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A Systemic Approach to Next Generation Infrastructure Data Elicitation and Planning Using Serious Gaming Methods

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A SYSTEMIC APPROACH TO NEXT GENERATION INFRASTRUCTURE DATA ELICITATION AND PLANNING USING SERIOUS GAMING METHODS

by

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ABSTRACT

A SYSTEMIC APPROACH TO NEXT GENERATION INFRASTRUCTURE
DATA ELICITATION AND PLANNING USING SERIOUS GAMING METHODS

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Infrastructure systems are vital to the functioning of our society and economy. However, these systems are increasingly complex and are more interdependent than ever, making them difficult to manage. In order to respond to increasing demand, environmental concerns, and natural and man-made threats, infrastructure systems have to adapt and transform. Traditional engineering design approaches and planning tools have proven to be inadequate when planning and managing these complex socio-technical system transitions. The design and implementation of next generation infrastructure systems require holistic methodologies, encompassing organizational and societal aspects in addition to technical factors. In order to do so, a serious gaming based risk assessment methodology is developed to assist infrastructure data elicitation and planning. The methodology combines the use of various models, commercial-off-the-shelf solutions and a gaming approach to aggregate the inputs of various subject matter experts (SMEs) to predict future system characteristics. The serious gaming based approach enables experts to obtain a thorough understanding of the complexity and interdependency of the system while offering a platform to experiment with various strategies and scenarios. In order to demonstrate its abilities, the methodology was applied to National Airspace System (NAS) overhaul and its transformation to Next Generation Air Transportation System (NextGen). The implemented methodology yielded a comprehensive safety assessment and data generation mechanism, embracing the social and technical aspects of the NAS transformation for the next 15 years.

This dissertation is dedicated to my mother...

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Thank you all very much.

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ACRONYMS USED

ADS-B	Automatic Dependent Surveillance - Broadcast
ALARA	As Low As Reasonably Achievable
ASDE-X	Airport Surface Detection Equipment Model - X
ASIAS	Aviation Safety Information Analysis and Sharing
ATC	Air Traffic Control
ATS	Air Traffic System
BTS	Bureau of Transportation Statistics
CAS	Complex Adaptive Systems
CAST	Commercial Aviation Safety Team
CATS	Compliance Activity Tracking System
CFIT	Controlled Flight into Terrain
CICTT	CAST/ICAO Common Taxonomy Team
COTS	Commercial-off-the-Shelf
DHS	Department of Homeland Security
DoC	Department of Commerce
DoD	Department of Defense
DoT	Department of Transportation
FAA	Federal Aviation Administration
FAR	Federal Aviation Regulations
FIS-B	Flight Information Services - Broadcast
GCOL	Ground Collision (CICTT Category)
GPS	Global Positioning System
HIPAA	Health Insurance Portability and Accountability Act
IAEA	International Atomic Energy Agency
ICAO	International Civil Aviation Organization
ICE	Icing (CICTT Category)
IRP	Institutional Review Board
JPDO	Joint Planning and Development Office
LDW	Logical Decisions® for Windows
MAC	Mid-Air Collision
MCDA	Multi-Attribute Decision Analysis
MLP	Multi Level Perspective
NAS	National Airspace System
NASA	National Aeronautics and Space Administration
NASSP	National Aviation Safety Strategic Plan
NextGen	Next Generation Air Transportation System
NMAC	Near Mid-Air Collision
NRC	National Research Council
NTSB	National Transportation Safety Board
OIG	Office of Inspector General
OOP	Object Oriented Programming
OR	Operation Research
OSTP	Office of Science and Technology Policy
PA	Policy Analysis
PBN	Performance Based Navigation

PNM	Probability Number Method
RAMP	Ground Handling (CICTT Category)
RAND Corp.	Research and Development Corporation
RI-A	Runway Incursion – Animal (CICTT Category)
RI-VAP	Runway Incursion – Vehicle, Aircraft or Person, (CICTT Category)
RPI	Responsible Primary Investigator
RRAM	Rapid Risk Assessment Model
RWSL	Runway Status Lights
SA	System Analysis
SACD	Systems Analysis and Concepts Directorate
SAIC	Science Applications International Corporation
SCF	System Component Failure (CICTT Category)
SCADA	Supervisory Control and Data Acquisition
SME	Subject Matter Expert
SOPR	Suggested Office of Primary Responsibility
SoS	System-of-Systems
SoSE	System-of-Systems Engineering
TA	Tailored Arrivals
TCAS	Traffic Collision Avoidance System
TIS-B	Traffic Information Services - Broadcast
TM	Transition Management
UAS	Unmanned Aircraft System
UNED	United Nations Environment Programme
UNIDO	United Nations Industrial Development Organization
VLJ	Very Light Jets
WAAS	Wide Area Augmentation System
WHO	World Health Organization

CHAPTER 1

INTRODUCTION

1.1 Background

The world is heavily dependent on various critical infrastructures in areas like transportation, communication, water, energy, banking and finance, etc. Critical infrastructures are "national infrastructures [...] so vital that their incapacity or destruction would have a debilitating impact on the defense or economic security of the United States"(U.S. Congressional Research Service, 2003, Jan. 29, pp. CRS-2). Today's critical infrastructures[1] are large-scale systems, comprised of multiple components, involving various stakeholders, technologies, policies and social factors (Frantzeskaki & Loorbach, 2008; Mayer, Bockstael-Blok, & Valentin, 2004). The interplay between the technology, users and policy makers creates the socio-technical aspect of infrastructures. Infrastructures inherently evolve over time to address changing needs by adapting and evolving to new situations, often not known in advance (Janssen, Chun, & Gil-Garcia, 2009). In recent years, various sociotechnical systems started to undergo a series of transitions. The definition of system transition is given as "a long-term fundamental change (irreversible, high-impact and of high-magnitude) in the cultures (mental maps, perceptions), structures (institutions, infrastructures and markets), and practices (use of resources) of a societal system" (Frantzeskaki & Loorbach, 2008, p. 1). In other words, the transition includes "a structural change in both technical and social subsystems" (Chappin & Dijkema, 2008, p. 1). These transformations are mandated by increased performability, sustainability and environmental efficiency requirements. However, modernization of these

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This dissertation uses APA Style

[1] Within this dissertation infrastructures and critical infrastructures are used interchangeably

infrastructures is being held back for reasons besides economics (Geels, 2005). Because large infrastructures like power, transportation, and communication contain multi-dimensional complexity and are essentially stable, transforming the existing systems to more efficient alternatives is challenging (Roos, de Neufville, Moavenzadeh, & Connors, 2004). The need to comprehend infrastructures at the societal level and understand technical, political and economic factors' interaction becomes more and more prominent (Hansman, Magee, de Neufville, Robins, & Roos, 2006).

The planning and implementation phases of such large-scale infrastructure transitions require close monitoring of performance parameters like safety, efficiency, and sustainability. Ensuring that infrastructure transition reveals a safer and more sustainable system has become a major challenge for society (Elzen & Wieczorek, 2005; Luna-Reyes, Zhang, Gil-García, & Cresswell, 2005). In order to do so, decision makers often need to test various strategies and perform analyses to characterize risk and other parameters. However, past strategies and historical data regarding previous infrastructure systems are no longer adequate for next generation infrastructure systems design because (1) previous systems evolved via incremental changes and system improvements which lead them to be unsustainable (i.e. congestion, energy shortage, air transportation delays, etc.) and (2) previous infrastructures were made to last and were robust but resistant to change which causes challenges (Elzen & Wieczorek, 2005; Frantzeskaki & Loorbach, 2008; Hansman, et al., 2006). Additionally, the increased presence of societal aspects in the socio-technical system structure causes complications in understanding and foreseeing solutions. The evolutionary nature of infrastructure systems and the ever-changing societal dynamics make every problem essentially unique, rendering historical data somehow ineffective (Brewer, 2007; Janssen, et al., 2009; Rittel & Webber, 1973).

The lack of empirical data causes decision makers to heavily rely on expert opinions for next generation infrastructure planning (Chytka, Conway, & Unal, 2006). The current research aims to develop a systemic framework to understand socio-technical systems and develop a test-bed for alternative scenarios while generating data. The goal is to help collect experts' opinions and aggregate data regarding the future state of the system while enhancing multilevel complexity communication among stakeholders. For that purpose, a serious gaming based platform is supported by various commercial-off-the shelf (COTS) software solutions to generate a simulation environment. The Next Generation Air Transportation System (NextGen) is used as a case study to demonstrate and validate the proposed methodology within the present work.

1.2 Future's different

Rittel and Webber (1973) state that past problems that 'professionals' (educators, housers, city planners, highway engineers, decision makers, etc.) solved were definable, understandable and consensual problems. Professionals were hired to eliminate undesirable conditions and reach the *commonly preferred* system state. Given the clear definition of the problem, during the 19th century, planners were able to solve issues like paving streets, connecting cities, eliminating dreaded diseases, delivering clean water to the majority of the population, providing social services to every city, etc. However, once these trivial engineering and decision making problems were dealt with, the more stubborn problems emerged. Besides the efficiency concept, equity was now being considered as a measure of accomplishment. The nation's pluralism and the differentiation of public values annihilate the idea of consensus. As the infrastructures evolved to their current states of interacting open societal systems, the traditional engineering design approaches tailored to solve technical issues were no longer valid (Rittel & Webber, 1973).

Besides the changing public dynamics and complexity of future systems, due to globalization, de-regulation, upcoming environmental concerns, and issues with the world economy, the future shape of infrastructures are more and more uncertain (Wenzler, 2008). Nowadays, each sector is facing varying degrees of discontinuous and rapid shifts in technology, deregulatory pressures, demand fluctuations, natural and human threats to operation, along with impacts of information technology on human factors, and shifting societal needs and expectations (Hansman, et al., 2006). The problems that businesses and organizations are facing are also becoming increasingly dynamic, ill-defined and complex with many variables and interactions. Given the reasons above, the future status of man-made systems like energy, transportation, warfare, agricultural or any other infrastructure cannot be predicted for prolonged timeframes. The next generation of infrastructure systems will be considerably different than the current system (Brewer, 2007).

1.3 Next Generation Infrastructures

A general definition of an infrastructure can be given as an essential system to the functioning of the economy (Bekebrede, 2010). Infrastructures include public and quasi-public utilities and facilities, and they are used by a large number of users (Janssen, et al., 2009). A more detailed description can be given as "infrastructures are facilities and their operations and the operating and management institutions that provide water, remove waste, facilitate movement of people and goods, and otherwise serve and support other economic and social activity or protect environmental quality (National Research Council, 1995, p. 121)." Infrastructure systems are viewed as socio-technical systems where hardware and software are the components of a more complex system, encompassing people, work processes, institutional and cultural factors (Luna-Reyes, et al., 2005).

Infrastructure systems have to evolve as performance requirements and demand constantly increase over time. The capacity increase coupled with better efficiency requirements mandate a constant modernization of infrastructure systems (Bekebrede, 2010). As a result, new technologies with promising capabilities were developed. Examples of these alternatives are the advances in nanotechnology, molecular biology, next generation energy sources or advancements in aviation.

Traditional infrastructure modernization includes adding these technologies to the existing infrastructure. Also known as incremental innovations, this method includes conventional technology development that takes place at the micro-level of systems (Hansman, et al., 2006). In fact, most current infrastructure systems evolved via incremental innovations where the new technologies that are developed are the variants of the existing systems that can be implemented without extensive instruction or training (Elzen & Wieczorek, 2005). Such infrastructure modernizations have been difficult, ineffective and inefficient to maintain. Consequently, a number of current infrastructure systems are unsustainable, showing signs of congestions, energy black-outs, flooding, etc (Frantzeskaki & Loorbach, 2008). It is believed that current infrastructure system deficiencies are related to the incremental innovation that took place during the late nineteenth and early twentieth centuries (Elzen & Wieczorek, 2005; Hansman, et al., 2006; Rittel & Webber, 1973). Elzen and Wieczorek argue that, instead of modernizing the infrastructure systems via incremental innovations, it is necessary to adopt the concept of "transitioning" the system which is defined as "a long-term change in an encompassing system that serves a basic societal function [...] where both technical as well as the social/cultural dimensions change drastically (Elzen & Wieczorek, 2005, p. 651)." The next generation infrastructure systems require a systems approach, addressing the infrastructures at societal as well as technological levels. It is imperative to include multiple perspectives and multiple disciplines in methodology development since real-world problems do not exist independently of their socio-technical, political, economic and psychological contexts. Hansman et al. pointed to the lack of rigorous methods for developing, evaluating and evolving future infrastructure architectures able to integrate legacy elements while also responding to new technologies, knowledge and demands (Brewer, 2007; Hansman, et al., 2006, p. 3). The next section will highlight the approach taken within this research to reach the aforementioned goal.

1.4 The need for a New Approach

Due to the presence of interdependency, multi-dimensional complexity (see Section 2.2.2) and societal factors, determining the system parameters of next generation infrastructure systems becomes a challenging task. Uncertainty -defined as the inability to determine the true state of a system caused by the lack of incomplete knowledge and random variability- is a major component in next generation infrastructure development (Chytka, 2003; Roos, et al., 2004). However, uncertainty is a much more prominent factor in large-scale infrastructure design versus the traditional engineering undertakings. Compared to specific engineering component designs (e.g. design of a power plant or a bridge) infrastructure systems (like electric power distribution, roadway network or internet) last longer and include more stakeholder interaction causing more uncertainties. Traditional engineering projects contain specific design parameters, mandated by clients, governmental requirements or design codes. The challenge in these projects is to optimize the output to meet the predetermined set of criteria. On the other hand, due to the presence of various competitive stakeholders, shifts in public perceptions and changes in the political environment affect the design requirements of infrastructure systems. Besides the unknown stakeholder strategies and the future political shifts, energy or transportation infrastructure planners are also unaware of the system-specific parameters like fuel prices, future customer demand, upcoming technologies, etc. (Vriesa, Subramahnianb, & Chappinc, 2009).

Decision makers, planners, and investors often rely on speculative knowledge and reach out for subject matter experts for their opinions (Ayyub, 2001; Chytka, 2003; Meyer & Booker, 1990). Current literature holds numerous structured expert elicitation methods. Expert elicitation methods are often used in obtaining quantified data in situations in which it is impossible to make observations due to technical difficulties, lack of resources or uniqueness of the problem (i.e. infrastructure systems design) (Bedford & Cooke, 2001). Consequently, traditional expert elicitation techniques perform best when used in traditional engineering problems. In these problems, the final state of the project, general requirements and objective are enclosed. It is possible to develop a prototype/model to test the acquired data with a simulation and observe the outcomes. However, when it comes to eliciting socio-technical systems, the societal part of the problem creates a challenge. These types of problems, due to their nature, don't allow planners to test their solutions. Each decision making strategy, after being implemented, can result in consequences for an extended period of time. The consequences of such decisions need to be observed across the social and technical aspects of the problem.

The problems associated with infrastructure development often come from both technical and social issues. For that reason, the interface between the two must be understood properly in order to develop an infrastructure transformation capability while embracing uncertainty (Hansman, et al., 2006). Creating a methodology aiming to outline the decision pathways of future systems and plan accordingly, while taking into consideration the technical, organizational, contextual and evaluative complexity of the system, also requires fundamental understanding of these interactions (Brewer, 2007; Hansman, et al., 2006).

