the instrumenting of surface vehicles for remote surveillance. The first alternative (B_1) focuses on optimizing for taxiing efficiency by calculating the most efficient taxi paths that include the movement of ground vehicles. The second alternative (B_2) focuses on optimizing for taxiing safety by calculating taxi routes with large separation between vehicles and increased driver responsibility. The third alternative (B_3) focuses on ground vehicle movement with ATC guidance.

Decision C addresses conducting low-visibility operations from the cockpit. The first alternative (C_1) focuses on efficiency by maximizing the arrival and departure capacity and allowing pilots to continue visual spacing in more conditions. The second alternative (C_2) focuses on arrival and departure safety by increasing the responsibility of ground vehicle drivers for visual separation. The third alternative (C_3) is to not approve low-visibility operations with cockpit assistance.

3.1.4.2 Decision Criteria

By examining the outputs of each alternative, its effect on a set of four decision criteria can be deduced, not only for that strategy decision but also for future strategy decisions. These decision criteria are as follows, with their respective metrics:

1. Implementation time or uptake rate (years)
2. Lifecycle cost and budget impact ($ millions)
3. Safety (% surface visibility)
4. Efficiency (% excess taxi time)

The first criterion—implementation time or uptake rate—is differentiated by whether or not a decision affects the public or private sector. In the public sector, implementation time refers to the time it takes for the responsible organization (most likely the FAA) to implement a decision. In the private sector, uptake rate refers to the time it takes companies, such as airlines, to implement a new policy or standard in their equipment or operations. This criterion measures the impact that one decision has on the scheduling of another decision, and will especially be dependent on whether or not two decisions can be implemented in parallel.

The second criterion—cost and budget—measures the impact that one decision has on the lifecycle cost or the allocated project budget of another decision. It is possible, for example, that a high-cost decision may make the implementation of another high-cost decision infeasible, due to budget constraints. This criterion should be viewed in the context of the budget allocation for the entire subsystem, in this case surface operations.

The third and fourth criteria—safety and efficiency—indicate the performance measures of the surface operations decisions. They are used to evaluate what percentage of the safety and efficiency goals are met by each decision, and the likelihood that a sequence of decisions meets the specified total performance goals. Safety of the surface operations subsystem is measured in terms of the percentage of moving surface vehicle visibility by an air traffic controller, whether it is visually or remotely. Efficiency is measured by the percentage of excess runway taxi time due to inefficient ground vehicle management.

3.1.4.3 Constructing the M-MODT

The data for the impacts of these decisions on each other was obtained from Andy Anderegg, and is rated in the format of *high*, *medium*, or *low* and whether the impact is positive or negative. To demonstrate the M-MODT methodology for surface operations, the following assumptions are made for simplicity:

1. For Decision A, only alternatives A_1 and A_2 are considered
2. For Decision B, only alternatives B_1 and B_3 are considered
3. For Decision C, only alternatives C_2 and C_3 are considered
4. Decision A will be made first, Decision B will be made second, and Decision C will be made last

The first step in the M-MODT is to evaluate the first-order effects of Alternatives A_1 and A_2 on Alternatives B_1 and B_3. To do this, the following question is asked:

"In a reasonable worst-case scenario, to what degree would Alternative A_1/A_2 affect the *schedule/cost/safety/efficiency* goal of the surface operations subsystem, when choosing Alternative B_1/B_3?"

The assessment of this question is summarized in Table 3 below, with blank cells signifying a low or insignificant impact:

Table 3. Surface Operations Decision A First-Order Effects

First-Order Effects		**Implementation Time/Uptake Rate**	**Lifecycle Cost/Budget Impact**	**Safety**	**Efficiency**
		(Years)	(Millions $)	(% Surface Visibility)	(% Excess Taxi Time)
Impact of...	*on Decision...*				
A1 (backup tower)	B1		High -		Medium -
	B3	High -			
A2 (unmanned tower)	B1		High -		Medium -
	B3	High +	High -	High +	

Note that in the first box, the *cost* goal of Alternative B_1 ranks as *"high –,"* meaning that choosing Alternative B_1 after Alternative A_1 constitutes a high risk of not meeting the cost or budget goal of the surface subsystem. Similarly, the *schedule* goal of Alternative B_3 ranks as *high –,"* meaning that choosing Alternative B_3 after Alternative A_1 constitutes a high risk of not meeting the implementation time goal of the subsystem.

Some goals, on the other hand, have positive impact ratings, since the combination of alternatives would complement each other in that objectives. These are denoted by a *"+"* in conjunction with an impact rating instead of a *"–."*

At this point in the process, all rows without at least one *"high –"* would be discarded, but this is not the case in this example.

The second step is to evaluate the first-order effects of Alternatives B_1 and B_3 on Alternatives C_2 and C_3, as well as the second-order effects of the combination of Decisions A and B on Alternatives C_2 and C_3. The results of this step are summarized in Table 4 and Table 5 below:

Table 4. Surface Operations Decision B First-Order Effects

First-Order Effects		**Implementation Time/Uptake Rate**	**Lifecycle Cost/Budget Impact**	**Safety**	**Efficiency**
		(Years)	(Millions $)	(% Surface Visibility)	(% Excess Taxi Time)
Impact of…	*on Decision…*				
B1 (taxi moving map)	C2	High -			
	C3	High -		Medium -	
B3 (with ATC guidance)	C2	Medium +			
	C3	High -		Medium -	

Table 5. Surface Operations Second-Order Effects

Second-Order Effects		**Schedule**	**Cost/Budget**	**Safety**	**Efficiency**
		(Years)	(Millions $)	(% Surface Visibility)	(% Excess Taxi Time)
Impact of…	*on Decision…*				
A1 + B1	C2	Medium +			
	C3	Medium -			
A1 + B3	C2	Medium +			
	C3	Medium -			
A2 + B1	C2	High +			
	C3	Medium -			
A2 + B3	C2	High +			
	C3	Medium -			

Note that the *schedule* impact of Alternative B_1 on C_2 is "*high –,"* but that the second-order effect of Alternatives A_2 + B_1 on C_2 is "*high +."* This means that choosing Alternative C_2 after B_1 has a potentially high negative impact on the schedule goal if no other decisions are taken into account. But because the combined effect of Alternatives A_2 and B_1 has a high positive impact on Alternative C_2, the risk of a negative effect is effectively canceled out. Several paths in this example lead to outcomes that should be highlighted as “red flags,” and these decision paths should be reexamined or avoided, at least until they can be studied further. The results of this analysis are shown in Figure 9 and Figure 10, with positive impacts denoted by green lines and negative impacts denoted by red lines.

From the alternatives considered in this example, the decision paths which fall within acceptable range for the four decision criteria are the following:

- $A_1 \rightarrow B_3 \rightarrow C_2$
- $A_2 \rightarrow B_1 \rightarrow C_2$
- $A_2 \rightarrow B_3 \rightarrow C_2$

This case study constitutes eight of the possible 32 permutations of decision sequences if each decisions only had two alternatives. If all three alternatives for each decision were taken into account, the number of permutations would rise to 162. Out of the eight sequences that were evaluated, five of the sequences potentially fall outside the acceptable range of decision criteria. If any of these sequences are appealing, they can be examined more carefully. If more resources cannot be devoted to studying these scenarios further, these decisions sequences can simply be discarded, which constitutes a 62.5% reduction in viable decision sequences.

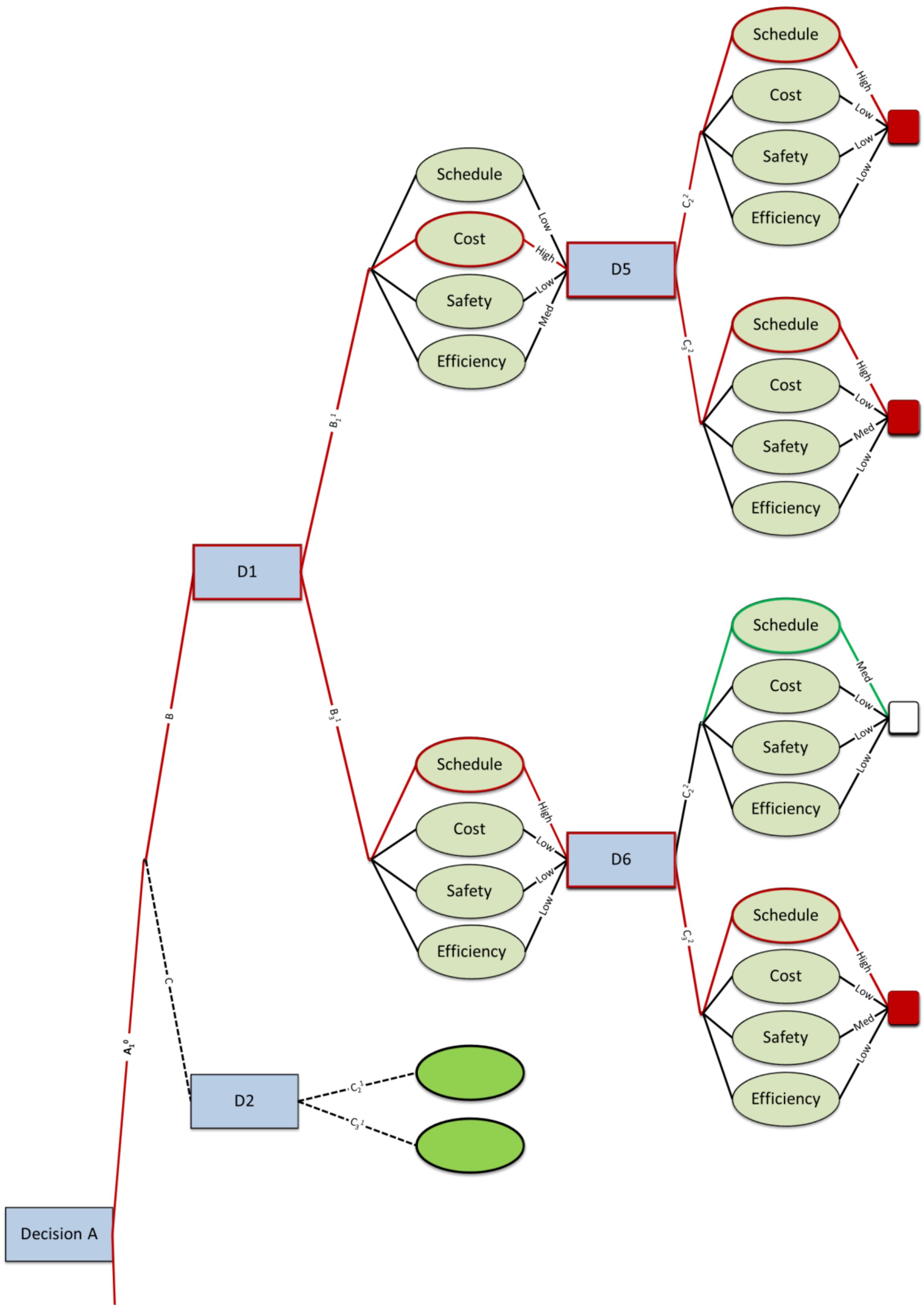

Figure 9. Surface Operations M-MODT – Branch A_1

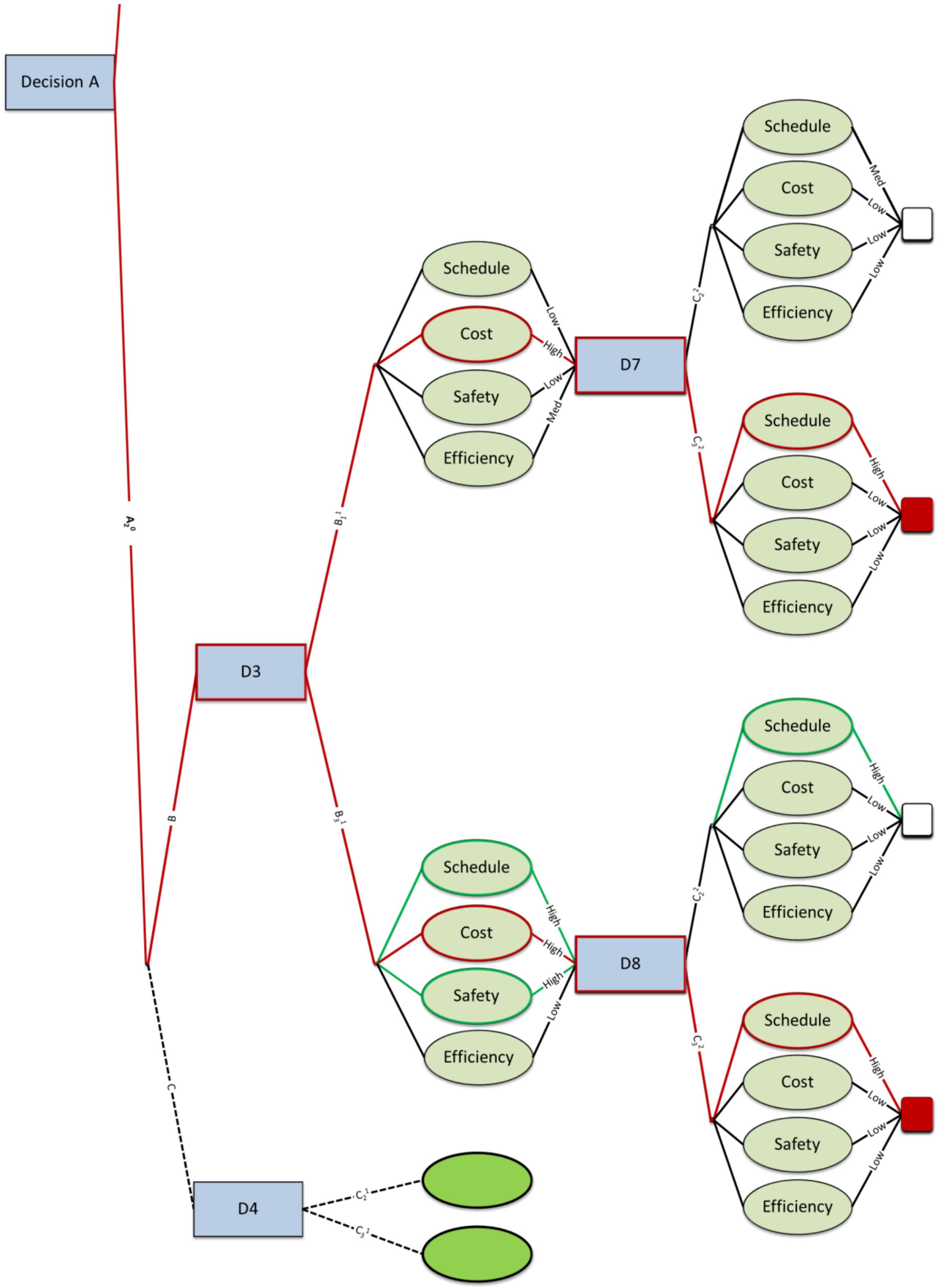

Figure 10. Surface Operations M-MODT – Branch A_2

3.2 UAS Integration into the NAS

In addition to the infrastructure decisions discussed in Section 3.1, another issue at the forefront of FAA's decisionmakers is the increasing demand for civilian UAS applications in the domestic airspace. Currently, no well-defined rules and regulations exist for evaluating UAS performance and their non-military use aside from a lengthy approval process for public and emergency applications. Given the new technology, policies, and procedures that must be integrated within the NAS, an already existing complex system-of-systems, it is conceivable that numerous new sources of risk will arise. This section addresses some of the challenges associated with integrating UAS into the airspace, primarily focusing on identifying potential sources of risk and relating them to the existing NAS.

3.2.1 UAS Risk Factors and HHM

To begin understanding UAS in terms of a SoS, the first step is to create an HHM. This requires examining the problem from multiple perspectives and to identify factors that influence, cause, or shape risks with respect to each of these perspectives. Beginning with as large a list as possible of states, inputs, and decision variables associated with UAS, the list could eventually be categorized into headtopics. An initial effort to categorize state variables and inputs and decisions into an HHM is shown in Figure 11 and Figure 12.

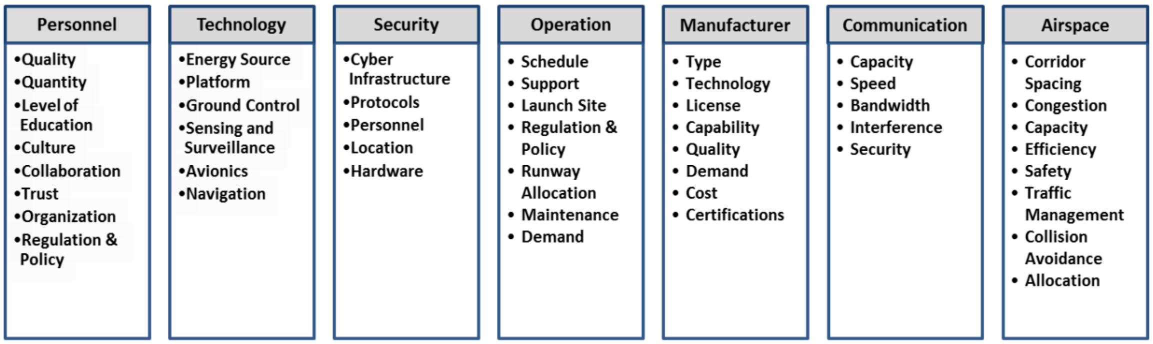

Figure 11. UAS State Variables

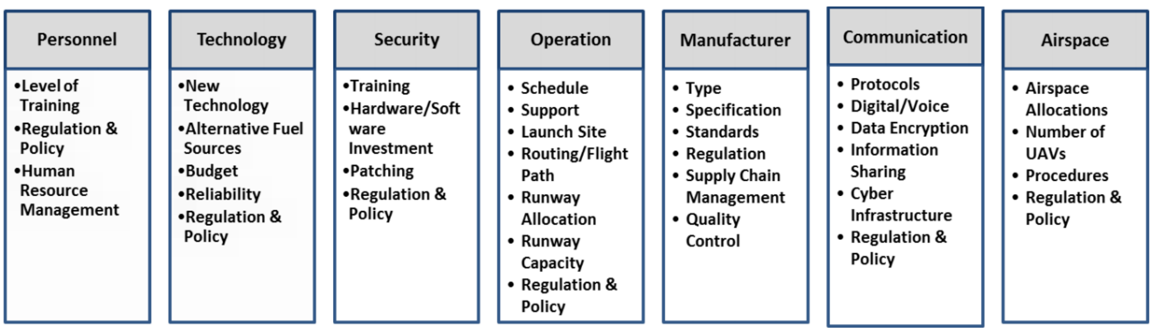

Figure 12. UAS Inputs and Decisions

This list should be considered comprehensive but not complete, as additional sources of risk may become apparent through further research.

Through discussion with members of MITRE's team involved with this effort, five over-arching UAS subsystems were developed to organize risk factors. These include people factors, technology factors, infrastructure factors, operational factors, and policy factors. Within each of these hierarchical subsystems, subtopics were developed that further break down risk factors within each hierarchy. The people factors subsystem is shown in Table 6, and the remaining hierarchies can be found in Appendix E: UAS Subsystems.