There is a need for an approach to adequately create a venue for infrastructure expert elicitation environment, allowing both the societal and technical aspects of the problem to surface, while enhancing communication throughout the stakeholders. Hansman et al. emphasize the need for rigorous methods for developing, evaluating, and evolving future infrastructure architectures incorporating legacy elements along with the introduction of new technologies, knowledge, and demand. Such a method requires being flexible to reflect the latest process in infrastructure transformation and transparent enough for decision makers to enhance system understanding.

The present research concentrates on developing a comprehensive methodology in order to support the infrastructure transformation by enhancing the stakeholder communication. The methodology utilizes a set of models and tools in order to help the decision making process of designing and evaluating scenarios for future technological implementations. The methodology consists of using a comprehensive, yet intuitive, risk calculation approach used in process industries, coupled with scenario-based serious gaming platform. The subject matter experts' opinions are collected for both stages, namely during the development and implementation of the methodology. This approach aims to substitute the need for historical data, by using a combination of subject matter expert (SME) opinions and projected scenarios, to help create a multitude of probable futures. The meaningful "experimentation" capability was developed over NextGen in order to demonstrate the feasibility of such an approach and obtain data regarding the future phases of the system with the help of several approaches and commercial-off-the-shelf solutions present in the engineering management toolbox (Hansman, et al., 2006).

1.5 Problem Domain

In order to implement the aforementioned methodology, NextGen development consisting of a system-wide upgrade of the National Air Transportation (NAS) is taken into consideration as the problem domain. The NAS is a complex global system with many public and private stakeholders involved with national defense, homeland security, commercial and general aviation and future commercial space transportation (JPDO, 2007).

During the Bush Administration, in 2003, Congress took a significant step toward transforming the current Air Transportation System (ATS) via the Vision 100 – Century of Aviation Reauthorization Act, mandating the advent of NextGen. The Vision 100 Act also created a unique cooperative partnership between public and private stakeholders such as the Department of Transportation (DoT), Department of Defense (DoD), Department of Commerce (DoC), Department of Homeland Security (DHS), National Aeronautics and Space Administrator (NASA), the White House Office of Science and Technology Policy (OSTP) and industry stakeholders by forming the Joint Planning and Development Office (JPDO) (JPDO, 2008a). JPDO is charged with developing concepts, architectures, roadmaps, and implementation plans for transforming the current national ATS into the NextGen.

NextGen goals include flying an increased number of passengers, cargo and types of aircraft more safely, precisely and efficiently, while using less fuel and creating less environmental impact. It is envisioned that by 2025, JPDO will manage a complete overhaul to the system, shifting the navigation and surveillance from ground-based to satellite-based solutions. Additionally, voice communications will be substituted by digital data exchange, and weather forecast delivery systems will be tied to a single authoritative source (FAA, 2009). According to the above document, during the next two decades the goal is to achieve a system that:

- *can provide two to three times the current air vehicle operations;*
- is agile enough to accommodate a changing fleet that includes very light jets (VLJs), unmanned aircraft systems (UASs), and space vehicles;
- addresses security and national defense requirements; and
- can ensure that aviation remains an economically viable industry (JPDO, 2007).

The implementation of NextGen related technologies began in 2005 and already received vast criticism including cost and schedule risks along with management challenges (U.S. Department of Transportation, 2010b). The NextGen transformation was selected as the problem domain for this research due to its high-level complexity and involvement of numerous stakeholders while experiencing complications on both social and technical aspects.

CHAPTER 2

LITERATURE REVIEW

This chapter will cover the main literature used to build the methodology for this research. This section will highlight the relevant aspects of systems thinking, complex infrastructure systems, system transition studies, serious gaming approach, and finally the uncertainty and expert elicitation.

2.1 Systems Thinking

The capability of accelerating and steering complex socio-technical transitions became one of the chief concerns of developed countries. A complex system is "a bounded set of richly interrelated elements for which the characteristic structural and behavioral patterns that produce system performance emerge over time and through interaction between the elements and the system interaction with the environment" (Keating, Souza-Poza, & Mun, 2004, p. 3). Transitioning from any current tightly coupled and complex infrastructure (e.g. electricity power infrastructure) for any reason (e.g. for fighting global climate change or eliminating dependency on imported oil, thus vulnerability, etc.) will pose great challenges for policy-makers since these infrastructures are decades old, fully matured, highly networked and relatively efficient system-of-systems (e.g. the existing petroleum based supply chain with massive inertia) (Bush, Duffy, Sandor, & Peterson, 2008).

Human history is packed with examples of attempts (and failures) to guide transitions at the meta-system level. For instance, although the United States spends more money on healthcare than any other nation in the world, the country's uninsured population, infant mortality and life expectancy levels fall behind other developed nations. In a similar fashion, the war on drugs had a small impact on cocaine cultivation, production and smuggling, despite the billions of dollars spent each year (Sterman, 2006). From the environmental aspects, levees and dams aimed at controlling flooding led to even more severe floods due to the disruption of natural excess water dissipation. Such examples not only were unsuccessful in achieving the desired state of the system, they also caused more damage to the existing setup.

Policy resistance, as described by Sterman (2001), is the side effect of any intervention aimed at transforming a system where interdependencies and complexity are not fully understood. Sterman states that "you can't do just one thing" and "everything is connected to everything else" (Sterman, 2001, p. 9). The solution is the ability to see the world as a complex system, that is, systems thinking. Once a holistic worldview is adopted, it is argued that learning will be much faster and efficient, leading to the ability to understand the leverage points in the system and finally avoiding the policy resistance. However, even systems thinking and systems engineering are currently challenged to address increasingly complex systems due to the (1) elevated levels of interdependency and interoperability, (2) potentially radical requirements shifts caused by factors beyond technical aspects like policy or organizational funding, and (3) presence of an exponential rise in demand and accessibility of information (Keating, et al., 2004). Evolution of the systems engineering field yielded to the System-of-Systems (SoS) concept in order to develop more robust approaches as complexity and interdependency of future infrastructures increase (Adams & Keating, 2011). The definition of SoS is "a Metasystem, comprised of multiple embedded and interrelated autonomous complex subsystems that can be diverse in technology, context, operation, geography, and conceptual frame .... These complex subsystems must function as an integrated Metasystem to produce desirable results in performance to achieve a higher-level mission subject to constraints" (Keating, 2005, p. 1). Consequently, system-of-systems engineering (SoSE) is defined as "the design, deployment, operation, and transformation of metasystems that must function as an integrated complex system to produce desirable results" (Keating, et al., 2004, p. 5).

Researchers quickly grasped the idea of treating large socio-technical transitions from a SoS perspective. The complex and interdependent characteristics of infrastructures led to the adoption of a SoS approach within the transition body-of-knowledge and innovation studies (Bush, et al., 2008; DeLaurentis, 2005; Gheorghe, Masera, Weijnen, & De Vries, 2006; Hansman, et al., 2006; Pfaender, DeLaurentis, & Mavris, 2003; Pruyt & Thissen, 2007). DeLaurentis (2005) argues that decision-makers within government and industry cannot gain adequate insight from conventional analysis methods that are designed to study a constrained part of the problem: "Current frames of reference, thought processes, analysis, and design methods are not complete for these SoS problems" (DeLaurentis, 2005, p. 1). The need for a holistic framework enabling decision-makers to judge upcoming reflections for the infrastructure design, policy considerations or technology adoptions is crucial (DeLaurentis, 2005; Sterman, 2001). Hansman, et al. (2006) point out that developing integrated socio-technical models and methodologies are necessary to describe the interactions between the technical infrastructure and its social context. The current research aims to develop this capability by developing a test-bed for technical, political, and economic factors interaction and uncertainties by adopting the holistic approach of systems engineering methodology given in Chapter 3.

2.2 Complex Infrastructure Systems

Infrastructures, defined as the "underlying foundation or basic framework," are man-made constructs to deliver and/or distribute utility services (energy, water, mobility) to the masses. They are considered to be capital-intensive large-scale systems consisting of physical and organizational interlinked components. They allow interaction of many actors (e.g. system users, developers, owners, policy makers, etc.) with often conflicting diverse objectives, means and strategies (Frantzeskaki & Loorbach, 2008; Loorbach, 2007; Rinaldi, Peerenboom, & Kelly, 2001). The future generations of these infrastructure systems will increase in size, scope, and complexity. A complex system can manifest itself with numerous elements or subsystems, has a high level of interrelationships between the elements or subsystems, and contains a high degree of hierarchical levels (Bekebrede, 2010). With the increased system complexity, subsystem and component interactions increase, yielding more unexpected emergent properties and unanticipated consequences. Consequently, the system interpretations regarding the problem context get more diverse due to biased and distorted views brought by an increased number of individuals or stakeholders (Brewer, 2007; Roos, et al., 2004). Depending on the issues considered, each stakeholder provides its own perspective and interpretation, seriously affecting decision making processes and systems operations[2].

2.2.1 Interdependency

Another prominent characteristic of complex infrastructure systems is interdependency. Dependency is a unidirectional linkage between two infrastructures where the state of one infrastructure is directly correlated to the other (Rinaldi, et al., 2001). Examples of dependency are the power and telecommunications utilities. Telecommunication infrastructure requires power to operate, but the opposite is not necessarily true. On the other hand, interdependency designates a bidirectional relationship between infrastructures, connected as a system of systems. Power infrastructures and water utilities are interdependent on each other where water, necessary for cooling purposes, is controlled by pumps and lift stations which in turn require power. There are four types of interdependencies: physical, cyber, geographic, and

[2] As Gheorghe (2004) stated, complex infrastructure systems are threatened with systemic risks, large-scale risks with trans-boundary ramifications, characterized by three major challenges; complexity, genuine uncertainty and ambiguity. These risks inhabit at the intersection of numerous aspects of critical infrastructure systems, namely, natural events, economic, social, and technological developments within a policy-driven environment.

logical interdependencies[3]. The NAS and the aviation system, as a part of the transportation infrastructure, also contain these interdependencies among airports, airline companies as well as other stakeholders and entities.

2.2.2 Complexity

Future infrastructure systems will experience a multi-dimensional complexity. In general, the complexities can be categorized under two main types, technical/physical and social/political complexity, where the main difference in these two is the presence of quantifiable and non-quantifiable factors (See Table 2-1, Adapted from Mayer, 2009, p.845).

Table 2-1 Technical/Physical and Social/Political Complexities (Mayer, 2009)

Technical/Physical Complexity	Social/Political Complexity
Quantifiable factors	Non-quantifiable factors
Many interdependent variables (system complexity)	Many interdependent, loosely coupled stakeholders (multi-actor complexity)
Cognitive uncertainty	Disputed or contested knowledge, values and norms
Emergent behavior (e.g. counterintuitive)	Strategic behavior to optimize own interests, making use of loop holes in the policy
Design phases (linear of iterative steps of building and using model)	Dynamic rounds and arenas; volatile, erratic policy-making processes
Best solution, best available knowledge, optimization, validity, fidelity	Accepted solution, negotiated knowledge, political compromises
Hard computer tools: simulations, models, decision support systems	Soft tools: participation, process management, think thank meetings

[3] *Physical interdependency*, as the name implies, arises from the physical linkage between the two infrastructure systems, e.g. railroad transportation and electric power generation. Fuel necessary for the power generation is delivered via railroad, which requires power at all times to operate rail signals, switches and controls. *Cyber interdependency* implies the information transfer between systems, increasingly used in all infrastructure systems with supervisory control and data acquisition (SCADA) systems utilized in electric power grid control. *Geographic interdependency* relates to the physical proximity of two or more infrastructure systems where a local environmental event can create disturbances in all the systems. A recent example for the geographic interdependency is the 2011 Tohoku Earthquake in Japan where the Fukushima Nuclear Power Plants experienced meltdowns caused by tsunamis. Finally, *logical interdependency* can be determined where one infrastructure is linked to another one without the presence of physical, cyber, or geographic connection. An example of such interdependency is the link between electric power and financial infrastructures. Electricity market deregulation legislation passed in 1996 lead to power crisis in late 2000 in California (Rinaldi, et al., 2001).

Roos et al. (2004) further detailed complexity: technical complexity, organizational complexity, contextual complexity, and evaluative complexity. *Technical complexity* involves the design of infrastructure systems, inherently more complicated than the primitive versions, aimed at solving trivial engineering problems. Besides the traditional engineering performance criteria like performance and cost, designers also consider sustainability, flexibility, adaptability, safety, security, vulnerability and robustness. *Organizational complexity* arises from the nature of large-scale infrastructure systems involving numerous organizations from public and private sectors along with non-governmental organizations. Managing the process and information flows, configuration of human resources between these organizations with different corporate culture and values is a challenging task. *Contextual complexity* involves the internalization of so called externalities that are often left out while designing traditional engineering. *Evaluative complexity* surfaces when the large array of stakeholder groups involved in or affected by the design of the infrastructure systems have different perspectives (Roos, et al., 2004). The evaluative complexity is stemmed by the presence of numerous social parameters in the infrastructure design. The next section will provide more details on social aspects of the problem.

Throughout the maturation of the present research, previous studies associated with multi-dimensional complexity of technical systems were performed. One of the studies involves the integration of unmanned aircraft system (UAS) integration to NAS (Ancel & Gheorghe, 2008). Although proven beneficial on several areas of application, the integration of UASs to NAS is considered a rather challenging task due to technical, societal, and political interdependencies inherently present within the airspace. The study investigated employing object-oriented programming (OOP) to demonstrate the multi-layer complexity of the integration plan while introducing a “business process” concept. For that purpose, UAS-NAS integration was modeled using TopEase® software which is developed upon the OOP paradigm. The model was able to provide a full visualization of the integration phases, covering aspects like safety, security, air traffic management, regulation and socio-economic issues, allowing stakeholders or decision makers to examine the different layers of the process while observing the overall safety and performance parameters (see Appendix A[4])

2.2.3 Socio-technical Issues

The complex socio-technical systems such as large-scale infrastructures are separated from common engineering tasks by the presence of a large number of mutually dependent public and private stakeholders with different perceptions, interests, values, and objectives (Bekebrede, 2010; Luna-Reyes, et al., 2005; Mayer, et al., 2004). Problems with a social context are more complex given the number of non-simple interactions among the components and players:

> In such systems, the whole is more than the sum of its parts, not in an ultimate metaphysical sense, but the important pragmatic sense that, given the properties of the parts and the laws of interaction, it is a non-trivial matter to infer the properties of the whole system (Brewer, 2007, p. 160).