Table 6. UAS People Factors Subsystem

Personnel – people who touch or affect the Unmanned system	**Culture –** how the beliefs drive actions and interactions	**Interactions -** cooperation and tensions between groups with different objectives

Quality
• Flight experience
  ○ UAS or manned
  ○ Familiarity w/ vehicle
• Accident history
	Values
	• Risk tolerance
	• Objectives
	• Autonomy-control
	• Transparency-secrecy
		Aircraft Owners
		• Manned & unmanned
		• Domestic & International
		• Public & civil
		• Compliant & militant

Crew • Size of crew • Roles: dispatch, PIC, mission spc, 1st officer, payload officer, maintainer	History • Recent negative events • Shared perspectives • Statistics	Manufacturers • Transparency • Supply chain • Customer vetting
Air Traffic • Staffing levels • Aircraft knowledge • Mission prep	Trust • Safety • Investment • Transparency	Communities • Airport operators • Population • Other airspace users

Training
• Certifications
• Aircraft specifics
• Mission prep & practice
• Level of Education
• Vehicle and mission specific trainings
	Militant
	• Intentional threats
	  • Terrorist, military
	• Mischievous
	  • Jammers, hackers, virus makers, etc.
		Operators
		• Compliant Pilot to ATC
		• Dispatch to ATM

Militants
• Hijacker/Hacker
• Non-cooperative
	Agencies
	  • Mission conflicts
	  • Trust
	  • Support roles
		Regulators
		• Harmonization

Affiliation (replaces type)
• Citizenship
• Public or civil
	Diversity
	  • Operators
	  • Decision makers	

Multiple stakeholders are inherent in any system. Thus, when evaluating a system, one must take into account multiple stakeholder perspectives on the issues highlighted by the system. Developing an effective program to reduce risk is not possible without taking into account these perspectives on a system. Lambert and Sarda stress the importance of this consideration to highlight interdependencies and relationships between system components that are not at first apparent (2005), and this warrants the inclusion of the Interactions column in Table 6 above.

Once the HHM and subsystems are defined to a large enough extent, it is possible to begin identifying the most important shared state variables, inputs, and outputs between the different subsystems. Using the set of risk factors found in the subsystems, and through collaborative efforts with MITRE, a watch list for the FAA of nine critical areas of concern was developed, regarding the integration of UAS into the NAS, dubbed the "Dirty Dozen." This list is abbreviated in Table 7, and can be found in its complete form in Appendix F: UAS "Dirty Dozen".

Table 7. MITRE's UAS Integration "Dirty Dozen"

1	If Crew Resource Management for distributed control and responsibilities across the team is inadequate to maintain situational awareness, then accident rates will likely prohibit routine civil and military UAS operations.
2	If the program office ignores the socio-economic dimension, then the coordinated transition is unlikely to result in routine access for civil UAS operations.
3	If harmonized standards don't address international security issues with routine file and fly operations, then UAS operations may be limited to domestic operations.
4	If reliability of vehicles and systems is inadequate to achieve comparable accident rates, then routine integration will likely not be approved
5	If vehicles respond differently on takeoff and landing, then surrounding population will fight with NIMBY environment arguments.
6	If UAS reporting requirements provide insufficient information to assess security risks, then UAS operations may remain domestic.
7	If safety/operational data are not made available in large enough volumes to build a safety risk management document, then operational approval of routine use may not be possible.
8	If agencies use their missions to justify special treatment and airspace reservations, then routine UAS operations for public aircraft may not be granted.
9	If the program office focus ignores the air security dimension, then granting routine access to civil UAS operations is unlikely.

3.2.2 Transition from UAS Accommodation to Integration

Public UAS use currently exists in a state of "accommodation" in the NAS. Operators of UAS must gain access through a Certificate of Waiver or Authorization, coordinating the flight with local aircraft authorities several weeks in advance of the operation. Additionally, only one UAS is allowed to fly at a time in each air traffic control (ATC) sector, the size of which varies across the nation. Each UAS also has an air traffic controller specifically assigned to monitor it, which equates to a state of declared emergency and represents a large use of available resources to accomplish one task. These kinds of restrictions are preventing UAS from being truly integrated in the NAS like other manned aircraft. In the last few years, the process and tools to coordinate individual flights has improved, and the DOD has focused on ground-based separation in uncontrolled airspace, effectively helping to create a sort of UAS-dedicated airspace. These efforts have not helped in progressing UAS towards true integration, as they still treat UAS separately from manned aircraft.

On February 14, 2012, President Barrack Obama signed a bill into law that effectively requires the FAA to come up with a full UAS integration plan for domestic airspace use within nine months. This section addresses some of the risks that arise in this transition process from UAS accommodation to integration.

The first step to identify these risks is to create an HHM of the changes that are needed in the transition of the FAA’s flight approval process for UAS. This HHM is shown in Figure 13.

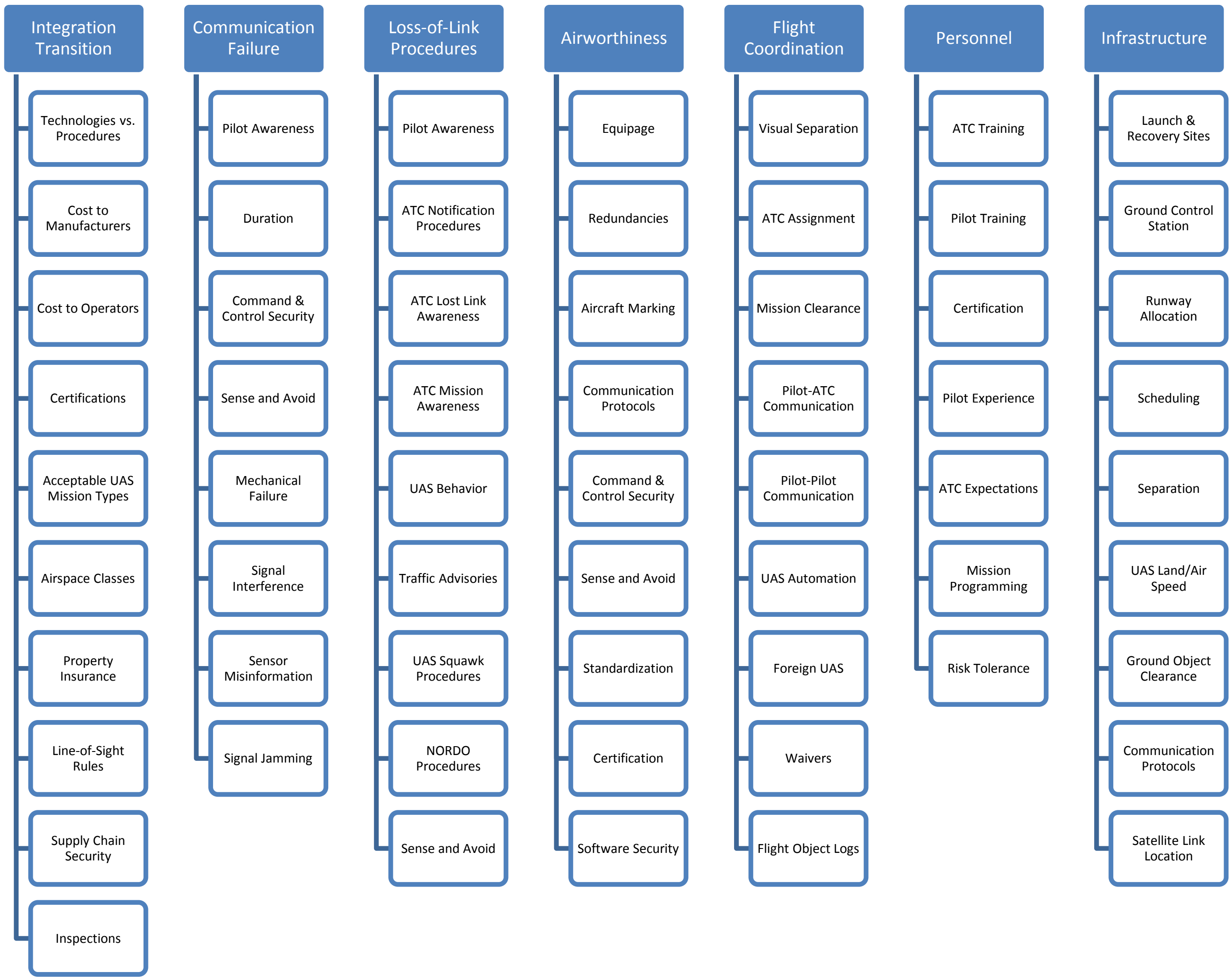

Figure 13. UAS Accommodation to Integration HHM

Along with this HHM, questions were developed for each subtopic to be posed to subject matter experts at MITRE, to assess which sources of risk are already being addressed by the FAA and which risks have not been thought of yet. A sample of these questions are shown below, and the full list of questions and answers can be found in Appendix G: UAS Accommodation to Integration Questions:

- Cost to Manufacturers – How will proposed solutions affect manufacturers? Will it differ depending on the size of the manufacturer? Is there an acceptable lowest-cost standard? Will it affect international and domestic manufacturers differently? What about manufacturer regulations and how they might be implemented across the world?

- UAS Behavior – What should be the expected behavior of a lost-link UAS? Should it continue on its current course or mission? Should it return to home base or try to gain higher altitude in order to try to reestablish the link? What behavior would be most disruptive to other traffic?

- Pilot Training – What kind of training does the pilot need to fly a UAS? Does he need to be a certified pilot with a number of training hours? Time spent in a simulator or other special training? Who will pay for new training procedures?

- Ground Control Station – Any rules on where these stations can be located in relation to the UAS, populated areas, and airports? Line-of-sight rules with regard to the UAS?

Using these questions and discussion with the MITRE team, the HHM was reduced to a set of sources of risk in the UAS integration process that are not yet being fully addressed or assessed by the FAA. This reduced HHM is shown in Figure 14.

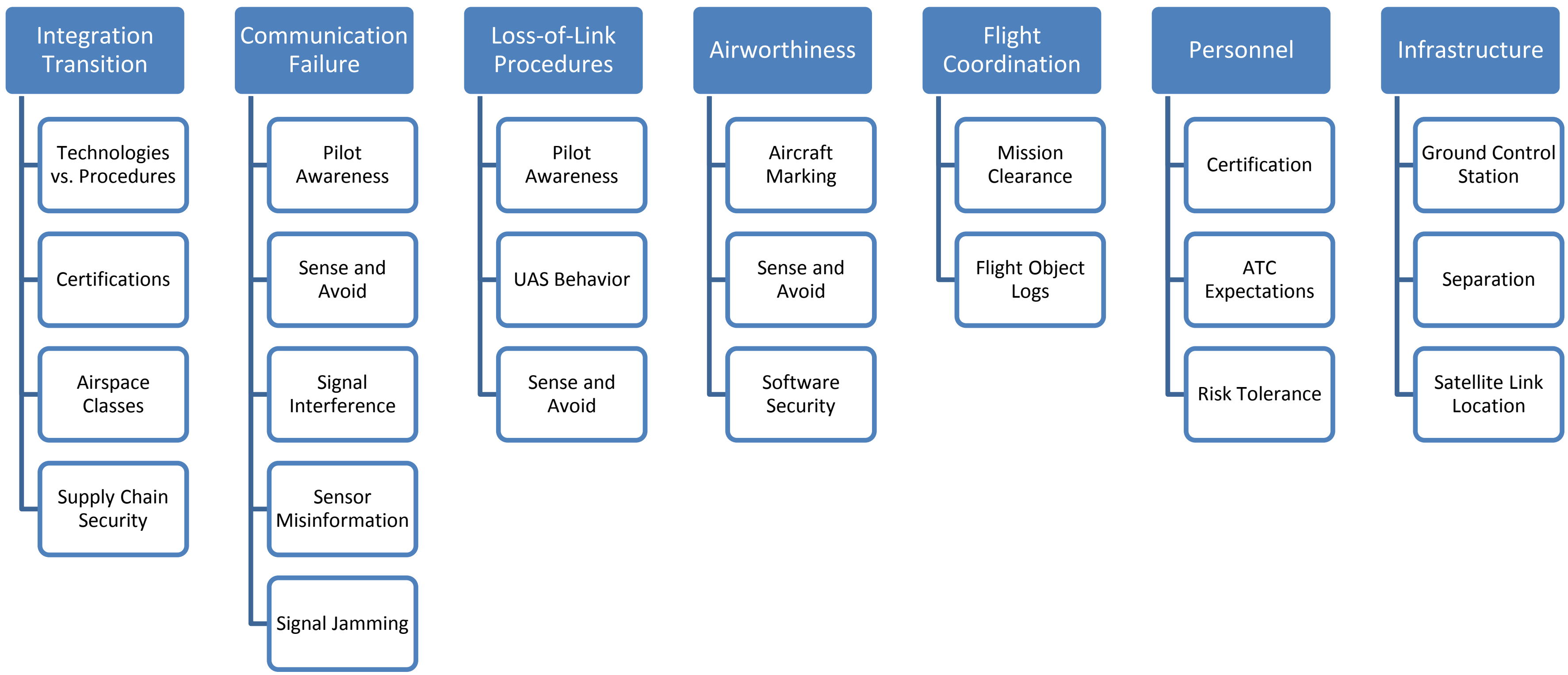

Figure 14. UAS Accommodation to Integration Reduced HHM

To determine how catastrophic each of these remaining sources of risk has the potential to be, an extreme scenario is developed for these subtopics, highlighting the worst case scenario that could ensue if the risk factors were not addressed properly. Then, through discussion with the MITRE team, each of these scenarios is rated on a severity scale of *Major*, *Hazardous*, or *Catastrophic*. This is the severity scale used by the FAA to categorize extreme events. Once again, a sample of these events is shown below, and the full list can be found in Appendix H: UAS Transition Extreme Scenarios. The colors used to represent severity are green for *Major*, blue for *Hazardous*, and red for *Catastrophic*.

- Airspace Classes – Flooding of Class G airspace by smaller UAS creates difficulties for other aircraft trying to use the space as an escape – could cause hazardous conditions for operators.

- Sensor Misinformation – Pilot believes UAS is located at location A when it is actually at location B, and accidentally maneuvers toward/into another manned aircraft – catastrophic.

- Aircraft Marking – Small-wingspan UAS markings confuse another manned aircraft pilot as to the distance/bearing of the UAS.

- Flight Object Logs – UAS is handed off between multiple pilots, but the pilots fail to tell each other about some sort of maintenance issue, causing the UAS to behave erratically and creating hazardous conditions for other aircraft and operators.

This categorization of sources of risk will hopefully aid MITRE and the FAA when creating rules and regulations that affect the subsystems of the UAS described in Section 3.2.1.

4 Analysis of Results

4.1 Shared States and Sources of Risk

To study the sources of risk within the NAS with a focus on the NextGen project, the important shared states between subsystems were first identified and used to rate the 90 decisions in terms of their impact on the NextGen project. This was accomplished by first dividing the NextGen system-of-systems into multiple subsystems and then listing the states and inputs most critical for each subsystem. The states and inputs that showed up in the greatest number of subsystems represent the ones that have the highest potential to be sources of risk propagating throughout the system.

To study the sources of risk within the UAS subsystem, the states of the subsystem were categorized into different factors, which led to the creation of the "Dirty Dozen" sources of risk associated with UAS integration into the airspace. The analysis leading up to the development of the "Dirty Dozen" sources of risk examined the aspects of infrastructure, technology, human factors, and policies that are involved in operating UAS in civilian airspace. The result of this analysis exposed some areas of concern within the UAS subsystem of the NAS that had not been previously assessed, most notably the interactions between the flight crews of manned and unmanned vehicles. These sources of risk should be taken into account when creating future airspace regulations.

To address the transition process from UAS accommodation to integration, an HHM was developed with all potential areas of concern that arise when changing to a less stringent flight approval process. Similar to the efforts related to the "Dirty Dozen," by breaking down the requirements to achieve full integration of UAS into the airspace, some sources of risk with the transition process were exposed that are not currently being studied in detail by anyone at MITRE or at the FAA. By providing extreme scenarios for each of these sources of risk, and rating the potential severity of these scenarios, they can be better understood, and serve as a starting point for future research on the UAS integration process.

4.2 Develop a Framework to Harmonize a Large Set of Strategy Decisions

After using shared states to determine which of the 90 decisions are likely to have the most impact on the future decision space of NextGen, a method must be applied to study how these decisions affect each other and the NextGen infrastructure. To accomplish this, the MODT methodology was modified to accommodate the sequential and combinatorial nature of these strategy decisions to create the M-MODT framework. Unlike MODT, the primary goal of M-MODT is not to find the Pareto-optimal decision-making sequence(s), but to assess each path in the tree for the purpose of discovering potential precursors to poor strategy choices over a period of time that arise from interactions between the decisions.

The M-MODT framework is also flexible enough to make use of varying amounts of data: it can be used initially to reduce the number of decision sequences to a manageable amount through a "first cut" with less accurate data, then the process can be repeated by collecting more detailed data to be used with the remaining decision sequences.

4.3 Show the Efficacy of the M-MODT Framework Approach

A set of decisions within the surface operations subsystem was evaluated in a case study using the M-MODT framework. The case study represents the first phase in assessing the impact that three decisions have on each other and on a subsystem.

The process of pursuing only *high*-risk paths serves to reduce the decision space to a more manageable size, as the permutations of possible alternatives quickly escalates. Even with just the three surface operation decisions discussed in Section 3.1.4, the total number of decision sequences is 162, but the M-MODT is used to decrease this number at every step, making the analysis much more tractable. Just by studying the eight decision sequences in the case study, the decision space can be reduced by 62.5%. This means that more effort can be placed into analyzing the scenarios that pose the greatest risks, or evaluating the scenarios that are most likely to meet every objective.

At the end of the process, the decisionmaker is left with a set of decision paths that potentially fall outside the acceptable range for the objectives. These paths can be studied in more detail if the particular decision sequence seems attractive for any reason, or simply discarded if there is no clear advantage to that decision sequence. The rest of the decision paths are likely to fall within the acceptable range for the objectives, and further analysis can be conducted on this remaining set in later phases of the approach.

5 Contributions and Conclusions

The major goal of this thesis has been to develop a systems-based risk analysis framework with which to streamline and harmonize decisions made during the three planning horizons (Alpha, Bravo, and Charlie) of the NextGen transition process. The importance of this effort is that no tractable methodological approach previously existed to ensure the coordination between a large number of interdependent decisions, that is also flexible enough to accommodate small and large data collection efforts.

This thesis largely builds on the concept of using state variables to define a system-of-systems and the significance of shared states between subsystems. Through identifying the most important shared states between subsystems, the effects of a decision can be assessed not only on the major subsystem it pertains to, but also on the system-of-systems that subsystem belongs to. Since it is becoming increasingly apparent to analysts and decisionmakers that man-made systems are becoming more and more connected, methodologies that focus on evaluating the interdependencies between decisions and subsystems are more needed than ever before.

5.1 Shared States within the NAS

In this thesis, the NAS system-of-systems was studied by breaking it down into physical infrastructure subsystems (*airport, airspace*, and *single flight operation*). These subsystems were then populated with state variables and inputs that constitute sources of risk within each subsystem, and mapped to the different NextGen objectives (*safety*, *efficiency*, *capacity*, and *environment*) and the *UAS integration* into the airspace. Using this breakdown, the most important sources of risk were identified as the states that show up in the largest number of subsystems (*technological capabilities, personnel quality, reliability, route flexibility, budget*, and *policies and procedures*), constituting interdependencies within the NAS, and which could thus have the most widespread effects on the system. These shared states were used in the analysis of the FAA's 90 strategy decisions regarding the NextGen project.

5.2 Identification of Critical Decisions in the 90 Decisions

The challenge in making the 90 decisions is that some of the decisions have the possibility of constraining the solution space for future decisions, depending on the alternatives chosen and the sequence in which the decisions are made. This could cost the NextGen project a lot of extra time and money if the interdependencies between these decisions are not taken into account. In order to identify which of the 90 decisions are the most important to examine in greater detail, the decisions were divided into the 18 infrastructure subsystems which they affect, then each decision was rated in terms of its impact on the six shared states mentioned in Section 5.1. Using this rating process, a small number of decisions stood out as having the largest impact on each subsystem.