Planning problems where technical, social and economic characteristics are intertwined are inherently challenging and require different tools in order to understand their inner workings. Sociotechnical contexts must be designed in systemic, e.g. they adopt the idea that all aspects of a system are interconnected and they all should be addressed jointly. A difference in emphasis on any of the components during the design phase (e.g. technology over social aspects) will cause the system to underperform (Clegg, 2000). Rittel & Webber (1973) coined the phrase "wicked problems" for such planning problems, essentially different from the pure technical problems that scientists and engineers deal with. Problems found in the natural sciences (or

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[4] Appendix A includes further details on the complex structure of UAS-NAS integration problem. Experience gathered from working with OOP and agents helped shaping the present research framework by assigning characteristics to different objects such as participants (or stakeholders), laws, and regulations, fuel prices, terrorist activities for the case study which will be covered in Chapter 4.

technical problems) are definable and separable, and their solutions are obtainable. On the other hand, problems related to social and policy planning are ill-defined, and they depend upon political judgment and common consensus for resolution. The next generation infrastructure planning problems contain the societal aspects Rittel & Webber define as "wicked," in addition to the multi-dimensional complexity that is synonymous with such systems. Rittel & Webber classify the problems engineers and scientists focus on as "tame" or "benign" where the mission is clear. These problems are clear in definition regardless of their complexity or whether they can be solved or not. On the other hand, planning-type problems are malignant in nature because they don't have a definitive formulation, they have no stopping-rule or there is no way to test the solution.

The presence of multiple stakeholders with various agendas creates policy resistance, arising from dynamic complexity. Dynamic complexity is an often counterintuitive complex system behavior caused by the interaction of agents over time (Sterman, 2000). Depending on the issue at stake, various perceptions, diverse interpretations and proprietary assumptions create diversity which is not necessarily a positive thing given the persistent lack of time and resources associated with modernization of complex infrastructure systems (Brewer, 2007). The presence of societal factors creates wicked problems where the solution requires understanding the problem, yet the problem cannot be understood ahead of time without tackling it first. The modernization of next generation infrastructure systems involves understanding the different levels of complexity involved with such systems.

2.2.4 Complex Adaptive Systems (CAS)

Infrastructures are often designed to meet certain criteria, arising from the needs of society. The new elements of infrastructure systems are engineered with the influence of various stakeholders during the development phases. Infrastructure systems evolve and adapt to the changing environment when users adopt new services and functions (Janssen, et al., 2009). The adaptation of the complex ensemble of users and organizations occurs as a result of the learning process, happening at multiple levels. Due to the characteristics mentioned above, infrastructures are often viewed and analyzed as Complex Adaptive Systems (CAS) (Bekebrede, 2010; Janssen, et al., 2009; Lei, Bekebrede, & Nikolic, 2010; Rinaldi, et al., 2001).

CAS are systems that have a large number of components (often called agents), adapting and learning as they interact with each other. Challenges like controlling the internet (viruses and spam), understanding markets, predicting changes in global trade, strengthening immune systems all represent CAS. Consequently, the agents of CAS can be from a wide array of contexts, namely cells, species, individuals, firms, nations, etc. and any coherent behavior emerging stems from the cooperation and competition amongst these agents[5].

2.3 System Transitions Studies

Several bodies of knowledge focused on understanding, planning, and forecasting future technological innovations affecting infrastructure systems. Researchers and policy makers investigated the technological advancements and how the transition from old technology to new ones occurred. Throughout history, mankind witnessed numerous technological substitutions. For instance, the fuel source for the energy sector was substituted many times: from wood to coal, to hydrocarbons (or fossil fuel), to nuclear fuels, and to renewable energy sources (Fisher & Pry, 1971; Geels & Schot, 2007). Similarly, electric vehicles, internal combustion automobiles and hybrid sources were substituted back and forth for personal

[5] The agents' interactions are often non-linear and system behavior cannot be deducted from the component behavior. The general characteristics of CAS are the presence of the adaptive agents (dynamic stakeholder behavior, learning and adapting to new conditions), co-evolution (entities evolve partially depending on each other), and the emergent behavior (new structures, patterns, and properties arise, e.g. self-organization) (Bekebrede, 2010; Holland, 2006; Morowitz & Singer, 1995). Bekebrede also demonstrated that serious gaming methods adequately address the CAS behavior of complex infrastructure properties. Serious gaming will be elaborated on Section 2.4.

transportation as technology advanced. In order to understand and model such transitions both quantitative and qualitative methods have emerged[6].

Researchers investigated numerous infrastructure and transition related phenomena using the aforementioned methods in energy, transportation and aviation infrastructures. Examples of such work include the EU Energy System including the evaluation of several electricity generation technologies (Geels & Schot, 2007; Pruyt & Thissen, 2007) or market penetration of fuel cell vehicles in the German automotive market (Keles, Wietschel, Möst, & Rentz, 2008) or biofuel usage in U.S. transportation infrastructure (Bush, et al., 2008). The air transportation infrastructure was also modeled to investigate capacity growth (Miller & Clarke, 2007), taxation strategies (Sherry, Mezhepoglu, Goldner, Yablonski, & Knorr, 2005), resource management (Galvin, 2002), unmanned aircraft system integration (DeLaurentis, Cagatay, Mavris, & Schrage, 2001; Pfaender, et al., 2003) or technology integration (Mozdzanowksa et al., 2007; Mozdzanowska, Weibel, & Hansman, 2008) issues. However, the studies cited above a) either work with the current well-understood system dynamics, b) model the future phases of the system only with a numerical approximation of societal effects or c) include solely the technical aspects of the system under consideration. The comprehensive integration of social and technical aspects of infrastructures cannot be represented with feedback models or object oriented methods.

With these methods, researchers aim to define the complex relationships and long-term behavior and policy resistance (Bekebrede, 2010; Mayer, 2009; Sterman, 2000). Although very

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[6] These methods were used for military planning purposes including logistics, convoy routing and bombing raids during the Second World War. Following the Second World War, decision sciences including operations research, systems analysis, and policy analysis were used to develop optimal solutions for well-structured planning and management problems. Methods derived from applied mathematics, modeling, game theory, decision analysis, and computer simulations were used to investigate the effects of changing technological, economic and social environments. System Dynamics, Cellular Automata, and Agent Based Models were developed to simulate complex systems where sensitive parameters and unexpected behavior determination (Mayer, 2009).

powerful in replicating past innovation trends and able to explain unexpected behaviors after they have surfaced, simulation methods contain important drawbacks. Simulations do not include the political and positional rationality of stakeholders and social actors in the model. It is proven difficult to investigate feedback loops (e.g. system dynamics models) between causes and effects in societal problems (van Dijkum, 2001). The stakeholders can only be a part of the model once their behaviors are determined and quantified (Bekebrede, 2010). However, as Rittel & Webber stated, in order to capture the societal aspects of the problem, the problem needs to be understood in the first place (Rittel & Webber, 1973). The other drawback of simulations is that they are often very complex and based on mathematical formulations, making simulations "black boxes" for decision makers and infrastructure planners (Bekebrede, 2010, p. 12; Duke, 1974). The lack of communication between simulation designers and policy makers creates a gap which has proven to be problematic and decreases efficiency of the model. With the introduction of participatory modeling or group modeling it is possible to eliminate the effects of a lack of communication between the modeler and the decision maker, but due to their nature, computer simulations are unable to represent the dynamic and uncertain patterns of societal behavior.

Besides numerical methods, another body-of-knowledge called Transition Management (TM), emerged in the Netherlands. TM studies are involved in examining large sociotechnical transformations such as global environmental change related to CO_2 emissions within the EU (Chappin & Dijkema, 2008; Geels, 2002, 2005; van de Kerkhof & Wieczorek, 2005). Sustainability within the transition process is one of the key components in TM research and the goal is to empower and support ongoing sustainable development from a coherent and systemic perspective (Loorbach, 2007). TM theory emphasizes that large-scale system change cannot depend on technological advancements alone but also requires manual institutional and sociocultural transformations. TM is build upon the multi-level perspective (MLP) of system innovation (see Figure 2-1)[7].

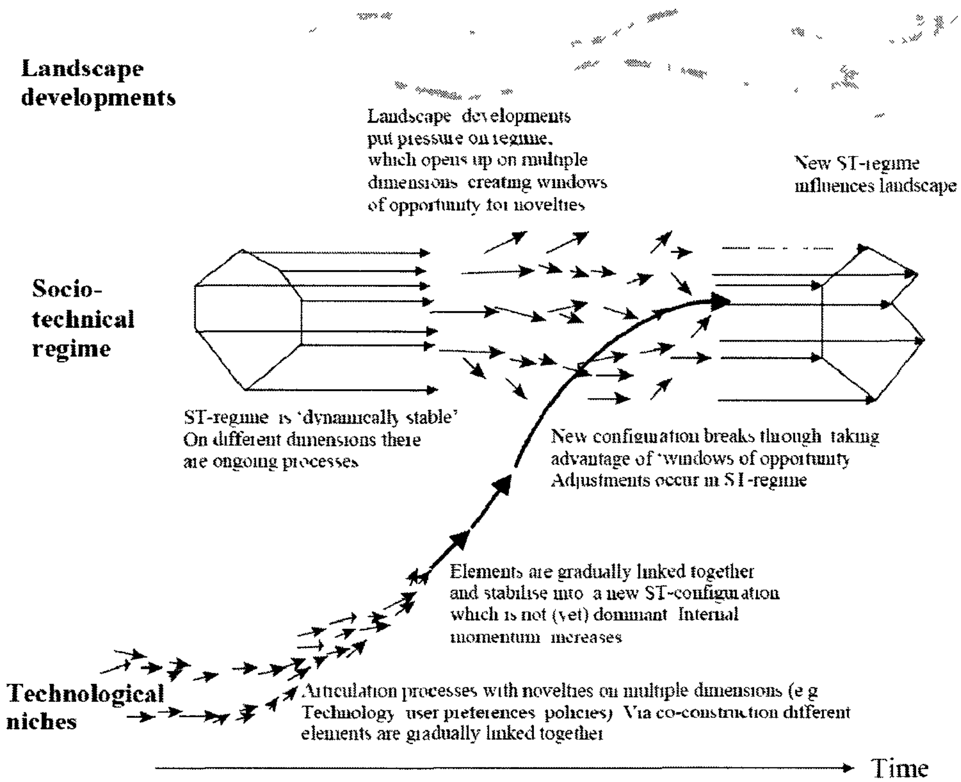

Figure 2-1 Transition Phases within the MLP approach (Geels, 2002)

Although it theoretically provides a framework for the transition process on large-scale technological systems, TM research is on the conceptual level and lacks the explicit

[7] The MLP is a framework to understand the inner workings of the system innovation occurrence and to help determining certain patterns. MLP consists of three levels, micro-level (niche), meso-level (regime) and macro-levels (landscape) and has a bottom-up approach. The technological niches are situated at the micro-level where radical innovations (or variations) take place (Genus & Coles, 2008). In a system transition, these innovations are linked together and stabilized. With the increased internal momentum, the new configuration breaks through the existing dynamically stable ongoing process through a window opportunity (i.e. congestion, environmental concerns, etc.) With the influence from the new configuration, the socio-technical regime adjusts itself to accommodate the competition created by the new technology. With time, the new technology replaces the old one and gets accepted at a wider range.

methodology to effectively learn and manage large-scale transitions. The MLP is presented as a global model, unable to cater to the complexity and ambivalence of specific case studies (Genus & Coles, 2008; Loorbach, 2007; van de Kerkhof & Wieczorek, 2005).

2.4 Serious Gaming and Policy Gaming

Over the last few decades, practitioners and management scholars increasingly criticized the conventional strategy making methods, arguing that rapidly changing environments require emerging and creative approaches. Serious gaming (simulation game or gaming, used interchangeably within the text) discipline is found to be increasingly useful within mainstream strategy literature involved with former strategy making approaches (Geurts, Duke, & Vermeulen, 2007). A definition of gaming simulation is given as a representation of a set of key relationships and structure elements of a particular issue or a problem environment, where the behavior of actors and the effects of their decision are a direct result of the rules guiding the interaction between these actors (Wenzler, 2003, pp. 146-147).

Serious gaming is an activity where two or more independent decision-makers seek to achieve their objectives within a limited context[8]: "The participants (or the players) of the game perform a set of activities in an attempt to achieve goals in a limiting context consisting of constraints and of definitions of contingencies (Greenblat & Duke, 1975, p. 106)". These games are labeled "serious" because their primary objective is educational and/or informative as opposed to pure entertainment.

[8] Serious games allow researchers to model problems with societal aspects which can often be found in next generation infrastructure transition efforts. The advantage of simulation gaming over traditional computer simulation models is that the stakeholders do not have to be represented by mathematical formulations; instead, they are played by the participants themselves (Bekebrede, 2010). Representing complex systems with serious gaming models save the model builders the need to build in the psychological assumptions since they are represented by the stakeholders.

Simulation games have many different forms and aim to provide insights for various goals. The common point on each simulation game is that reality is simulated through the interaction of role players using non-formal symbols as well as formal, computerized sub-models when necessary. This approach allows the group of participants to create and analyze future worlds they are willing to explore. Lately, large organizations reported serious gaming simulation uses for their organizational change management efforts (Wenzler & van Muijen, 2009).

Duke (1974) argues that formal complexity communication methods are inadequate when it comes to problems of the future due to their exponentially increasing complexity. He believes that "the citizen, the policy researcher or other decision maker must first comprehend the whole –the entirely, the system, before the particulars can be dealt with" (Duke, 1974, p. 10). The serious gaming method approach with respect to other techniques is given in Figure 2-2. Gaming simulation techniques can handle "many variables" and are distinguished from other techniques by being relatively uncalibrated and intuitive (Duke, 1974, p. xv). Each serious game is situation specific; consequently, they should only be performed within the intended and designed context. Failure to do so will result in poor results[9].

[9] Researchers argue whether simulation and gaming is a standalone academic field of study or a useful tool that can be used by other disciplines. The source of the ongoing debates is stemmed from the interdisciplinary nature of these games. The simulation and gaming is certainly an advanced tool in various areas like education, business, and urban studies, environmental issues etc. yet, to date, gaming researchers are still working towards a common theory and an established field of academic study (Shiratori, Arai, & Kato, 2003).

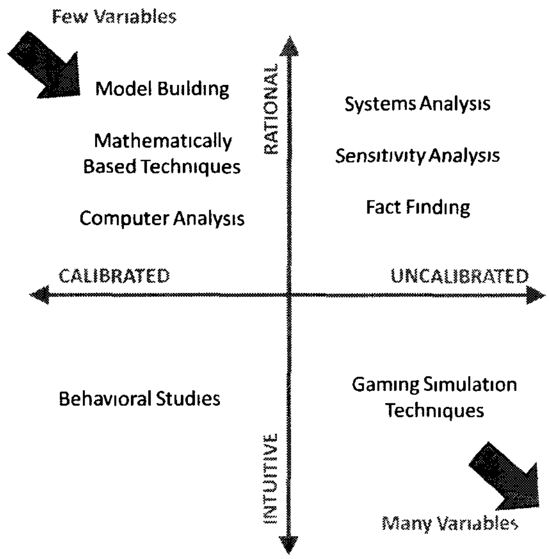

Figure 2-2 Schematic Location of Gaming/Simulation (Duke, 1974)

2.4.1 Brief History

The earliest and the most common uses of simulation gaming are so-called war games dating back to the 19th century and involved exploration, planning, testing, and training of military strategies, tactics and operations in a simulated interactive and sociotechnical environment (Mayer, 2009). With the emergence of decision sciences like operations research (OR), systems analysis (SA), and policy analysis (PA), the early serious gaming efforts initially received large skepticism. However, simulation and gaming methods (or soft systems thinking) became an alternative to formal complexity modeling techniques like systems analysis, systems dynamics and operational research. These techniques were successfully applied to well-structured problems; yet, when considering the ambiguous and often ill-structured and complex systems, their contribution was limited since adequate theory and empirical data were absent. Serious gaming methods are able to provide decision makers with an environment in which the totality of the system and its dynamics are present. With a holistic approach that includes the wide-range of perspectives, skills, information, and mental models of the involved parties, the quality of the decision-making environment increases dramatically (Geurts, et al., 2007; Wenzler, 2008).