5.3 Development of M-MODT Framework

To address the sequential nature of the 90 Decisions, this thesis developed the M-MODT framework, which builds on the importance of the state space and makes use of the state space analysis conducted through HHM modeling. The M-MODT allows a decisionmaker to evaluate the effects of one decision on the options available for future decisions, while keeping a focus on a set of objectives with which to gauge system performance. The significance of the M-MODT is its flexibility in accommodating various levels of data collection and its ability to address the combinatorial problem associated with making decisions in different sequences.

The M-MODT framework constitutes an iterative methodology by which more data can easily be added to the analysis over time in order to refine the comprehensiveness of the decision-making process. In an initial effort, the M-MODT can be used to bring to the attention of the decisionmaker potential high-risk situations that can materialize several years in the future from making poor decisions in the earlier stages of a project. Iterative efforts that add more information to the methodology can be used to more fully assess the risks of a decision-making process, and to better determine how future objectives may be affected.

5.4 Deployment of M-MODT to Surface Operations

In this thesis, the M-MODT was deployed on a real set of decisions related to surface operations in NextGen. The three pairs of decisions examined in this case study will shape the architectural alternative space of the airport surface subsystem. The M-MODT study revealed some precursors to how certain decision-making sequences could potentially have adverse consequences on the alternative space of the subsystem in the future, and represents the first phase of analysis of these decisions.

5.5 Development of UAS "Dirty Dozen" Sources of Risk

This thesis examined the UAS subsystem of the NAS by breaking it down into the state variables and inputs that describe and affect the subsystem from multiple perspectives. From this effort, the UAS subsystem was organized in terms of five overarching factor groups (*people*, *technology*, *infrastructure*, *operational*, and *policy*), and populated with the state variables pertinent to each group. This made it possible to identify which states affect multiple aspects of the UAS and where interdependencies exist within the UAS subsystem, constituting the most widespread sources of risk. These sources of risk were used to aid in the development of the "Dirty Dozen" areas of concern for the introduction of UAS into the NAS.

5.6 Analysis of UAS Transition from Accommodation to Integration

In addition to the "Dirty Dozen," this thesis examined the process of transitioning domestic UAS use from accommodation to integration. HHM modeling was used to generate a categorized list of sources of risk specific to the UAS integration process. Through discussion with subject matter experts at MITRE, this list was reduced to a set of sources of risk that have yet to be assessed in full by teams at MITRE or at the FAA. This set was complimented by an extreme scenario for each source of risk, giving an example of adverse consequences that could arise if that risk were not addressed and planned for before full UAS integration occurs, along with a rating for the severity of each scenario.

5.7 Conclusion

This thesis contributed to confronting a real challenge that faces the FAA in the development of NextGen over the next decade. The 90 strategy decisions are crucial in determining the future protocols, procedures, and technological capabilities of NextGen, and if these decisions are not approached carefully and systematically, the FAA could encounter drastic budget and schedule problems in the completion of the NextGen project. Equally important is how the FAA deals with the constantly increasing demand of domestic UAS and the process through which these are integrated into the airspace without disrupting existing operations.

6 Future Work

6.1 NextGen and 90 Decisions

The M-MODT case study discussed in Section 3.1.4 only evaluates eight of the 162 possible decision sequences in the surface decision subspace, as a proof of concept of the methodology. Future work would include employing the methodology to the remaining 154 decision paths. Additionally, the case study uses *high*, *medium,* and *low* ratings to describe the impact of decisions on the four decision criteria. Future iterations of the methodology should use the numeric ratings described in Section 3.1.4.2 to more accurately express the impact of decisions.

The M-MODT methodology described currently addresses the combined shared state space of a SoS to estimate the overall impact a decision has on one subsystem. A next step in the evolution of this methodology could include a way to assess the impact a decision would have on other subsystems, and to more directly take this impact into account when evaluating the risks involved with the possible decision paths. As more and more decision sets are evaluated, additional interdependencies between subsystems may be uncovered, which could be used as another set of inputs into the decision-making process outlined by this methodological framework.

6.2 UAS Integration Risk Factors

The identification of the UAS “Dirty Dozen” risk scenarios in Section 3.2.1 is the first step in the risk analysis process of UAS operations in the airspace. Future work should include evaluation of the likelihood and severity of each of these scenarios, and risk management steps to identify and evaluate options to mitigate these risks.

The risk analysis process for the transition from UAS accommodation to integration in Section 3.2.2 includes severity ratings for each of the described risk scenarios. The next step in the risk analysis process is to evaluate the likelihood of each of these scenario, and risk management steps to identify and evaluate options to mitigate these risks.

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8 Appendix A: NextGen States and Inputs

8.1 Table 8. Airport State Variables

Efficiency	Safety	UAS Mission	Capacity	Environment
1. Technological Capabilities	1. Technological Capabilities	1. Technological Capabilities	1. Technological Capabilities	
3. Personnel Quality	3. Personnel Quality	3. Personnel Quality	3. Personnel Quality	
5. Situational Awareness	5. Situational Awareness	5. Situational Awareness		
6. Runway Configuration	6. Runway Configuration		6. Runway Configuration	
	7. Culture	7. Culture	7. Culture	
8. Budget			8. Budget	8. Budget
9. Reliability (6 Sigma)	9. Reliability (6 Sigma)	9. Reliability (6 Sigma)	9. Reliability (6 Sigma)	9. Reliability (6 Sigma)
10. Trust	10. Trust	10. Trust	10. Trust	
12. Congestion	12. Congestion			
13. Routing Flexibility				
21. Runway Usage		21. Runway Usage	21. Runway Usage	
				24. Noise

8.2 Table 9. Airport Inputs/Constraints/Decisions

Efficiency	Safety	UAS Mission	Capacity	Environment
a. New Technology b. Flight Path e. Runway Allocation f. Training i. Policies & Procedures j. Number of Airplanes k. Schedule o. Demand	a. New Technology f. Training i. Policies & Procedures	a. New Technology f. Training i. Policies & Procedures h. Regulation	b. Flight Path e. Runway Allocation f. Training i. Policies & Procedures k. Schedule o. Demand	a. New Technology e. Runway Allocation o. Demand

8.3 Table 10. Flight Operation State Variables

Efficiency	Safety	UAS Mission	Capacity	Environment
1. Technological Capabilities	1. Technological Capabilities	1. Technological Capabilities	1. Technological Capabilities	
			2. Corridor Spacing	
3. Personnel Quality	3. Personnel Quality	3. Personnel Quality	3. Personnel Quality	
4. Positional Accuracy	4. Positional Accuracy	4. Positional Accuracy	4. Positional Accuracy	
5. Situational Awareness	5. Situational Awareness	5. Situational Awareness		
7. Culture	7. Culture	7. Culture	7. Culture	
9. Reliability (6 Sigma)	9. Reliability (6 Sigma)	9. Reliability (6 Sigma)	9. Reliability (6 Sigma)	9. Reliability (6 Sigma)
10. Trust	10. Trust	10. Trust	10. Trust	
	11. Standardization			
12. Congestion	12. Congestion	12. Congestion		
14. Flight Path Flexibility		14. Flight Path Flexibility		
	17. Product Reliability			
	18. Digital/Voice Comm.			
23. Fuel Usage				23. Fuel Usage
				24. Noise
				25. Reliability

8.4 Table 11. Flight Operation Inputs/Constraints/Decisions

Efficiency	Safety	UAS Mission	Capacity	Environment
a. New Technology	a. New Technology	a. New Technology		a. New Technology
b. Flight Path		b. Flight Path		b. Flight Path
f. Training	f. Training	f. Training	f. Training	
n. Airspace Accessibility	h. Regulation	h. Regulation		
q. Airspace Congestion				
r. Corridor Spacing			r. Corridor Spacing	
				s. Ground Delay
				t. Alternate Fuel Sources

8.5 Table 12. NextGen State Variables

Efficiency	Safety	UAS Mission	Capacity	Environment
1. Technological Capabilities	1. Technological Capabilities	1. Technological Capabilities	1. Technological Capabilities	
2. Corridor Spacing			2. Corridor Spacing	
3. Personnel Quality	3. Personnel Quality	3. Personnel Quality	3. Personnel Quality	
4. Positional Accuracy	4. Positional Accuracy	4. Positional Accuracy	4. Positional Accuracy	
5. Situational Awareness	5. Situational Awareness	5. Situational Awareness		
7. Culture	7. Culture	7. Culture	7. Culture	
8. Budget			8. Budget	8. Budget
9. Reliability (6 Sigma)	9. Reliability (6 Sigma)	9. Reliability (6 Sigma)	9. Reliability (6 Sigma)	9. Reliability (6 Sigma)
10. Trust	10. Trust	10. Trust	10. Trust	
11. Standardization	11. Standardization	11. Standardization		
12. Congestion	12. Congestion			
13. Routing Flexibility				
14. Flight Path Flexibility		14. Flight Path Flexibility		
16. Personnel Scheduling	16. Personnel Scheduling	16. Personnel Scheduling	16. Personnel Scheduling	
	17. Product Reliability			
	18. Digital/Voice Comm.	18. Digital/Voice Comm.	18. Digital/Voice Comm.	
21. Runway Usage		21. Runway Usage	21. Runway Usage	
23. Fuel Usage				23. Fuel Usage
				24. Noise

8.6 Table 13. NextGen Inputs/Constraints/Decisions

Efficiency	Safety	UAS Mission	Capacity	Environment
a. New Technology	a. New Technology	a. New Technology		
b. Flight Path		b. Flight Path	b. Flight Path	b. Flight Path
d. Collaboration		d. Collaboration		
e. Runway Allocation			e. Runway Allocation	
f. Training	f. Training	f. Training	f. Training	
	h. Regulation	h. Regulation		
i. Policies & Procedures	i. Policies & Procedures	i. Policies & Procedures	i. Policies & Procedures	i. Policies & Procedures
j. Number of Airplanes		j. Number of Airplanes		
k. Schedule		k. Schedule	k. Schedule	
		n. Airspace Accessibility		
o. Demand		o. Demand	o. Demand	
q. Airspace Congestion				
r. Corridor Spacing			r. Corridor Spacing	
				t. Alternate Fuel Sources