In the late 1940s the RAND Corporation (Research and Development) created methods for systems and policy analysis to improve governmental decision making. Although gaming alone was still not considered to be a scientific approach within the policy analysis toolbox, the decision making society saw gaming as the 'language of complexity', a very useful approach to designing computer models. Several European Nations, especially the Netherlands, practiced various gaming exercises and gaming styles like spatial planning of the country at the national scale (participants played the roles of private and public investors, governmental licensers, stakeholders, and citizens). In the late 1990s, a large number of scientists leaned into the computer-based simulations given the developments on that platform. They adopted the concepts and technology derived for games for entertainment purposes and developed games like SIM HEALTH (U.S. Health care simulation), SPLASH (water resource management), and NITROGENIUS (multiplayer, multi-stakeholder game aiming to solve nitrogen problems). By 2000, games started to be employed for purposes like healthcare, policy making, education, etc. with the adoption of the oxymoron, *serious games* (Mayer, 2009).

2.4.2 Serious Gaming Uses

Serious games are developed to serve several different purposes. However, the most important contribution of gaming methods is their ability to enhance communication among various actors. This lead researchers to utilize gaming methods intensively in complex system exposition where complex systems with social aspects are examined (G. Bekebrede, Mayer, van Houten, Chin, & Verbraeck, 2005; Duke, 1974). Policy-gaming exercises carry various objectives like understanding system complexity, improving communication, promoting individual and collective learning,[10, 11] creating consensus among players, and motivating participants to enhance their creativity or collaboration (Geurts, et al., 2007). Policy games are often used in understanding complex infrastructure systems which will be covered within the next section.

2.4.3 Serious Gaming and Infrastructure Design

The complexity involved with system transition of large infrastructure systems is given in Sections 2.2 and 2.3. The discrepancies associated with such infrastructure transitions are related to the lack of understanding of societal aspects of these systems. For that reason, several serious gaming exercises are developed to assist decision makers, experience system complexity and train stakeholders. Serious games can represent the multi-level system architecture by proprietary rules at the player level, interaction of the players, and the system levels. The complexity associated with infrastructures (both the technical/physical and social-political levels) is integrated within the gaming platform for stakeholders to experience an abstract representation of the system and make informed decisions (Mayer, 2009). Several infrastructure systems are represented using serious games.

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[10] Serious gaming methods are often used as an educational technique to train players from high-school students to professional emergency responders (Greenblat & Duke, 1975; Shiratori, et al., 2003). Additionally, gaming methods are often employed in tandem with various fields; e.g. war-gaming, business-gaming, policy-gaming, urban-gaming, etc. Policy-gaming exercises assist organizations in exploring policy options, developing decision making and strategic change support. Such policy exercises can be used in a variety of problems; from deregulating public utility sectors, to reorganizing the Office of the Secretary of Defense, to restructuring cities with urban planning games, to investigating various policy options for global climate change, to restructuring UK's National Health Care System, crisis management at National Levels (Brewer, 2007; Crookall & Arai, 1995; Geurts, et al., 2007; Mayer, 2009; Wenzler, Kleinlugtenbelt, & Mayer, 2005)

[11] Games that are designed for individual learning can be categorized under three main objectives; training participants for a situation/scenario, changing participants' mental model with increased awareness, and attaining participants' support. Games where the collective learning is aimed three categories of objectives are observed; discovering (understanding a situation and exchanging ideas), testing (carrying out experiments to check the value or effectiveness of the options), and implementing (realizing the organizational change for training purposes) (Greenblat & Duke, 1975; Joldersma & Geurts, 1998)

Unlike hard-system methods, the gaming and simulation approach is quite flexible and easily adaptable to other quantitative methods, scenarios, and computer models (Mayer, 2009). Policy gaming methods can help both participants and modelers understand the big picture and identify critical elements of the complex problem at hand. Because of the iterative and experimental nature of these gaming and simulation environments, participants are able to test different approaches within both a safe environment and a condensed timeframe (Wenzler, 2008). INFRASTRETEGO is an example of a serious gaming-based decision making tool, aimed at encapsulating the Dutch electricity market. Game developers used the game to examine strategic behavior in a liberalizing electricity market while examining the effectiveness of two main types of regulatory regimes. Strategic behavior is the use of administrative and/or regulatory processes such as stalling, delaying, or appealing interconnection negotiations, engaging in anti-competitive pricing, or other methods that can be encountered within liberalization of utility industries. Empirical research indicates that strategic behavior may affect the level playing field and public values in a negative way. Overall, the game was able to identify the undesirable, unintended and unforeseen effects of strategic behavior phenomena. Serious gaming enabled monitoring and measurement of strategic behavior as it occurred since participants did not have any fear of litigation and were able to report the development of the strategic behavior which cannot be observed in real-world situations (Kuit, Mayer, & de Jong, 2005; Wilson et al., 2009)[12].

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[12] Similar to INFRASTRATEGO, games like THE UTILITY COMPANY and UTILITIES 21, along with other market, policy or performance simulation models are related to deregulation of utility companies (Wenzler, et al., 2005). One example of a fully-computer based simulation game is SIMPort, involving infrastructure planning and land designation for the extension on Port of Rotterdam. SIMPort is used to support the actual decision making process characterized by high level of uncertainty, path dependence and strategic stakeholder behavior, coupled with technical, political and external factors such as national and global economy (G. Bekebrede, et al., 2005; Warmerdam, Knepflé, Bidarra, Bekebrede, & Mayer, 2006). Furthermore, games like RESCUE TEAM and KING OF FISHERMEN are examples of games geared towards teaching and training of business ethics which were the causes of two major corporate accidents in Japan's nuclear industry (Wenzler, et al., 2005).

2.5 Uncertainty and Expert Elicitation

2.5.1 Uncertainty

Uncertainty is one of the core elements that need to be taken into consideration when analyzing and designing next generation infrastructure systems. Sound risk decision strategy formulations require prior identification and quantification of uncertainties (Chytka, 2003). Uncertainty is defined as the inability to determine the true state of a system and is caused by incomplete knowledge or stochastic variability (Chytka, p. 9). There are two types of uncertainty in engineering, classified as internal and external. Internal uncertainty is caused by (1) limited information in estimating the characteristics of model parameters for a given, fixed model structure and (2) limited information regarding the model structure itself. External uncertainties come from variability in model prediction caused by plausible alternatives, also referred to as input parameter uncertainty (Ayyub, 2001; Chytka, 2003).

The design and implementation process of socio-technical systems does not contain specifications, regulations or codes as in the case of designing traditional engineering systems. Instead, designing for uncertainty requires that policy makers to make decisions in situations where scenarios of competitive forces, shifts in customer preferences, and changing technological environment are largely unpredictable (Cooke & Goossens, 2004; Roos, et al., 2004). The uncertainty emerges from two sources: knowledge of the system and knowledge of the social response. Table 2-2 outlines the four types of problems arising from these initial conditions. As previously covered, large-scale infrastructure transitions are often considered as wicked (or ill-structured) problems (located at the bottom-right hand corner of the table).

Table 2-2 Uncertainty and Problem Types

Knowledge on Technical & Physical Parameters → / Knowledge on Social & Political Parameters ↓	High	Low
High	Substantial information on the system and its environment with substantial agreement on the objectives, solutions and effects (tame problems)	Technical solutions are available but their consequences either create social conflicts or they are not fully comprehended (untamed political problems)
Low	There is no uncertainty or conflict regarding the parameters or consequences on the social aspects, however the knowledge on the physical system parameters is limited (untamed technical problems)	Little consensus on both the technical and social aspects of the problem is present. Solutions and their future consequences along with the societal responses are unknown (wicked problems)

Infrastructure planners and designers need to obtain data regarding the future phases of the system transition. The required data for both developing the socio-technical transition model and for governing risks should mostly be provided using expert judgment and elicitation, which will be covered next.

2.5.2 Expert Elicitation and Aggregation Methods

Expert judgment is "Expert judgment data given by an expert in response to a technical problem. An expert is a person who has background in the subject area and is recognized by his or her peers or those conducting the study as qualified to answer questions" (Meyer & Booker, 1990, p.3). Expert judgment is used when information from other sources like observations, experimentation, or simulation is not available. Subject matter expert opinions are often employed on the estimation of new, rare, complex or otherwise inadequately understood cases, future forecasting efforts, or to integrate/interpret existing qualitative/quantitative data (Meyer & Booker, 1990). Multiple methods exist regarding the different elicitation techniques such as group interaction, independent assessment, questionnaires, qualitatively obtained data, calibrating expert judgment data, knowledge acquisition dynamics, and learning process studies. (Chytka, et al., 2006; Cooke & Goossens, 2004; Gustafson, Shukla, Delbecq, & Walster, 1973; Keeney & von Winterfeldt, 1989)

Large-scale socio-technical systems are made out of multiple components, involving various stakeholders, technologies, policies and social factors (Frantzeskaki & Loorbach, 2008). The multi-dimensional aspect of the next generation infrastructure systems requires decision makers to take into consideration all the complexity and uncertainty associated with such systems (Roos, et al., 2004). Decision and policy makers often require expert opinions to comprehend and manage the complexity within such systems. The data regarding various subsystems within the meta-system needs to be obtained from a group of experts and combined (or aggregated) in order to assist the decision making process (Cooke & Goossens, 2004). Individual expert's assessments are elicited and aggregated by mathematical and behavioral approaches (Chytka, 2003; Cooke & Goossens, 2004; Cooke & Singuran, 2008). Aggregation algorithms such as the Bayesian method[13], Logarithmic Opinion Pool, and Linear Opinion Pool[14] are used to combine the expert opinions regarding a system with known results. However, for future events with unknown results, behavioral methods and linear opinion pool were found to be more adequate (Figure 2-3).

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[13] Bayesian approaches are used for subjective type of information where knowledge (i.e. probabilities) is a combination of objective (prior) and subjective (obtained from the experts) knowledge. Although subjective expert opinion is integrated into the knowledge, Bayesian method still requires prior knowledge regarding parameter which doesn't exist for future events with unknown results (Ayyub, 2001; Bedford & Cooke, 2001).

[14] The opinion pool methods combine the elicited distribution via linear or logarithmic weighted averages. The opinion pools have been used in fields like meteorology, banking, marketing, etc. where there the experts weighting factors are validated with either historical data or the observance of the event which was very near term (Chytka, 2003).

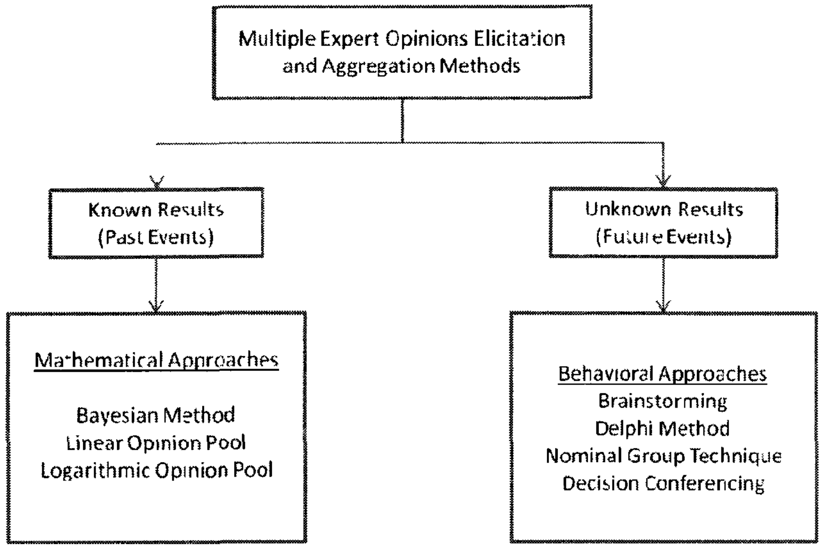

Figure 2-3 Expert Elicitation and Aggregation Methods

The behavioral approaches seek to come to a consensus among the participants through different forms of interaction including brainstorming, the Delphi Method[15], the Nominal Group Technique[16] and Decision Conferencing[17] (Ayyub, 2001; Cooke & Goossens, 2004; French, et al., 1992). Behavioral approaches suffer from different expert personalities leading to dominance of certain individuals or group polarizations.

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[15] Delphi method was heavily used in 1960s and 1970s on long-range technological innovation forecasting studies and policy analysis. The process involves an initial estimation session, followed by discussions and revision of the initial assessments. Typically the opinions converge to a high degree of consensus following two or three iterations (Meyer & Booker, 1990). The Delphi method is no longer used as extensively since it does not carry uncertainty indicators and it falls short on complex system forecasts with multiple factors (Cooke & Goossens, 2004).

[16] The Nominal Group Technique (NGT) allows expert interaction by presenting and discussing their assessments in front of the group. Following the discussions, each expert ranks the portrayed opinions silently where the aggregated ranking of these opinions represent the consensus among stakeholders. Scenario analysis revolves around two questions (1) how a certain hypothetical condition can be realized, and (2) what are the alternatives for preventing, diverting, or facilitating the process. Decision and event trees along with respective scenario probabilities are used to predict a future state (Ayyub, 2001)

[17] The decision conferencing is used to establish context and explore the issues at hand. It is used to facilitate making decisions and reaching consensus on complex issues such as planning the events following the Chernobyl disaster. Decision conferencing is often based upon multi-attribute decision analysis (MCDA) and help simulate discussions and eliciting issues. Events are often short, two-day conferences where the interested parties and experts gather to formulate and implement policy actions to offer the best way forward (French, Kelly, & Morrey, 1992)

The mathematical approaches covered above are often used to determine the technical parameters of systems at hand including the performance or safety values of newly developed systems. However, uncertainties resulting from the interdependency of stakeholder groups also have to be considered when modeling next generation transition efforts. Similarly, behavioral approaches received large criticism since participants of these methods had the urge to over-simplify their assumptions. Because complex systems often exhibit strongly counter-intuitive behavior, researchers simply cannot rely on intuition, judgment, and arguments from experts when eliciting behavioral data regarding complex systems (Linstone & Turoff, 1975): "[...] everything interacts with everything and the tools of the classical hard sciences are usually inadequate. And certainly most of us cannot deal mentally with such a magnitude of interactions" (Linstone & Turoff, p. 579). Also, when it comes to employing experts to elicit data, researchers often realized that specialists usually focus on the subsystem and mostly ignore the larger system characteristics. The mathematical or behavioral aggregation methods cannot be adequately used for gathering data from experts when it comes to large-scale system transitions.