9 Appendix B: NextGen State and Input Definitions

9.1 State Definitions

1. *Technological Capabilities* – Ability to deliver capability-based services for flights
2. *Corridor Spacing* – Ability to operate independent flows
3. *Personnel Quality* – Proficiency and consistency in delivering expected services & performing tasks
4. *Positional Accuracy* –Knowledge of aircraft locations relative to each other and their intended path
5. *Situational Awareness* – How well informed is the responsible person to make aviation, navigation and separation decisions
6. *Runway Configuration* – Ability of an airport to operate multi-runway operations
7. *Culture* – Community attitude to the approach for: (7.1) safety assurance and (7.2) joint investment making
8. *Budget* – Funding outlook for operations and improvements (8.1) level, (8.2) stability
9. *Reliability (Design for 6 Sigma)* – Service delivery process and Minimum Equipage List designed defect rates
10. *Trust* – Confidence in others to deliver: (10.1) safety commitments or (10.2) joint investment commitments
11. *Personnel Quantity* – Numbers of trained personnel
12. *Congestion* – Form and level of excess demand for available capacity
13. *Routing Flexibility* – Options available to ATM to resolve congestion
14. *Flight Path Flexibility* – Options available to users to complete flight objectives
15. *Standardization* – Commonality of procedures and minimum equipment across operating flight information regions and airports
16. *Personnel Scheduling* – Resources on duty relative to resources needed to deliver expected capacity for demand
17. *Product Reliability* – Continuity of technology capability availability for minimum NAS services
18. *Digital/Voice Communication* – state of means for communications between flight crews and ATC
19. *Noise* – People impacted by noise
20. *Fuel Usage* – Fuel consumption (actual or ideal) for given flight objectives

21. *Runway Usage* – Coordination between arrivals, departures and surface operations for feeding runways
22. *Airspace Accessibility* – Dependence of access to airspace based on actions or equipage of a flight
23. *Demand* – Fleet mixture in terms of (23.1) aircraft and (23.2) types of missions/operations
24. *Responsibilities* – Who is responsible to make (24.1) navigation and (24.2) separation responsibilities
25. *Delay Location* – Distribution of where is delay taken on ground or airborne

9.2 Input Definitions

a. *New Technology* – Delta in technology capabilities, positional accuracy, communications, engine efficiency,

b. *Routing/Flight Path* – Paths used to satisfy the demand

c. *Budget* – Resources available

d. *Collaboration* – Joint decision making for investments to real-time resource contention resolution

e. *Runway Allocation* – Additional configurations (airspace changes)

f. *Training* – Improvements to personnel quality or introduction of new technologies

g. *Runway Capacity* – Additional capacity (physical changes)

h. *Regulation* – Preference for new services

i. *Policies & Procedures* - Favorable to new services

j. *Number of Airplanes* – Fleet or flights

k. *Schedule*– When and where the flight wishes to travel

l. *Standards* – New standards, have the property of diverging or converging standards

m. *Alternate Engines* – Changes in fuel types or performance of engines

n. *Airspace Accessibility* – Open more services to least equipped

o. *Demand* – Numbers and mixture of fleet and types of operations needed

10 Appendix C: Strategy Decision State Impact Rubric

10.1 Shared States

Technological Capabilities – Ability to deliver capability based services for flights

- Very High = changes ability to support a mixed environment operation
- High = changes introduction of a single new service
- Low = any other impact

Personnel – Proficiency and consistency in delivering expected services & performing tasks

- Very High = changes numbers and function of trained personnel required
- High = changes the responsibilities or function of the personnel
- Low = any other impact

Budget – Funding outlook for operations and improvements (8.1) level, (8.2) stability

- Very High = change the justification for a significant investment line, that could change the stability/level of budget
- High = absorbs significant funding, greatly reducing remaining investment options
- Low = any other impact

Reliability (Design for 6 Sigma) – Service delivery process and Minimum Equipage List designed defect rates

- Very High = changes the continuity of operations for minimum NAS services
- High = changes the reliability of a single critical component of the overall mission
- Low = any other impact

Routing Flexibility – Options available to ATM to resolve congestion

- Very High = provides degree of freedom to how facilities manage airspace
- High = changes the options available to users to complete flight objectives
- Low = any other impact

10.2 Input definitions and ratings

Policies & Procedures – favorable to new services

- Very High = regulatory changes affecting not only services, but aviation sectors
- High = changes affect fundamental services
- Low = any other impact, e.g., Standards

Stakeholders – those who can generate exogenous forced changes

- Very High = changes Trust – Confidence to deliver: (10.1) safety or (10.2) joint investment commitments or sense of equity
- High = changes business model or private sector investment – fleets, schedules, runways & airports
- Low = any other impact

11 Appendix D: Surface Decisions Inputs and Outputs

11.1 Decision A – Remote Air Traffic Control Tower

1. Resilience as regards catastrophic loss of an air traffic control tower (backup facility)
    a. Inputs
        i. *Technology* – remote monitoring of surface (visual or surveillance), integrated as part of larger investment in remote tower
        ii. *Information* – unique identification of all vehicles
        iii. *Airports* – sensor coverage for high density or high risk areas
    b. Outputs and by-products
        i. *Safety* – possible increase in surface collision precursors from blind spots
        ii. *Capacity* – goal is 80% throughput of the primary facility in the event of loss
        iii. *Trust* – loss if safety incidents occur
        iv. *Budget* – requires resources for full backup, practice and training
        v. *Degraded Modes* – expected efficiency in degraded mode is 80% of primary

2. Cost efficiency/budget savings (man fewer low traffic volume towers with dedicated staff)
    a. Inputs
        i. *Technology* – remote monitoring of surface (visual or surveillance), integrated as part of larger investment in remote tower
        ii. *Information* – unique identification of all vehicles
        iii. *Policy* – augmented rules for "untowered" airport
        iv. *Procedures* – remote tower position, serving multiple airports
        v. *Airports* – surveillance for low density operations
    b. Outputs and by-products
        i. *Safety* – possible increase in surface collision precursors from blind spots or controller attention to multiple airports, possible benefit over lone controller fatigue
        ii. *Trust* – workforce concern with loss in number of positions
        iii. *Budget* – requires investment and maintenance by airport or FAA, the goal is to reduce lifecycle cost over tower operations

3. Safety and capacity at one-in/one-out airports (provide remote controller a surface view)
    a. Inputs
        i. *Technology* – remote monitoring of surface (visual or surveillance)
        ii. *Policy* – augmented rules for "untowered" airport
        iii. *Procedures* – augmented one-in/one-out procedures
    b. Outputs and by-products
        i. *Safety* – goal is reduced risk of missed vehicle
        ii. *Capacity* – if goal is increase in throughput, is there not enough to justify it
        iii. *Trust* – possible workforce concern as step to remote tower for force reduction
        iv. *Budget* – requires investment and maintenance by airport or FAA
        v. *Degraded Modes* – expected efficiency in degraded mode is 80% of primary

11.2 Decision B – Instrumenting Surface Vehicles for Remote Surveillance

1. Taxi efficiency (account for all obstacles in an aircraft path to or from the runway)
   a. Inputs
      i. *Technology* – path tracking for all surface (visual or surveillance)
      ii. *Information* – movement intent of all vehicles, not just aircraft
      iii. *Policy* – role of FAA in managing non-movement area, or expanded movement area
      iv. *Airports* – high density or high risk of primary loss
   b. Outputs and by-products
      i. *Safety* – positive control of all vehicles, federal liability
      ii. *Efficiency* – reduce excess taxi, account for surface vehicles in calculating best taxi path
      iii. *Capacity* – risk precise choreography making the system brittle, causing bigger breakdowns
      iv. *Trust* – everyone directed to take action regardless of what they see
      v. *Budget* – expand FAA workload of managing surface to include ground vehicles
      vi. *Degraded Modes* – expected efficiency in degraded mode is 80% of primary

2. Safety on surface (increase vehicle visibility and/or responsibility vehicle drivers)
   a. Inputs
      i. *Technology* – ADS compatible or TIS-B fills in the blanks
      ii. *Information* – vehicle unique identification assignments
      iii. *Policy* – role of FAA in managing non-movement area, or expanded movement area
      iv. *Procedures* – vehicle drivers must be trained and separation responsibility must be clear
   b. Outputs and by-products
      i. *Safety* – the goal is fewer incursions and near-miss collisions
      ii. *Efficiency* – taxi time and gate efficiency disrupted by pop-up warnings, immediate move to hot stand by facility
      iii. *Trust* – who owns or can record the data, monitoring the competition
      iv. *Budget* – discussion over who pays to implement – FAA or airport
      v. *Degraded Modes* – one failed box means someone is invisible (needs visual confirmation)

11.3 Decision C – Low-Visibility Operations from the Cockpit

1. Arrival/Departure Capacity (pilots continue visual spacing in more conditions)
    a. Inputs
        i. *Technology* – path tracking for all surface vehicles (visual or surveillance)
        ii. *Policy* – role of FAA in managing non-movement area
        iii. *Airports* – high density or high risk of primary loss
    b. Outputs and by-products
        i. *Budget* – expand FAA workload of managing surface to include ground vehicles
        ii. *Degraded Modes* – expected efficiency in degraded mode is 80% of primary

2. Safety on surface (increase vehicle visibility and/or responsibility vehicle drivers)
    a. Inputs
        i. *Technology* – ADS compatible or TIS-B fills in the blanks
        ii. *Information* – vehicle unique identification assignments
        iii. *Procedures* – Vehicle drivers must be trained, responsibility for separation clear
        iv. *Airports* – update all vehicle fleet identification means
    b. Outputs and by-products
        i. *Safety* – the goal is fewer incursions and near-miss collisions
        ii. *Efficiency* – the goal is to move to hot stand by facility immediately
        iii. *Budget* – requires resources for full backup
        iv. *Degraded Modes* – expected efficiency in degraded mode is 80% of primary

12 Appendix E: UAS Subsystems

12.1 People Factors

Personnel – people who touch or affect the Unmanned system	**Culture –** how the beliefs drive actions and interactions	**Interactions -** cooperation and tensions between groups with different objectives

Quality
• Flight experience
    ○ UAS or manned
    ○ Familiarity w/ vehicle
• Accident history
	Values
	• Risk tolerance
	• Objectives
	• Autonomy-control
	• Transparency-secrecy
		Aircraft Owners
		• Manned & unmanned
		• Domestic & International
		• Public & civil
		• Compliant & militant

Crew • Size of crew • Roles: dispatch, PIC, mission spc, 1st officer, payload officer, maintainer	History • Recent negative events • Shared perspectives • Statistics	Manufacturers • Transparency • Supply chain • Customer vetting
Air Traffic • Staffing levels • Aircraft knowledge • Mission prep	Trust • Safety • Investment • Transparency	Communities • Airport operators • Population • Other airspace users

Training
• Certifications
• Aircraft specifics
• Mission prep & practice
• Level of Education
• Vehicle and mission specific trainings
	Militant
	• Intentional threats
	    • Terrorist, military
	• Mischievous
	    • Jammers, hackers, virus makers, etc.
		Operators
		• Compliant Pilot to ATC
		• Dispatch to ATM

Militants
• Hijacker/Hacker
• Non-cooperative
	Agencies
	    • Mission conflicts
	    • Trust
	    • Support roles
		Regulators
		• Harmonization

Affiliation (replaces type)
• Citizenship
• Public or civil
	Diversity
	    • Operators
	    • Decision makers	

12.2 Technology Factors

<table>
<tr><th>Platform Technology – elements affecting the aircraft dynamics</th><th>Manufacturing – how the aircraft and systems were constructed</th><th>Command and Control – all means of controlling the vehicle, its adherence to ATC and its payload</th><th>Communications – all the links with the aircraft</th></tr>
<tr><td>Structural
Flexible Wings
Fixed Wings</td><td>Source
Domestic vs. Foreign
Government vs. Private</td><td>Control Method
Autonomous (programed)
Autonomous with Backup Remote Pilot
Remotely Piloted</td><td>Reliability Standards</td></tr>
<tr><td>Navigation system
Fight control computer or system
Precision navigation system
Sense & Avoid System</td><td>Quality Control
Certified
Amateur (kit, custom)
Reliability
Vehicle
Control systems</td><td>Ground Control Technology
Avionics/ flight display
System Health Monitoring and Prognostics Display
Graphical Images and Position Mapping
Secure Communications</td><td>Radio frequency links
C2 Link
ATC links
Payload links</td></tr>
<tr><td>Communications systems
ATC
Control link
Mission links</td><td>Specifications
Built to standards
Proprietary</td><td>SCADA
Mechanisms
Protocols
Personnel
Safeguard controls</td><td>Networks</td></tr>
<tr><td>Propulsion system
Energy Source</td><td>Resources
Materials
Suppliers</td><td>Payload Systems
Sensors and RF devices
Dispensable loads</td><td>Ownership
Commercial
Government
Dedicated or not</td></tr>
</table>

12.3 Infrastructure Factors

Launch & Recovery Sites – means for UAS to touch the earth	**Control Facilities –** means for command and control	**Airspace –** means for organizing the traffic to fill each flight's mission	**Cyber infrastructure –** means for communicating
Runway • Geometry • Capacity • Location	Location • Domestic vs. Foreign • Government vs. Private	Capacity • Throughput • Required performance	Hardware Software Protocols
Takeoff • Vertical • Horizontal (runway or rail)	Communications lines • Reliability	Design • Corridor spacing • Separation • Routes	Connections
Vehicle Maintenance • Reliability • Security • Backup	Command and Control Systems • Maintenance • Security	Special activity airspace • Constraints • Schedule	Policies Procedures Personnel
Security • Physical • Cyber	Security • Physical • Cyber	ANSP services • Communications • Navigation • Surveillance	Organizational Culture
Recovery • Vertical • Horizontal • Net • Wire • Crash		Capacity and Flow Management • Congestion resolution • Special activity airspace	
Management	Management		

12.4 Operational Factors

Aircraft Flight Operations – vehicle ops in the air	**Organizational Operations –** how UAS owner operates	**Support Services –** services supporting the flight	**Schedule –** when operations occur
Control • Personnel • Comm • Navigation • Surveillance • SCADA? • Performance Envelope • Reliability • Responsiveness	Fleet management • Dispatch • Maintenance • Programming	Preflight services • Maintenance • Inspection • Security checks	Traffic Demand • Mission • Volume and Congestion • Location
Cyberinfrastructure	Mission Control • Planner • Specialist • Flight leader	ANSP services • Air traffic control • Weather Advisories • Traffic Advisories • System Advisories • Search & Rescue	Flight Path • Accuracy of flight plans (punctuality in 4DT) • Point to point • Planned aerial • Unplanned aerial
Mission ops • priorities • RF Interference •	Flight Ops • Launch officer • Pilot • Comm officer	Preparation • Mission Planning • Fuel • Payload • Programming	Traffic Synchronization • Flow constraints • Sequencing and spacing
		Personnel	Flight duration
		Security	

12.5 Policy Factors

Regulation and Policy – doctrine for the operations	**Security –** UAS as a national security risk	**Liability –** who pays for damages
Airspace • International • Domestic • Special Activity Airspace	Cyber • Malicious Penetration • Malicious Attacks • Protocols • Infrastructure	Manufacturing • Mechanical failures • SCADA (Sys of sys) failures • Interface failures
Flight Operations • Operator specifications • FAR (Part type) • Size of Vehicle • Civil or public • Use of vehicle	Flight Risk & Reporting • Vehicle waivers • Pilot credentials • Vehicle Registry • Special interest flights • Restricted areas • Hazardous payloads	Operator • Pilot error • Maintenance error • Operating/programing errors
Manufacturing • Certifications • FARs • Aviation Circulars • Reliability expectations	Physical • Facilities • Personnel • Location (control, maintenance, launch) • Infrastructure • Protocols	ANSP • Operational errors • Inadequate services
International • Chicago convention • ICAO regulations		Insurance coverage • Public or Civil • Foreign or domestic

13 Appendix F: UAS "Dirty Dozen"

1	If Crew Resource Management for distributed control and responsibilities across the team is inadequate to maintain situational awareness, then accident rates will likely prohibit routine civil and military UAS operations.
1a	If pilot and dispatcher qualifications are inadequate to achieve comparable accident rates to GA operators
1b	if agility of ground control or reprogramming capability is not as responsive as manned aircraft performance
1c	If autonomous UAS are allowed the programmer fills all the roles, perform all checks and inform the rest of the system of its intent
1d	If the pilot, dispatcher and mission commander are not co-located, but networked together, then collaboration tools must deliver crew responsiveness equivalent to any other flight
2	If the program office ignores the socio economic dimension, then the coordinated transition is unlikely to result in routine access for civil UAS operations.
2a	If sense and avoid is reliability must be proven without operating in controlled airspace
2b	if vehicles respond differently on takeoff or landing, then surrounding population with fight with NIMBY environment argument
2c	if airspace design change and UAS capabilities are out of sync, then UAS ops will be limited to exceptions - no progress
2d	If manned aircraft industry resists UAS
3	If harmonized standards don't address international security issues with routine file and fly operations, then UAS ops may be limited to domestic operations
3a	If UAS reporting requirements provide insufficient information to assess security risk for each flight
3b	if international agreements make it impossible to prosecute malicious acts across national boundaries or require unknown flights met with significant military response
3c	If a few hostile events may cause denial of access for all, then civil users may not pursue the UAS opportunity
3d	If operators such as drug runners regularly use UAS, then trust is lost and all UAS operations may be limited to domestic operations only
4	If reliability of vehicles and systems is inadequate to achieve comparable accident rates, then routine integration will likely not be approved
4a	If sense and avoid is reliability must be grown, then confidence will not be there to start
4b	If GPS is primary means for navigation and surveillance, then as a single point of failure for navigation of the aircraft it will not likely support routine UAS operations
5	if vehicles respond differently on takeoff or landing, then surrounding population with fight with NIMBY environment argument
6	If UAS reporting requirements provide insufficient information to assess security risk, then UAS operations may remain domestic
7	If Safety/Operational Data are not made available in large enough volumes to build a safety risk management document, then operational approval of routine use may not be possible.
8	If agencies use their missions to justify special treatment and airspace reservations, then routine UAS operations for public aircraft may not be granted
8a	If agencies hold to the notion of disposable UAS, then reliability and capability will not reach levels needed for routine use
9	If the program office focus ignores the air security dimension, then granting routine access to civil UAS operations is unlikely.

14 Appendix G: UAS Accommodation to Integration Questions

Key risks or uncertainties used to judge the interaction of state changes in the HHM.

14.1 Integration Transition

Technologies vs. Procedures – Which issues should be solved via a technology solution vs. a procedural/policy solution? Without a policy manufacturers could make different assumptions to deliver performance and cost expected by their customers, with the effect of creating a more complex control environment for the FAA? What are the costs associated with each, and who will pay these costs? What incentives will be offered to manufacturers and/or airports who comply with new standards?

Cost to Manufacturers – How will proposed solutions affect manufacturers? Will it differ depending on the size of the manufacturer? Is there an acceptable lowest-cost standard? Will it affect international and domestic manufacturers differently? What about manufacturer regulations and how they might be implemented across the world?

Cost to Operators – Will costs to UAS operators (for meeting standardization, certifications, etc.) deter consumers from using the system? Incentives to meet all standards/certifications?

Certifications – Who will conduct and pay for aircraft and pilot certification procedures? . The roles in UAS operation don't have to cleanly map to existing roles like pilot and dispatcher. How will these procedures be conducted? International versus domestic certifications – how will you certify UASs that might be coming into the U.S. NAS from a foreign country?