2.5.3 Serious Gaming and Data Generation

A literature review revealed a limited number of studies regarding use of serious games as a data generation method. A study conducted by Rosendale (1989) employed role-playing as a data generation method about the use of language in speech act situations. The study was designed to reveal basic characteristics about how invitations within platonic and romantic situations occur. The gaming method was the only adequate method to gather data in these situations because authentic interactions cannot be observed without violating participants' privacy. Although Rosendale states that the role-play method has been shown to be a valid and reliable method, the limitations of using this method brought up questions about its validity and ability to represent real world interactions between humans (Rosendale, 1989).

Similar to Rosendale, Demeter (2007) also suggested using role-play as a data collection method related to apology speech acts by analyzing how apologies take place in different situations. Participants, chosen from English majors at a university from Romania, were engaged in a role-playing environment and asked to apologize within the scenarios presented to them. The naturally occurring discussions were collected and compared against another method called discourse completion tests (DCT). The author concluded that in some instances, role-playing produced more realistic data since it allowed participants to actually speak instead of writing their responses and they were more authentic since a natural setting was created by the scenarios (Demeter, 2007). Another qualitative study using role-playing to generate data was conducted by Halleck (2007). The gaming method was used to evaluate a nonnative speaker's oral efficiency using simulated dialogues. The biggest advantage of using role-playing is given as its ability to simulate a real conversation environment without violating participants' privacy.

Besides generating data for speech act studies, the only study related to data elicitation was the REEFGAME, simulating the marine ecosystems in order to learn from different management strategies, livelihood options and ecological degradation (Cleland, Dray, Perez, Trinidad, & Geronimo, 2010). The data generation ability of the game was limited to the decision-making processes of the stakeholders (fishers) which can be categorized under collective learning regarding complexity, and it was not elaborated on any further.

Considering the studies above, the literature survey did not provide any intensive data generation study conducted with serious gaming approaches, demonstrating the uniqueness of the study at hand.

CHAPTER 3

A METHODOLOGY FOR TECHNICAL AND SOCIAL INFRASTRUCTURE TRANSITION

The history of infrastructure development shows that the majority of the challenges associated with transitions are related to social aspects, rather than technology related issues. The pressure from various stakeholders with different agendas renders the infrastructure transition rather challenging. For this reason, decision makers and other stakeholders must experiment with design alternatives and their implications. Methodologies related to increasing communication, understanding, and alignment among stakeholders from diverse backgrounds, objectives and roles need to be employed in concert. Developing a model comprising these interrelationships, along with the induced technical and social complexity is the main approach of this research. The model should include drivers for change (new technologies, congestion, decay, efficiency and reliability, changing needs, etc.), constraints (existing structure, cost, environmental, social, and political impacts and externalities) and also context (government intervention, stakeholder actions, social factors, economic and political opportunities including developing new standards and protocols) (Hansman, et al., 2006).

The developed methodology in this dissertation consists of creating a platform capable of integrating technical infrastructure transition and its social context. This platform is aimed to serve both as an expert elicitation venue (similar to questionnaire or interviews in formal expert elicitation methods) and as a means of aggregation (combining opinions from multiple experts via approaches like the Bayesian method, opinion pools, etc.). Components of the proposed methodology (serious gaming, expert elicitation, and complex infrastructures) and their significance have been discussed in previous chapters. This chapter will provide a more holistic capture of the research methodology, design, development and execution of the elicitation approach as well as discussions of its validity.

3.1 A System-of-Systems Engineering Methodology

The reasoning behind undertaking large and complex infrastructures such as the air transportation system with a system-of-systems approach is given in Section 2.1 of the literature review. As previously defined, the SoS understanding includes embracing and undertaking the problem as a Metasystem, ensuring unison functioning of the interrelated and independent systems (Adams & Keating, 2011). Consequently, within the case study covered in this dissertation, the various systems constituting NAS (airlines companies, airports, government organizations, public, etc.) are treated as part of a higher-level system in addition to their internal structures.

The current research is geared towards developing a next generation infrastructure planning and data elicitation venue to extract and aggregate expert opinions for large-scale sociotechnical systems. As Keating et al. (2004) argued, a methodology provides a framework and is more general than a detailed method or tool, yet more specific than a philosophy. This framework should be designed to be effectively tailored in order to guide action. The characteristic attributes of a SoS engineering based methodology identified by Keating et al. are found to be suitable with the transformation efforts of large sociotechnical systems. The attributes are adapted from Keating, et al. and are given in Table 3-1. Attributes were employed to ensure that the proposed methodology meets the attributes of a system-based approach.

Table 3-1 System-of-Systems Engineering Methodology Attributes (Keating, et al., 2004)

Methodology Attribute	Methodology Attribute Description
Transportable	Capable of application across a spectrum of complex systems engineering problems and contexts.
Theoretical and Philosophical Grounding	Linkage of the methodology to a theoretical body of knowledge as well as philosophical underpinnings that form the basis for the methodology and its application.
Guide to Action	The methodology must provide sufficient detail to frame appropriate actions and guide direction of efforts to implement the methodology. While not prescriptively defining "how" execution must be accomplished, the methodology must establish the high level "whats" that must be performed.
Significance	The methodology must exhibit the "holistic" capacity to address multiple problem system domains, minimally including contextual, human, organizational, managerial, policy, technical, and political aspects of a system of systems problem.
Consistency	Capable of providing replicability of approach and results interpretation based on deployment of the methodology in similar contexts.
Adaptable	Capable of flexing and modifying the approach configuration, execution, or expectations based on changing conditions or circumstances – remaining within the framework of the guidance provided by the methodology, but adapting as required to facilitate systemic inquiry.
Neutrality	The methodology attempts to minimize and account for external influences in application and interpretation. Provides sufficient transparency in approach, execution, and interpretation such that biases, assumptions, and limitations are capable of being made explicit and challenged within the methodology application.
Multiple Utility	Supports a variety of applications with respect to complex systems of systems, including, new system design, existing system transformation, and assessment of existing complex system of systems initiatives.
Rigorous	Capable of withstanding scrutiny with respect to: (1) identified linkage/basis in a body of theory and knowledge, (2) sufficient depth to demonstrate detailed grounding within the systems engineering discipline, and (3) capable of providing transparent results that are replicable with respect to results achieved.

The proposed methodology within the current research involves combining tools from various disciplines: namely, serious gaming, risk assessment, expert elicitation, etc. Although it was developed within the NextGen framework, owing to its modular nature, the methodology may be adapted to suit different SoS level problems by modifying the embedded risk simulation mechanism or employing different COTS software adequate for the system at hand. The next section will provide details of the developed methodology and its systemic approach.

3.2 Gaming Cycles

Considering the SoS engineering requirements given above, a modular, flexible, and consistent methodology was created. The methodology consists of three phases: pre-gaming, gaming, and post-gaming. Each phase is supported by 'add-ons', including formal expert elicitation methods and ranking tools. With the help of these tools and techniques, data (both quantitative and qualitative) are gathered regarding the problem at hand(Ancel, Gheorghe, & Jones, 2010).

During the *pre-gaming* phase, it is necessary to collect all the gaming variables depending on the modeled system. Such variables include scenarios, stakeholders and their interactions, historical data regarding the system and information on the parameter(s) upon which the success of the transition process will be measured. The computer based simulation mechanism keeps track of the process throughout the gaming exercise. Depending on the application, the computer based simulation can evaluate risk or reliability of an infrastructure system or keep track of generation capacity or throughput of a certain utility. Once the adequate numerical simulation mechanism and all the supporting data are collected, the game is developed. Developing the game is an iterative process where versions are often tested by playing with several groups and then fine-tuning.

The *gaming cycle* includes the execution of the gaming exercise with the participation of experts. The game usually starts with the presentation of the scenario to the participants. Participants are asked to perform according to their predetermined roles. Considering the new information they have been presented, participants are asked to make collective decisions about the investigated parameters. The decisions are taken as the input variables for the computer assisted simulation mechanism where initial conditions for the next step are calculated. The iterative process enables participants to experience and shape the future phases of the transition process. The presence of participants (preferably experts or real stakeholders) social values, norms and beliefs provides the realistic input for the social interaction and the decision making process.

The *post-gaming* phase of the methodology involves data collection and analysis which surfaced during the gaming cycle. At this level the elicited data are arranged and presented back to the participants for further analysis and feedback. Although not performed, depending on the type of data elicited, it is possible to use several other types of COTS software to organize and analyze the data. In order to illustrate the methodology described above, the example from the problem domain, NextGen, was given in Figure 3-1. The high level gaming architecture of the expert elicitation methodology within the problem domain context is given below.

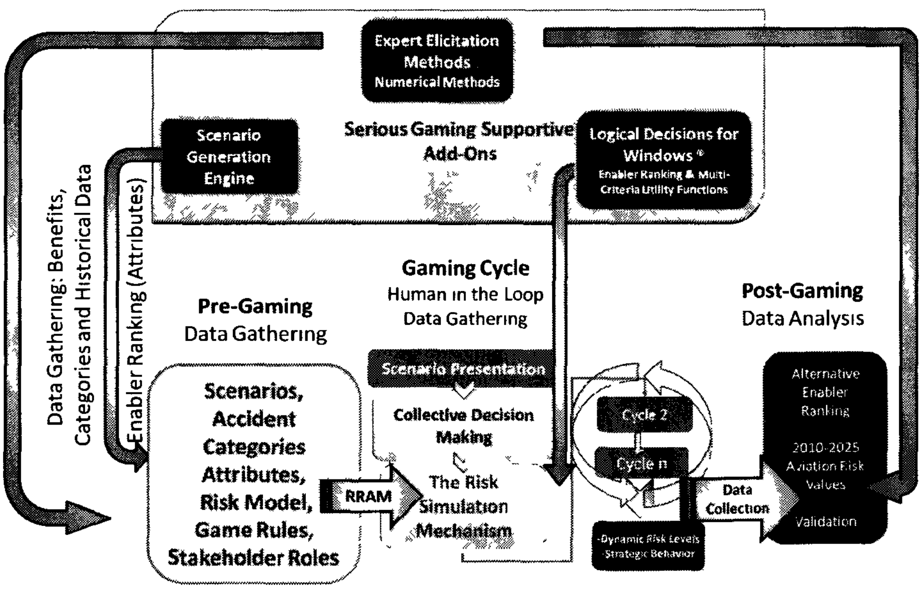

Figure 3-1 Serious Gaming Methodology - High Level Gaming Architecture

The problem domain is defined as 'determining the 2025 NAS safety values' by examining the chief safety related NextGen enabler and technologies. Within the NextGen framework, expert opinions and literature review provide scenarios, realistic timelines, involved stakeholders, technologies and other components of the infrastructure that are being modeled. The game cycles represent decision making milestones for these enablers. Data regarding enablers' characteristics (i.e. cost, benefit, timeline, equipage risk, etc.) are inputted to a risk simulation mechanism. This risk simulation mechanism is based upon an intuitive identification and prioritization approach called Rapid Risk Assessment Model (RRAM) and is adapted to the NextGen framework and embedded in the gaming cycle. The gathered data along with the risk simulation mechanism are then embedded into the serious gaming architecture. The gaming platform serves as the expert elicitation and aggregation arena since expert interactions from various stakeholder groups enable a realistic debate environment for discussion and examination of the social aspects of technology implementations along with technological aspects. The ost-gaming phase of the methodology includes data analysis and validation. The behavior knowledge generated throughout the gaming exercise, along with the 2010-2025 dynamic aviation risk values and alternative ranking constitutes the outcome of the elicitation method. This knowledge is used as the input for the sensitivity and other analyses and becomes the 'elicited data' of the proposed methodology. An overview of the components within the method will be provided next.

3.3 Pre-Gaming (Data Collection)

3.3.1 Gathering Gaming Variables

Within this section data regarding NextGen scenarios, game rules, stakeholder roles, future accident categories, NextGen enablers and technologies and their attributes are collected. By their nature, next generation aviation technologies and other parameters carry uncertainties (e.g. advantages of a certain technology in 15 years, cost-benefit values, etc.). Consequently, the data need to be obtained mainly by eliciting expert opinions.

For that purpose, a preliminary data gathering session based on single-point estimations was organized during the development stage of the game where experts provided their opinions regarding the benefits of future technology implementations (Cooke & Goossens, 2004). The gathered data was later embedded in the gaming variables. However, traditional mathematical expert elicitation methods are not fully suitable for this type of data generation since the data cannot be verified in the near future and uncertainty indications should be present. The literature survey concluded that the Linear Opinion Pool developed by Chytka, (2003) for the cases where the results remain unknown for extended periods of time, is the most suitable for this study[18].

Besides the technical data requirements, game designers determine the current status of the infrastructure system by gathering the most recent historical data in order to create an initial condition for the game. Such data may include but are not limited to the anticipated infrastructure transitioning approaches, apparent stakeholder rules (organizational structures, etc.), existing accident categories or other values of interest that will be tracked down, etc. Once the clues regarding the current status of the infrastructure and the anticipated transitioning approach are determined, the general outlines of the scenarios need to be created.

[18] The Linear Opinion Pool enables decision-makers (i.e. game builders or facilitators for this case) to mathematically aggregate expert opinions with the lack of likelihood functions and expert creditability assessments. The experts are queried regarding the unknown parameter and then asked to provide its uncertainty assessment rating. The results are then aggregated and distributions on each parameter are obtained. This methodology allows game designers to obtain data required for enabler ranking during the pre-gaming section.

3.3.2 Scenario Development

Scenarios constitute one of the main elements of complex models, simulations or serious games. The scenario allows the modelers to create the environment in which the particular system operates. Similar to other gaming parameters (e.g. the technological advancement contributions or their timelines), the scenario to be investigated is often determined by subject matter experts. In order to support strategic planning efforts, workshops, serious games, think-tanks or other behavioral expert elicitation techniques (Delphi Method, Nominal Group Technique, etc.) are often organized (Jacobs & Statler, 2006; Wiek, Binder, & Scholz, 2006). An example for such a study was conducted in 1997 by the National Research Council (National Research Council, 1997). Experts from academia, aviation related public and private sectors, scientists, consultants, the armed forces, and government agencies were able to determine five scenarios with great depth for the next 15 to 25 years. Out of five chosen scenarios, the aviation industry experienced three of the predicted futures, including the 9/11 attacks, a steep increase in fuel prices, and the effects of the global market in aviation.

When constructing a scenario, the overall goal must be formed during the initial stage of the process. Goal formation includes the determination of the expected results, system boundaries, knowledge base, stakeholder functions, etc. Once the goal is clarified, the scenario is constructed in an iterative manner. On the other hand, developing scenarios for gaming purposes is highly dependent on the type of the simulation's goals. If the purpose of the game is to offer policy recommendations or implications, the scenario has to play a dominant role. If the purpose of the game is educational, the scenario must be able to promote creative thinking and imagination in its participants (deLeon, 1975).