Acceptable UAS Mission Types – Are all mission types considered acceptable, or are there some that may disrupt other air traffic, peoples' privacy, etc.? Who determines this?

Airspace Classes – Should there be any additional rules and regulations for UAS in the airspace classes?

Property Insurance – How will public and commercial UAS be insured? Who will be responsible for damage to private property? Are there major differences of insuring U.S. versus international property? I.e. if a U.S. UAS damages foreign property, or a foreign UAS damages U.S. property

Line-of-Sight Rules – Will certain UAS be mandated to stay within the LoS of the ground pilot? How is this decision made?

Supply Chain Security – What safeguards will exist to keep UAS equipment clean of contraband parts? This could include viruses, outdated software, etc. Will certain countries be on a list of unwanted manufacturers, and who determines this?

14.2 Communication Failure

Pilot Awareness – How does a pilot know that a communication failure has occurred? How does he know what type of failure has occurred?

Duration – How long should a pilot wait to reestablish communication before taking further action?

Command & Control Security – What regulations/minimum technology standards should exist in order to ensure a certain level of C2 security?

Sense and Avoid – What regulations/minimum technology requirements should exist to ensure sense and avoid capabilities? What about emergency procedures?

Mechanical Failure – Any specific regulations regarding UAS mechanical failure? What about emergency procedures? .

Signal Interference – Any specific regulations regarding UAS signal interference with ground pilot or other aircraft? What about emergency procedures?

Sensor Misinformation – How will situations be handled in which the UAS sensors provide conflicting information to the pilot, ATC, or other aircraft?

Signal Jamming – Any specific procedures to deal with signal jamming or hijacking?

14.3 Loss-of-Link Procedures

Pilot Awareness – How does a pilot know that a communication failure has occurred? What should the appropriate actions for a pilot in this situation be?

ATC Notification Procedures – At what point should the pilot alert ATC?

ATC Lost Link Awareness – How can an ATC become aware that a UAS has lost its link to the pilot (aside from being notified by the pilot)?

ATC Mission Awareness – To what level should the ATC be aware of the type of mission the UAS is flying? Will this help in identifying a lost link or other erratic behavior?

UAS Behavior – What should be the expected behavior of a lost-link UAS? Should it continue on its current course or mission? Should it return to home base or try to gain higher altitude in order to try to reestablish the link? What behavior would be most disruptive to other traffic?

Traffic Advisories – Any special regulations on ATC giving traffic advisories when a lost link occurs?

UAS Squawk Procedures – Should there be a standardized squawk procedure for all lost-link UAS, or should they differ depending on the payload/mission?

NORDO Procedures – How should lost-link UAS procedures compare with no-radio (NORDO) procedures?

Sense and Avoid – What is the minimum level of automated sense and avoid capabilities that need to be present on a lost-link UAS?

14.4 Airworthiness

Equipage – What should be the minimum level of technology present on different kinds of UAS to make traffic with other aircraft seamless?

Redundancies – Minimum redundant technologies?

Aircraft Marking – Any special rules on aircraft marking, especially for very small UAS, to help other aircraft identify their location/bearing?

Communication Protocols – Any specialized communication protocols or radio frequencies for UAS?

Command & Control Security – Same as above.

Sense and Avoid – Same as above.

Standardization – How will standardized equipment be decided and who will decide on this? Who will pay for required standardized equipment? Will airlines utilizing UASs receive some incentives to comply with requirements?

Certification – How will equipment be certified for airworthiness and who will be in charge of the certification process? Who will pay for the certification process?

Software Security – How will the patching of software bugs be handled? How can it be insured that manufacturers' fixes be incorporated into operators' vehicles? Who will validate these procedures?

14.5 Flight Coordination

Visual Separation – How will UAS comply with FVR, and will other aircraft have to take into account the fact that they are dealing with a UAS? How will other aircraft know they are dealing with a UAS?

ATC Assignment – How will the transition away from a specialized assigned ATC be handled? Should there be special ATC emergency procedures for UAS?

Mission Clearance – Should any particular UAS mission types have to be specially certified before flying? .

Pilot-ATC Communication – How should communication between pilot and ATC be handled for different types of airspace? Should there be special protocols for UAS?

Pilot-Pilot Communication – Any special protocols for UAS pilots communicating with other aircraft? Any special markings on the vehicle?

UAS Automation – Should there be any regulations for what UAS actions can be automated vs. manual piloting? For example, take-offs and landings at different classes of airports?

Foreign UAS – Can foreign UAS be flown in U.S. airspace? Any special procedures or waivers? Can U.S. UASs be flown in foreign airspaces without special permissions and advanced coordination?

Waivers – Will UAS pilots need to obtain special waivers for any particular types of missions or vehicles?

14.6 Personnel

ATC Training – What new training procedures should ATC go through before handling UAS in their zone? Who will pay for new training procedures?

Pilot Training – What kind of training does the pilot need to fly a UAS? Does he need to be a certified pilot with a number of training hours? Time spent in a simulator or other special training? Who will pay for new training procedures?

Certification – How will training be certified and who will do the certification process?

Pilot Experience – Do pilots of UAS need a different amount of experience than pilots of manned aircraft, and what kind of experience is necessary? Different levels of UAS experience perhaps?

ATC Expectations – What should be the expectations an ATC should have of the behavior of a UAS? Should they be different from a manned aircraft?

Mission Programming – Do pre-programmed UAS automation procedures have to be verified or tested before flying in airspace with other aircraft? Who will perform these verifications?

Risk Tolerance – UAS pilots may have a higher risk tolerance than other pilots since they do not actually sit in the vehicle. How can this be accounted for?

14.7 Infrastructure

Launch & Recovery Sites – If a UAS can be launched or recovered without a runway, should there be regulations about the manner in which these UAS can be deployed into the airspace?

Ground Control Station – Any rules on where these stations can be located in relation to the UAS, populated areas, and airports? Line-of-sight rules with regard to the UAS?

Runway Allocation – Given that UAS may have different ground- and air-speed and ground collision avoidance capabilities, how will this impact runway allocation at airports?

Scheduling – Should there be any rules regarding the scheduling of UAS flights at airports with certain control tower hours?

Separation – How will proper vehicle separation be handled in different airspace classes? Any special rules for UAS?

UAS Land/Air Speed – Should ATC and other aircraft have special consideration for UAS with reduced maneuverability in certain situations?

Ground Object Clearance – Pilots of UAS may not be able to detect objects on the runway as well as pilots in a cockpit. Should there be any regulations regarding a minimum frequency/intensity of checking runways for unwanted objects?

Communication Protocols – Same as above.

15 Appendix H: UAS Transition Extreme Scenarios

Key: Catastrophic Hazardous Major

15.1 Integration Transition

Technologies vs. Procedures – A performance standard is put into place that would cost manufacturers millions/billions of dollars to comply, deterring competition from smaller manufacturers.

Certifications – High certification costs deter smaller manufacturers.

Airspace Classes – Flooding of Class G airspace by smaller UAS creates difficulties for other aircraft trying to use the space as an escape – could cause hazardous conditions for operators.

Supply Chain Security – Parts manufactured cheaply on a mass scale become integrated in certain lines of UAS and cause high levels of mechanical/electronic failures after the product is sold – hazardous conditions.

15.2 Communication Failure

Pilot Awareness – Software fails to report a communication failure and the pilot does not know something has gone wrong until a catastrophic event has occurred.

Sense and Avoid – A manned aircraft expects the UAS to behave a certain way, but because no communication is present the two aircraft fail to avoid each other – catastrophic event.

Signal Interference – Accidental signal interference from civilians using certain radio frequencies causes small UAS communication "black hole."

Sensor Misinformation – Pilot believes UAS is located at location A when it is actually at location B, and accidentally maneuvers toward/into another manned aircraft – catastrophic.

Signal Jamming – Intentional jamming by malicious user causes UAS to fly to an unknown location.

15.3 Loss-of-Link Procedures

Pilot Awareness – Lost link is not reestablished in timely manner and UAS behaves unpredictably to another aircraft, causing potentially hazardous condition.

UAS Behavior – UAS programmer is unaware of proper lost-link behavior and programs UAS to behave in a manner unpredictable to ATC/other manned aircraft, causing catastrophic collision.

Sense and Avoid – Automated sense and avoid on UAS does not operate correctly and fails to maneuver out of the way of another aircraft, causing catastrophic crash.

15.4 Airworthiness

Aircraft Marking – Small-wingspan UAS markings confuse another manned aircraft pilot as to the distance/bearing of the UAS.

Sense and Avoid – Poor sense and avoid technology causes UAS pilot to not detect another aircraft nearby and maneuvers the vehicle into the aircraft – catastrophic.

Software Security – Poor maintenance or programming is not checked before a flight mission, causing a failure/unpredictable behavior while airborne – hazardous condition for other aircraft.

15.5 Flight Coordination

Mission Clearance – A low-class UAS plans to fly in/around a populated area, loses communication and crashes into a building, injuring or killing civilians – catastrophic.

Flight Object Logs – UAS is handed off between multiple pilots, but the pilots fail to tell each other about some sort of maintenance issue, causing the UAS to behave erratically and creating hazardous conditions for other aircraft and operators.

15.6 Personnel

Certification – Someone with improper or non-existing credentials performs poor maintenance on a UAS, causing a hazardous condition.

ATC Expectations – A manned aircraft needs to escape into uncontrolled airspace, but ATC does not know what to expect of civilian UAS in that space, causing him to direct the manned aircraft into a potentially hazardous situation.

Risk Tolerance – UAS pilot is less risk averse than if he were sitting in the cockpit and flies in dangerous proximity to other aircraft, creating accidental catastrophic collision.

15.7 Infrastructure

Ground Control Station – UAS involved in some accident does not have a way to find out who was piloting the aircraft at the time.

Separation – UAS pilot is unaware of other aircraft and does not abide by normal separation rules, causing a hazardous condition for other aircraft.

Satellite Link Location – Proper communication link is not handed off between links correctly, causing communication failure and a hazardous condition.