3.4 Gaming Cycle

3.4.1 Serious Gaming as a Way of Understanding Infrastructures

Luna-Reyes et al. (2005) state that the presence of social and organizational factors can cause up to 90% of the information system project failures, resulting in not delivering the expected benefits. For that reason, it is crucial to integrate such societal factors into the design of large-scale infrastructure design processes. As mentioned in Sections 2.4 and especially 2.4.3, simulation gaming methods have recently shown promise in large-scale sociotechnical system planning efforts. Their ability to integrate the social and technical aspects of infrastructure development delineates these methods as the most appropriate candidate for creating a venue combining computer assisted stakeholder interaction. In this way, serious games provide insights into how to address issues arising from the interaction of players, roles, rules and scenarios. Mayer describes serious gaming derived applications as " [...] a hard core of whatever the computer model incorporated in a soft shell of gaming (usually through some form of role-play)" (Mayer, 2009, p. 835). In order to support the case study, the RRAM described below is used as the hardcore computer model to measure throughout the exercise[19,20]. The more detailed demonstration of gaming methodology, Section 4.2, provides the gaming cycle overview within the NextGen context.

[19] Besides the RRAM, the commercially available decision support software, Logical Decisions® for Windows (LDW) v.6.2, was selected as a supportive COTS add-on. The software assists the gaming process by helping participants evaluate and prioritize among the available decisions they have throughout the game (Logical Decisions, 2007). LDW's dynamic ranking capability of various alternatives provides real-time support in selecting alternatives according to their parameters (e.g. cost/benefit values, environmental impact, implementation risks and timelines, etc.). In the light of present information at any given time, informed participants are encouraged to alter their value judgments, visualizing the tradeoffs of each option before making their decisions.

[20] In addition to LDW, other software packages like Precision Tree® and TopRank® from Palisade Company were investigated for gaming support. This combination enables the graphical representation of possible decision outcomes gathered from the serious gaming data gathering session using decision trees and influence diagrams in an organized manner. TopRank® performs automated and multi-way "what if" sensitivity analysis for the organized decision trees identified by the gaming process.

3.4.2 Rapid Risk Assessment Model

The RRAM serves as the estimation and quantification of risk values, comprised of separately calculated accident probabilities and their respective consequences. The probabilities within the model are estimated via the Probability Number Method (PNM), and the consequences are approximated via numerical manipulations. The RRAM is supported by historical and expert elicited data as well as the gaming to numerically generate the risk values throughout the methodology.

The RRAM was used as the risk simulation mechanism selected for the case study. However, depending on the problem at hand, this model can be replaced with any adequate software, method, or an existing study measuring aspects like network capacity, throughput, financial status, etc. The adaptability of the gaming method allows developers to switch and/or combine different approaches which will provide a systemic view of the problem. Details regarding RRAM are given below.

3.4.2.1 Introduction

The RRAM was created through the joint effort of the International Atomic Energy Agency (IAEA), the United Nations Environment Programme (UNED), the United Nations Industrial Development Organization (UNIDO), and the World Health Organization (WHO) under the United Nations umbrella[21]. The model and the associated method were developed as an affordable solution for a quick turn-around needed to determine risks associated with handling, storage, processing and transportation of hazardous materials. The risk assessment methodology (including the PNM approach) was supported by an extensive database containing various types of substances (i.e. flammable, toxic, or explosive gases or liquids), safety

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[21] The director of this dissertation, Dr. Adrian Gheorghe, was a part of the Scientific Secretariat and brought in expertise regarding decoding, modifying and adapting the probability number method to the issue at hand.

precaution measures, population densities and environmental factors, etc (International Atomic Energy Agency, 1996). However, as opposed to answering questions such as the maximum number of fatalities or effect of distance, the PNM induced risk assessment methodology was more focused on prioritization of actions in the field of emergency preparedness.

3.4.2.2 Consequences and Probabilities

Risk is defined as the product of the probability of an accident and its respective consequences (Bedford & Cooke, 2001). The IAEA study estimates probabilities and consequences separately. The consequences of an accident (e.g. an event caused by storage or transportation of certain hazardous materials) are calculated via simple numerical manipulations, taking into consideration the characteristics of the substance and correcting factors regarding the area, population density, accident geometry, etc. The required data to form the components of the equation is obtained through previous modeling efforts and expert opinions[22]. On the other hand, the probabilities are estimated via PNM where the probability of a certain accident happening is calculated via a dimensionless 'probability number', N, which is in turn transformed to actual probabilities. The probability number is adjusted/updated according to the various correcting factors. The relationship between the probability and *N* is given via $N = |\log_{10} P|$. The risk is defined as the product of the consequences and the probabilities of unwanted outcomes (hazardous events). For the NextGen case study, the

[22] In a similar fashion, the probability of an accident involving hazardous material storage or transportation is calculated via utilizing the probability numbers. An average probability number representing a base assumption for each case is determined then adjusted with correcting factors. These factors represent various categories, from the presence of safety systems and precautions to the operational frequency of the substance. Once the base probability number is adjusted, it can be converted into probabilities. The probability number method was applied to industrial applications where the sole consequence parameter is fatalities. However for the cases where multiple damages are present, methods can be used to aggregate various consequence factors. Refer to Appendix B – Probability Number Method (APPENDIX B – RAPID RISK ASSESSMENT MOD) for further information.

adequate interpretation and calculation steps were adopted and integrated which generates the risk simulation mechanism (see Section 4.3 for further information).

3.4.2.3 Estimation of the Societal Risks

The previous section provided calculations of human casualties (fatalities) associated with an accident, along with the probabilities of such accidents occurring. The risk to the public from these activities is estimated by combining these two values. The consequences are categorized with respect to the fatalities and the probability classes are categorized by the order of magnitude of the number of accidents per year (e.g. societal risk operational instrument). The consequence–frequency (x-y) diagram is created. The main goal is to obtain a list of activities whose risks have to be further analyzed before others. The risk matrix representation is one of the primary outcomes of the method.

3.5 Post Gaming (Data Analysis)

Throughout the gaming effort, the discussions and possible negotiations within the opposing parties are important findings that can lead to different problem solving approaches. The results of a game run are analyzed to examine if the gaming exercise influenced the beliefs, intentions, attitudes, and behavior of participants, yielding to a better understanding of complexity (Joldersma & Geurts, 1998). The serious gaming exercise serves both as an individual and collective learning platform for the stakeholders, leading to an elevated level of knowledge over the system (Wilson, et al., 2009). The individual learning takes place during the decision making process where each stakeholder group represents its respective point of view. The reflective conversations between the participants enable feedback and help participants build informed judgments. Therefore, the presence of realistic interactions among players helps the testing and evaluation of NextGen related technologies in the future (Joldersma & Geurts, 1998). Also, like individual learning, collective or organizational learning provides insight into the system at hand (i.e. NextGen aviation safety values).

3.5.1 Data Collection

Besides collective and individual learning, another main contribution of the gaming methodology is generated data. Considering the nature of predicting future states of complex infrastructure systems, fusing simulation mechanisms with the soft gaming method creates the best possible venue for expert elicitation for cases when the game is played with real stakeholder and subject matter experts. In order to collect, sort, and visualize the data, an intuitive but comprehensive mechanism was developed for this methodology which will be discussed in Section 5.2. Since the validity of the extracted data cannot be revealed until the future states of the system are attained, the sole way of doing so is to check the internal validity of the generated methodology again by using expert opinions.

3.5.2 Expert Feedback

Expert feedback is a main contributor in all phases of the methodology. Experts from all stakeholder groups help shape possible scenarios, provide numerical data regarding the future technological enablers and also assist in evaluating the developed methodology in different categories. Expert participation in all three phases of the gaming-based elicitation methodology is prominent since it allows game developers to constantly modify the gaming components by taking participant comments and recommendations into consideration. Due to the large level of the system, no one expert is sufficient for gathering all the data needed to develop gaming based on the given methodology. For that reason the methodology, provides a common elicitation aggregation opportunity for next generation infrastructure development. The validation section further iterates the expert feedback embedded in the validation questionnaire given in Appendix C.

3.6 Methodology Integration

The sections covered within this chapter (pre-gaming, gaming, and post-gaming) constitute the use of several models (RRAM, PNM), methods (serious gaming, expert elicitation), COTS solutions (LDW, TopRank®), and data sources. It is crucial to seek seamless integration between the components of this methodology in order to create an efficient representation of the reference system. Besides the methodology components, the adequate capturing of the characteristics of the system (e.g. motivation for change, constraints, system context, as well as the societal, technical, and economic aspects.) carries vital importance for the validity of the generated data. Because system characteristics vary with the context, the steps the modeler needs to take change from problem to problem. For this reason, the adaptation of this methodology to other infrastructure system transitions most likely requires modifying the contents of the tools and approaches, yet it is important to develop a thorough balance in the methodology integration to capture both societal and technical aspects of large infrastructure transition problems.

3.7 Validation

The early adopters of gaming were quite skeptical of its abilities to test strategies or forecast developments with confidence. They concluded the major benefit of the game was to suggest research priorities and identify major problems related to policy and action requirements (Mayer, 2009). The main criticism of the field was caused by gaming's eclectic, diverse and interdisciplinary nature along with the lack of defining terms and concepts (Gosen & Washbush, 2004). However, the failure to implement sustainable infrastructure models indicated that the multi-dimensional complexity of modern systems required different approaches and design principles (Roos, et al., 2004). As an alternative answer, research studies employing gaming methods increased exponentially after the 1970s (Duke, 1974)[23].

The literature review demonstrated three relevant validation definitions regarding the contents of this research. Peters et al. (1998) review the concept of validity under four criteria, as suggested by Raser (1969): psychological reality, structural validity, process validity, and predictive validity. Greenblat (1975) describes the types of validity related to gaming models with common sense or face validity, empirical validity, and theoretical validity. Chytka (2003) provides a validation triad containing performance, structural and content validities to validate her methodology. The common traits of these validation approaches are given in Table 3-2.

Embarking from the definitions of Greenblat (1975) and Peters et al. (1998), face validity or psychological reality refer to the realistic gaming environment experienced by the participants. For a game to be valid, the environment must portray similar characteristics to the reference system. The empirical validity given by Greenblat designates the closeness of the game structure to the reference system. The definition given by Peters et al. separate the empirical validity into

[23] Although one can come across a vast amount of literature regarding the validity of experimental situations (internal and external validity), measurement instruments (content and construct validity), and the specific research method or its results, the concept of validity regarding simulation games is barely elaborated in the literature (Peters, Vissers, & Heijne, 1998). The validity of gaming usage was mostly investigated regarding its ability to enhance education and training. Researchers studied the specific gaming attributes that contribute to learning outcomes and evaluation of gaming methods training effectiveness (Feinstein & Cannon, 2002; Gosen & Washbush, 2004; Wilson, et al., 2009). Simulation approach received several criticisms regarding its ability to serve as an educational tool where the main concerns focused on internal and external validities. For the cases where the changes on the classroom environment or generalizability of the learning effects to outside classroom situations were problematic (Gosen & Washbush, 2004). Very generally, the validity within the simulation games can be given as the correspondence between the model and the system itself (or the reference system). However, this definition is not very accurate since the level of correspondence between the model and the referent system is unknown; it could mean that the model has to one-to-one representation of the complex system or only few components of the system are modeled. Additional criteria are necessary to distinguish the level of association between the model and the system being modeled (Peters, et al., 1998). The conclusions reached via a simulation game should be similar to those that can be experienced in the real-world system (Feinstein & Cannon, 2002).

two sections: structural validity (covering the game structure, theory and assumptions) and process validity (concerning the information/resource flows, actor interactions, negotiations, etc.). For the simulation to be valid, all the elements of the game (actors, information, data, laws, norms, etc.) should be *isomorphic*, meaning the elements and relations do not necessarily have to be identical but should be able to demonstrate congruency between them. Finally, the last element covered by both definitions is related to the theoretical validity: the models' ability to reproduce historical outcomes or predict the future, and conform to existing logical principles.

Table 3-2 Validation Parameters

Greenblat (1975a)	Peters et al. (1998)	Chytka (2003) – Validation Triad
Common Sense (Face validity)	Psychological Reality	Performance Validity
Empirical Validity	Structural Validity	Structural Validity
	Process Validity	Content Validity
Theoretical Validity	Predictive Validity	

Chytka (2003) developed a validation triad[24] (based on the validation square cited in (Pedersen, Emblemsvag, Ellen, & Mistree, 2000)) in order to assess the aggregation methodology which was developed within her dissertation. The aggregation methodology provided risk analysis in an aerospace conceptual vehicle design that relies heavily on subjective expert judgment which is hard to validate. Although in a different context, Chytka's validation

[24] The validation triad consists of three components, namely, performance, structural and content validities. These components are elaborated within an unstructured interview process to obtain the validity of the methodology. The performance validity includes the efficiency of the methodology and the usefulness of the uncertainty representation. The structural validity is concerned with the usability and added value of the methodology and its applicability beyond the test case. Finally, the content validity is involved with the appropriateness of the aggregation method chosen for the study

approach was found to be relevant to the research at hand since both involve complex systems lacking an adequate quantitative validation possibility.

The current research methodology relies heavily on subjective assessments obtained from experts at all levels (pre-gaming, gaming, and post-gaming phases). Subsequently, the validation parameters of the methodology require subject matter expert opinions. Validation of the research in this dissertation depends on subjective methods where there is no predictable, stable and data rich environment. Consequently, the outcomes of the methodology cannot be put to test (i.e. 2025 NAS safety values). The validation of the proposed methodology was obtained via a developed validation questionnaire which was based upon the previous works cited within this section. This questionnaire was supplied to the participants along with the preliminary game results in order to receive validation feedback. Appendix C includes the validation questionnaire.

3.8 Human Subjects Research Requirements

The described methodology involved subject matter expert participation during the development and execution phases. Additionally, the earlier phases of the study were funded by federal support which implied the review of the research by the Institutional Review Board (IRB) before any data collection in order to protect the rights and well-being of human research subjects.[25,26] Appendix D provides the Institutional Review Board (IRB) approval of informed consent document and use of photo/video materials for data extraction and analysis (ODU IRB 10 – 157).

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[25] The IRB examines the research to ensure compliance with Code of Federal Regulations Title 45 Part 46 (45CFR46) and State Legislation (Virginia Code 32.1-163.16). IRB requires detailed definitions of the research scope, project design considerations, experimental procedures, questions and briefings presented to participants and contents of the informed consent document. The informed consent document provides information regarding the study, compensations, benefits, and potential risks along with precautions taken to mitigate them. The IRB requires training of researchers and responsible primary investigators (RPIs) on Health Insurance Portability and Accountability Act (HIPAA) Privacy Rule

[26] http://www.odu.edu/ao/research/compliance/humans.shtml

CHAPTER 4

PROBLEM DOMAIN: NEXT GENERATION AIR TRANSPORTATION SYSTEM SAFETY

NextGen implementation efforts have been used as the problem domain to demonstrate the developed methodology in Chapter 3. This chapter will discuss how NextGen was adapted to the methodology. A brief introduction to NextGen is then followed by sections on gaming cycle overview, data requirements, assumptions, game rules, stakeholders, and scenarios.

4.1 NextGen Overview

The United States' National Airspace System (NAS) is a vast, multi-layered array of operations covering virtually everything involving air transportation. With well over 800 million passengers, NAS requires input from more than 15,000 air traffic controllers to assist 590,000 pilots on board 239,000 aircraft that take off and land at 20,000 U.S. airports. This extremely complex system is closely tied to the national economy, contributing $1.2 trillion annually and over 5 percent of the gross domestic product while generating 11 million jobs and $369 billion in earnings. The air transportation industry allows the positive growth of U.S. trade balance, enables just-in-time business models, serves businesses and helps bring friends and family closer (FAA, 2009).

Within recent years, delays have heavily impacted passenger travel, and they are forecasted to be even higher in the future as the demand for air transportation is expected to increase. In addition, future airspace is expected to accommodate unmanned aircraft systems and commercial space vehicles as well. Furthermore, the entire system is expected to operate within acceptable safety levels and environmental impact guidelines (FAA, 2009; U.S. Department of Transportation, 2010a).

4.1.1 NextGen Benefits

The goal of NextGen is to make air transportation safer and more reliable while improving the capacity of the NAS and reducing the impact of aviation on the environment. So far, the FAA was able to deliver some of the projected advantages of newer technologies like Automatic Dependant Surveillance-Broadcast (ADS-B). The advantage of using ADS-B over legacy airspace surveillance is most visible over areas like the Gulf of Mexico where radar coverage is not adequate. One other benefit of NextGen technologies is related to improved access to runways during low visibility due to weather or geographical obstacles. The Wide Area Augmentation System (WAAS), along with other satellite-based technologies, improved runway access for both large and small airports (FAA, 2010).

Improvements to ground safety and operations are also becoming more visible, reducing delays around the NAS, as reported in the NextGen Implementation Plan 2010 (FAA, 2010). Aircraft in airports in New York, Philadelphia and Texas are enjoying runway access capabilities without crossing other close-by runways. Besides improved access, runway safety and airport efficiency is also increased via tools like Airport Surface Detection Equipment – Model X (ASDE-X) which enabled a 50% drop on runway incursions in 2009 (FAA, 2009, 2010).

Airspace access and safety will be re-shaped within the NextGen framework, allowing more direct routes, time and fuel-saving procedures, and more efficient use of the available airspace throughout NAS. The Performance Based Navigation (PBN) procedures, along with Optimized Profile Descents at various airports, demonstrated significant fuel reduction, shorter flight times and lower environmental impact with savings up to 25 gallons of fuel per landing in addition to the 60 to 90 gallons of fuel savings when using the Tailored Arrivals (TA) which enable pilots optimal profiles from the high altitude space down to the runway level (FAA, 2010). The projected NAS will be able to achieve the next level of safety for the flying public while advanced airframe technologies, sustainable alternative fuels and new procedures will shrink aviation's environmental footprint to overtime (FAA, 2010).

4.1.2 NextGen Challenges

The complex nature of the NAS, combined with numerous operational and management challenges, threatens NextGen efforts. NextGen is expected to yield significant benefits in terms of reducing delays, saving fuel, enhancing safety and so on; however, these ambitious goals also pose a great source of risk with billion dollar investments from both the government and the airline industry. The NextGen Implementation plan requires the co-operation of the FAA with several partnerships and stakeholders such as airline companies, airports and manufacturers (FAA, 2010). However, reports from the Office of the Inspector General (OIG) reveal that the Federal Aviation Administration (FAA) is facing difficulties in developing a strategy to engage stakeholders, not to mention managing and integrating multiple NextGen efforts (U.S. Department of Transportation, 2010b). Also, challenges like multi-dimensional research and development along with complex software development, workforce changes, mixed equipage, and policy issues need addressing. Uncertainties and the lack of historical data related to shaping a future aviation system also inhibit the ability to use formal risk analysis methods and other vital knowledge needed by decision makers.

There are a number of challenges that need to be tackled to achieve the increased capabilities described within the NextGen goals. Increasing system capacity while maintaining efficiency, increasing safety and still maintaining an economically viable industry is a must.

The mixed equipage issue reveals during the transition process where the implementation of new technologies conflict with the existing installed counterparts. The variable maturity time of interdependent projects poses challenges to NextGen planners (FAA, 2010). The early adopters of newer technologies will be able to experience the benefits. However, the FAA should still be able to accommodate the lesser equipped aircraft. Also, the cost associated with adopting the new technology by the aircraft operators from the airlines, general aviation or military should be presented with a solid business case since stakeholders would not be investing in new avionics if there are no services to support them.

Even more than the associated cost, safety is a major challenge before the next generation air transportation. The safety aspect is the primary factor behind the design, development and approval process of new functions and capabilities in order to meet the required level of integrity (JPDO, 2008b). The JPDO's National Aviation Safety Strategic Plan (NASSP) is designed to ensure that the safety considerations are covered within safety practices (Safety Management Systems throughout the industry and government) and systems (safer interfaces within human and autonomous interfaces within air and ground based systems). The NASSP also draws attention to the coordination of international policies, technologies and procedures to create a seamless level of safety across air transportation systems (JPDO, 2008a).

4.2 Gaming Cycle Overview

The gaming section of the methodology developed within this research is based on a platform adopted from a policy gaming play sequence from Geurts, Duke and Vermeulen (2007). An adapted version of the play sequence is employed to accommodate the NextGen safety framework (see Figure 4.1). The gaming sequence is supported by the simulation mechanism and COTS software described in the previous chapter. The sequence is initiated by the presentation of the game to the stakeholders including the game rules, general idea about NextGen goals and available resources. Different stakeholder groups comprised of participants from various backgrounds are formed, and their respective goals in the game are provided (e.g.

the FAA concerned with safety, commercial airlines with economic feasibility, etc.). The groups are asked to evaluate and select from the list of technological advancements related to safety enhancements. However, implementation of each intervention requires using limited resources. Additionally, the airlines and the government have to agree on some of the decisions due to their conflicting agendas. Following the discussions among participants, the next year's strategic decisions are inputted into the risk simulation mechanism (based upon the RRAM) and updated NAS risk values which constitutes the initial conditions for the next cycle. The simulation mechanism will also update the consequences respective to the simulated timeframe. The game is iterated until the desired year is reached (2025). The gaming simulation concludes with debriefing and discussions in order to create the foundation for data gathering and analysis.

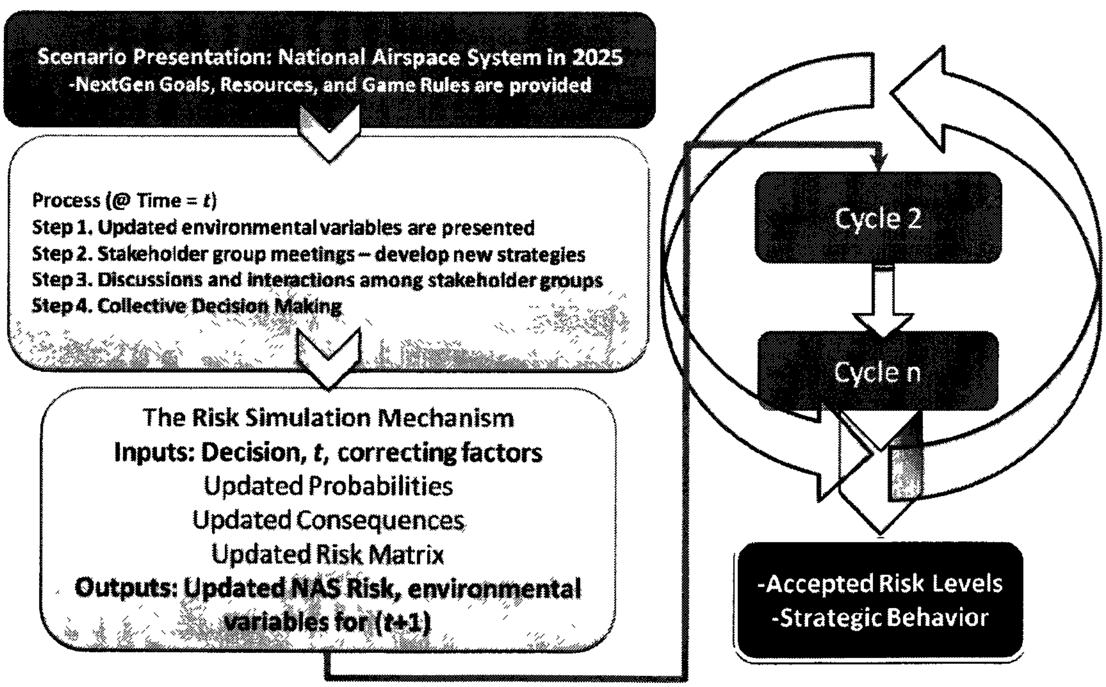

Figure 4-1 NextGen Safety Risk Assessment Gaming Sequence

4.3 Adaptation of RRAM to NextGen

The RRAM including the PNM is chosen as the backbone for the developed methodology's risk estimation engine due to its intuitive structure and ease of expandability. The three main components of the RRAM approach -consequences, probabilities and societal risks- are transferred to the NextGen Safety Assessment Methodology and fused with the policy gaming efforts provided above to develop the intuitive NextGen Safety Assessment methodology. The following sections will highlight the adaption and assumptions made during this transformation.

4.3.1 Consequences

The consequences (the x-axis of the risk matrix, see Figure 4-4) in the IAEA study were determined as fatalities per accident, which is a function of the affected area, population density and the presence of mitigation measures. In a similar way, the consequences within the NextGen safety assessment methodology were based on *fatalities*, considering that the ultimate goal of NextGen related safety efforts within JPDO is concerned with saving human lives. The consequences are estimated as a product of various components comprised of:

- the baseline fatality rate of Federal Aviation Regulations (FAR) Part 121 aviation (NTSB, 2010),
- the air traffic density rate (function of *t*), and
- the presence of the correcting factors regarding the survivability rate in accident scenarios.

The crash survivability correcting factors (i.e. fire/smoke mitigation, survivability of aircraft structures, and accident response procedures) are adopted from the National Science and Technology Council and are provided in Table 4-1. The formula is developed to estimate accident fatalities per 100,000 flight hours.

$$C_i = F_{baseline} \times \delta_i \times n_{survival\_rate,i}$$

where:

C_i	Consequences at time, *t*
$F_{baseline}$	Average Fatality Rate for FAR Part 121
δ_i	NAS Air traffic density at time, *t*
$n_{survival\_rate,i}$	Correcting factors on crash survivability rate (Table 4-1)

Table 4-1 Crash Survivability Correcting Factors (National Science and Technology Council, 2010)

Crash Survivability Correcting Factors $N_{survival\_rate}$	No Presence of Correcting Factors	**1:** Enhanced Post-impact fire/smoke mitigation (-15%)	**1+ 2:** Improved crash survivability of aircraft structures (-15%)	**1+2+3:** Improved evacuation and accident response procedures (-15%)
	Initial Value : 1.0	0.85	0.70	0.55

4.3.2 Probabilities

The y-axis of the risk matrix consists of the probabilities associated with the accident scenarios, resulting in the consequences described above. The probability number method does not calculate the probability as a frequency (e.g. x/100,000FH); this is done in two steps where first the probability number is constructed and then transformed into probability frequencies. Since the methodology is designed to evaluate the future NAS safety related technological developments, the correcting factors are selected mainly from NextGen JPDO's Avionics Roadmap (2008b) and subject matter experts within the Systems Analysis and Concepts Directorate (SACD). The tools, methods, and programs covered below do not constitute an exhaustive list; however, efforts from both NASA and FAA guided programs are covered. Based on the references above, the formula to calculate the probability number, N_t, is developed.

$$N_t = N^*_t + n_{rs} + n_{asr} + n_{icing} + n_{ac} + n_{Wxa} + n_{wva}$$

where:

N_t	Calculated probability number for the system at time = t
N^*_t	The average probability number for the current NAS setup
n_{rs}	Correction parameter related to runway safety and collision avoidance
n_{asr}	Correction parameter for aircraft systems reliability technologies
n_{icing}	Correction parameter for icing mitigation technologies
n_{ac}	Correction parameter for airborne collision avoidance
n_{Wxa}	Correction parameter for weather avoidance precautions
n_{turb}	Correction parameter for turbulence (wake) avoidance solutions

The calculated probability number N_t will be updated at each time frame and be used as the initial average probability number N^*_t for each system. The respective correcting factor tables for the categories will be provided next.

4.3.3 Categories and Enabler Selection

The categories provided above were selected based on the National Transportation Safety Board (NTSB) aviation accident statistics covering years 1996 – 2007 and potential accident areas in the future with the introduction of increased traffic within the FAA Part 121 – Commercial Air Carrier Category. The aviation occurrence categories defined by the Commercial Aviation Safety Team (CAST) and International Civil Aviation Organization (ICAO) were also employed to facilitate the data gathering process (CAST/ICAO Common Taxonomy Team, 2008). The enablers for each of the categories above obtained from various programs within NASA's Aviation Safety (NASA, 2010) and from FAA FY2011 Budget Estimates (U.S. Department of Transportation, 2010a). Information on cost, operational timeline and content were taken from the Joint Planning and Development Office (JPDO) and other publications (FAA, 2010; JPDO, 2008a, 2008b; NASA, 2009a, 2009b, 2009c). The categories and the respective technologies/methods provided below are limited to safety related areas. The technologies associated with increased capacity or reduced environmental impact goals are not within the scope of this research. Appendix E provides detailed information on the enabler categories, definitions, associated costs, timeline and benefits.

Within the gaming cycle, the selection of the enablers is done by the participants of the relevant stakeholder groups. Participants decide on the timeline and collaborations regarding the adoption of the predetermined enablers under several categories. Participants are asked to evaluate enabler benefits, costs, mixed equipage risk and implementation timeline, then review their budget and plan for the near future in order to make the decision about when to "purchase" the enablers and how to construct collaborations whenever it is possible. During this process, the Logical Decisions for Windows® (LDW) software is employed to assist the participants (namely airlines and airport authorities) in examining each alternative at any time-step. Using LDW's "Dynamic Sensitivity" option under the Results tab, participants change the utility function parameters to determine the ranking within the enablers. The adjusted weight for each measure (i.e. benefit, cost, implementation timeline, and mixed equipage risk) re-arranges the ranking of the alternatives, providing the participants with the prioritized list of enablers to purchase. Figure 4-2 and Figure 4-3 provide snapshots for enabler rankings for airport and airline stakeholders, respectively.

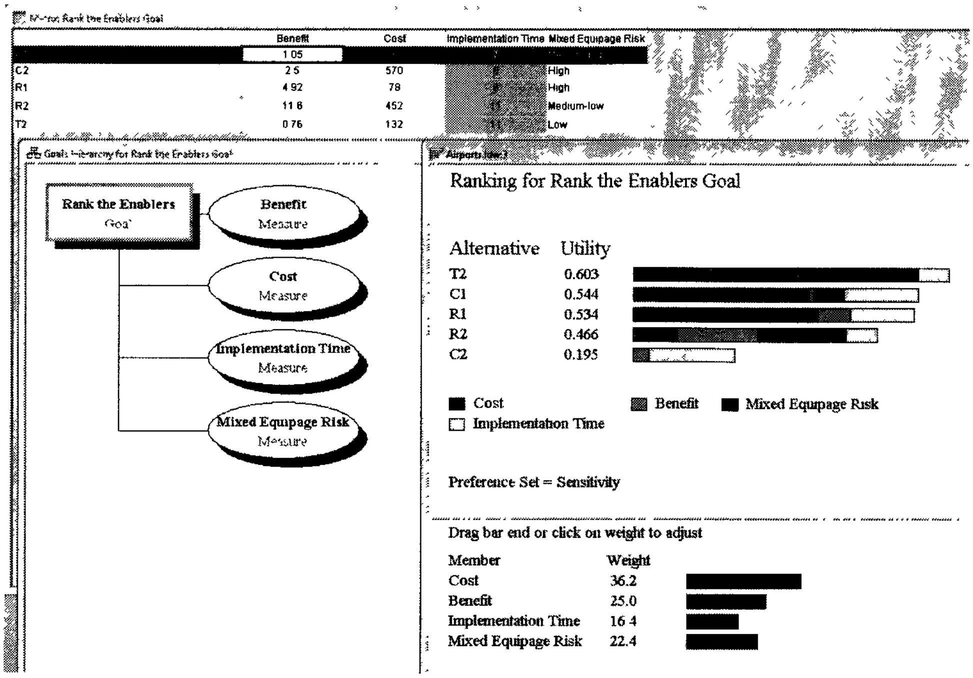

Figure 4-2 Airport Enablers LDW Snapshot

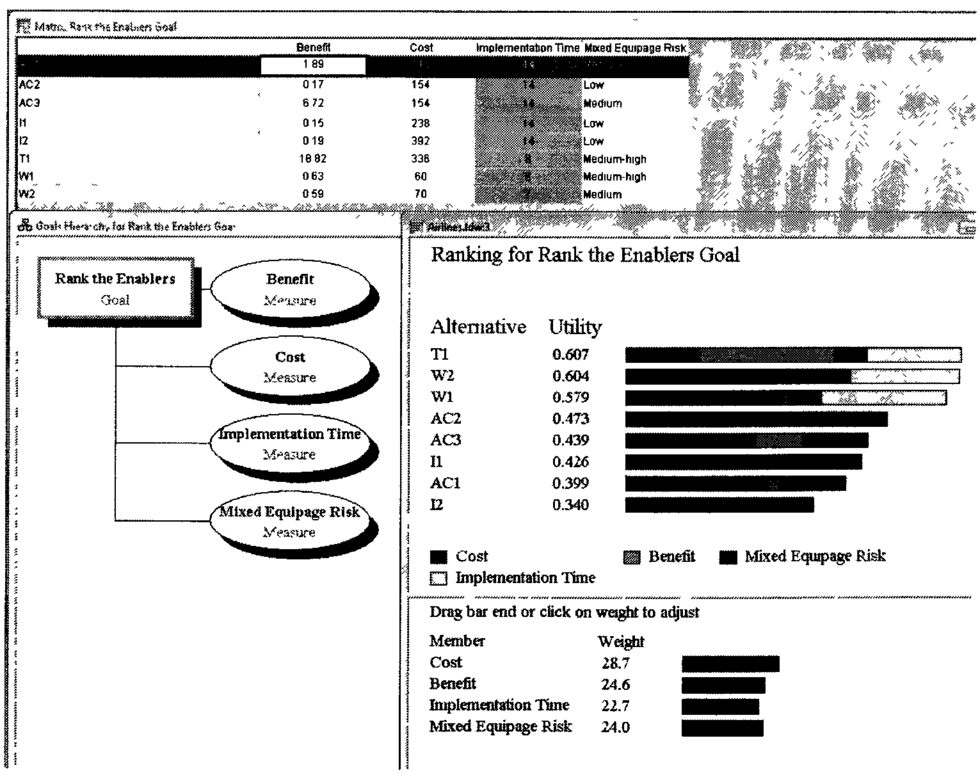

Figure 4-3 Airlines Enablers LDW Snapshot

4.3.3.1 Runway Safety and Collision Avoidance Category

The runway safety and collision avoidance category contains accidents that occur on the ground. Associated CAST/ICAO definitions for this category are Ground Handling (RAMP), Ground Collision (GCOL), Runway Incursion – Animal (RI-A), and Runway Incursion – Vehicle, Aircraft or Person (RI-VAP). This category is divided into 2 sub-categories: R1 - Capacity/Safety Related Runway Enablers and R2 - Runway Visibility. Respective NextGen and other technologies/methodologies in order to reduce accidents observed within the R1 category are: Airport Surface Detection Equipment – Model X (ASDE-X), and Runway Incursion Reduction Program. The R2 category includes the Runway Status Lights (RWSL), Moving Maps, Terminal Area Hazard Sensor, and Automatic Surveillance- Broadcast (ADS-B) (as the key enabler technology which is the prerequisite for ASDE-X).

4.3.3.2 Aircraft Systems Reliability Category

This category contains accidents related to system component, failure or malfunction of aircraft. It is divided into three categories, comprised of Powerplant, Structure, and Software & Systems (A/C1, A/C2, A/C3). NextGen technologies and mitigation measures for A/C1 category are: Propulsion Health Management System, Aircraft Catastrophic Failure Research; for A/C2 category: Airframe Health Management System, Continued Airworthiness for Airframe Structures; and for A/C3 category: Software Health Management System and Aircraft Systems Health Management System.

4.3.3.3 Icing Mitigation Category

Although icing is not considered a safety hazard within the current air transportation infrastructure (with less than 1% of accidents occurring within the timeframe), this category is included in the framework since the increased NextGen capacity eventually will require flying in potentially icy flight envelopes. The icing mitigation category is divided up to two sub-categories; icing occurring on aircraft structures (i.e. aerodynamics and control surfaces) and engine icing, I1 and I2, respectively. Future technologies/methodologies aiming to mitigate icing in category I1 are Iced Airframe Aerodynamics Modeling and Prediction Methods, Icing Remote Sensing, and Atmospheric Hazards – Icing. Icing category I2 enablers are External Hazards – Icing, Engine Icing Modeling, Advanced Sensors and Materials.

4.3.3.4 Airborne Collision Avoidance Category

The airborne collision avoidance category is related to mid-air collisions (MAC), near mid-air collisions (NMAC), TCAS alerts, loss of separation and potential loss of separation occurrences. Similar to icing accidents, within the timeframe there hasn't been a mid-air collision. Also, the near-mid air collisions and loss of separation incidents are around 1% of total accidents. Given the assumption that future aviation will have a higher level of NMAC, MAC and Loss of Separation due to increased capacity, these values are taken from the incident database for the same period of time. The airborne collision avoidance category is divided into two main categories, NMAC (C1) and Loss of Separation (C2). The technologies to mitigate risk of mid-air collision are enhancements to TCAS for category C1. Category C2 enhancements are Loss of Separation Assurance and Wide Area Augmentation System (WAAS) for Global Positioning System (GPS). The Loss of Separation Assurance technology requires ADS-B technology to be acquired.

4.3.3.5 Weather (Thunderstorm) Avoidance Category

The weather avoidance category is comprised of accidents related to the presence of thunderstorm or lightning (WSTRW) as the primary cause and the controlled flight into terrain (CFIT) due to low visibility. The two categories within the Weather related accidents are

Thunderstorm (W1) and Visibility (W2). One of the anticipated technologies to prevent weather related accidents for the W1 category is Integrated Weather in the Cockpit enabler which requires Data Link enhancements to be in place. Accidents related to weather related visibility will be improved by the integration of Synthetic Vision to the aircraft fleet.

4.3.3.6 Turbulence Avoidance Category

The final category is turbulence (wake) avoidance. According to collected data, the wake turbulence is the primary cause for aircraft accidents. The category is split into two sub-categories: in flight turbulence encounter, (Category T1) and ground wake vortices (Category T2). The Forward Looking Interferometer, Aircraft Wake Database, Wake and Wind Based Procedures are methods and technologies under development to mitigate turbulence in flight (T1). Wake Turbulence Mitigation for Arrivals and Departures will be implemented for Category T2 type accidents.

4.3.4 Probability, Severity Definitions, and Risk Matrix Thresholds

The risk matrix and respected definitions that are used within the methodology are adopted from the FAA's Safety Management System Manual (FAA, 2008). This graphical means of determining risk levels is chosen since the methodology aims to calculate the likelihood (probability) and the severity (consequences) for each risk independently where the risk is the product of these two (Figure 4-4). The 'traffic light' approach (or ALARA principle) is taken where the red areas demonstrate the unacceptable risk areas, caused by an event carrying catastrophic consequences, major consequences with a high likelihood value. The yellow and green areas signify the medium and low risk levels, respectively. The definitions of the x and y-axis are given within the following tables (Table 4-2 and Table 4-3) in the context of NextGen safety assessment methodology.

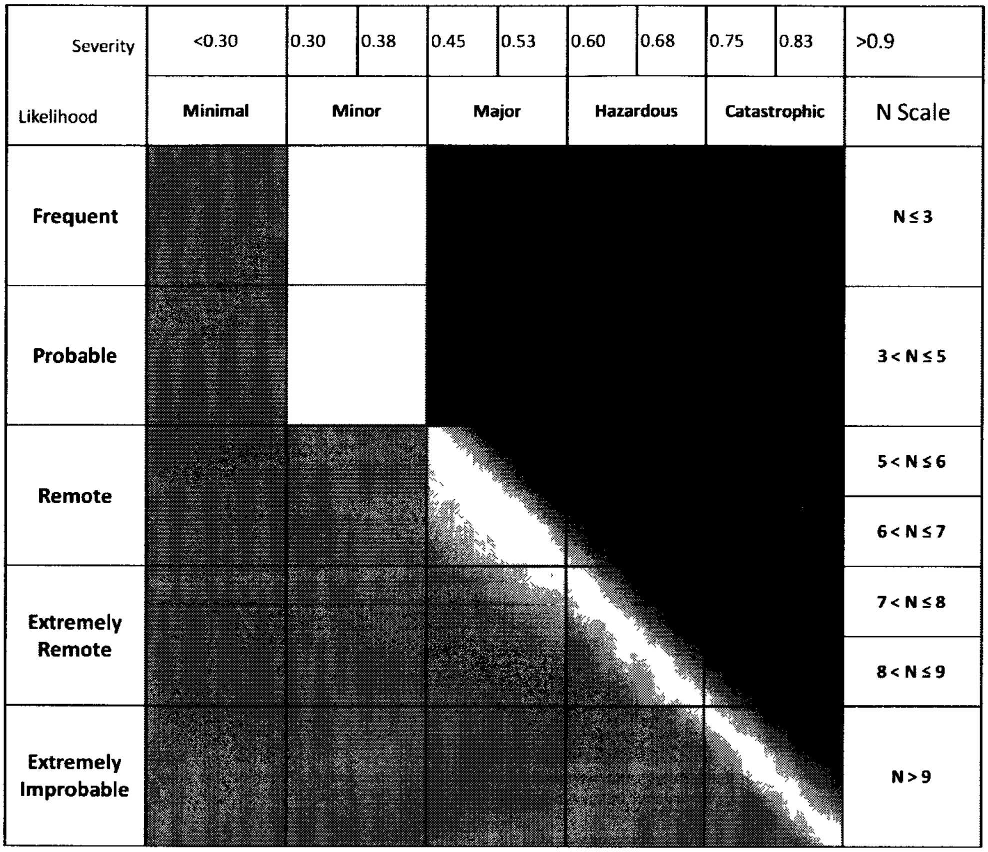

Figure 4-4 Risk Matrix Adapted from FAA (FAA, 2008)

The severity levels are defined based upon the FAA risk definitions, on the five-point Likert scale, ranging from minimal to catastrophic. The historical average of 0.291 fatalities per 100,000 flight hours is taken from the NTSB website (2000-2009) and is assumed to be a minor risk that the aviation industry inherently carries. The consequences axis on the matrix demonstration will have the two extremes on the x-axis.

Since there have been years without any fatalities within the FAR Part 121, the lower-end of the axis is assigned as '0'. The upper end of the scale is the worst-case scenario where there are no crash survivability efforts in 2025 where the NAS air traffic density is 2.5 times the current density. Within this setup, the threshold value for catastrophic consequences will be: $C_{2025} = 0.291 \times 2.5 \times 1 = 0.727$. (Table 4-2).

Table 4-2 Consequences Definitions

Consequences →	Minimal 5	Minor 4	Major 3	Hazardous 2	Catastrophic 1
Fatalities / 100.000FH	0	0.291	0.436	0.582	0.727
Normalized	0	0.25	0.5	0.75	1

Similarly, the probability axis values are given in Table 4-3 where the probability ranges from frequent to extremely improbable. Since the methodology is focused on estimating the overall NAS accidents causing fatalities, the FAA's quantitative probability definition for NAS systems and ATC Operational definitions are adopted. Also, the corresponding probability numbers are calculated and given in the table. The baseline accident rates (0.208/100,000FH for 2000-2009) indicate an initial average of N: 5.681 (Remote) before any NextGen related technology implementation is present $\left(N = \left| \log_{10}^{0.208/100\,000} \right| = 5.681 \right)$. This results in a 'Low Risk' area, the intersection of severity 4 and likelihood C.

Table 4-3 Probability Definitions

Probability ↓	NAS Systems & ATC Operational (Quantitative)	Probability of Occurrence	Probability Number N
Frequent **A**	Probability of occurrence per operation/operation al hour is equal to or greater than 1x10^{3}	$P \geq 1x10^{3}$	$N \leq 3$
Probable **B**	Probability of occurrence per operation/operation al hour is less than 1x10-3, but equal to or greater than 1x10^{5}	$1x10^{-3} > p \geq 1x10^{5}$	$3 < N \leq 5$
Remote **C**	Probability of occurrence per operation/operation al hour is less than or equal to 1x10^{5} but equal to or greater than 1x10^{7}	$1x10^{5} > p \geq 1x10^{7}$	$5 < N \leq 7$
Extremely Remote **D**	Probability of occurrence per operation/operation al hour is less than or equal to 1x10^{7} but equal to or greater than 1x10^{9}	$1x10^{7} > p \geq 1x10^{-9}$	$7 < N \leq 9$
Extremely Improbable **E**	Probability of occurrence per operation/operational hour is less than 1x10^{9}	$p < 1x10^{-9}$	$N > 9$

4.4 Data Requirements

In order to support the decision making process, various data sources have been used throughout the methodology. Due to the nature of the problem at hand, a combination of numerical and elicited data has been used in various sections. Historical data concerning the current aviation accident rates and fatalities for FAA Part 121 are taken from NTSB general aviation statistics (NTSB, 2010) and the Aviation Accident and Incident Data System. This database was obtained from the Aviation Safety Information Analysis and Sharing (ASIAS) department of the FAA's Office of Aviation Safety in April 2009[27]. Within the database, the most current detailed categorization of aviation accident and incident data was up to 2006; however

[27] Data gathered by Joni Evans at NASA Langley Research Center, May 25th, 2010

the NTSB website contained accident values up to year 2009. In both cases, for the average calculation, the past 10 years were taken into consideration. Appendix F outlines the data obtained from the NTSB website and Aviation Accident and Incident Data System.

The serious gaming exercise also required intense SME participation due to lack of data regarding future NAS systems. For most cases, the benefits of future enablers were solely based on SME opinions. In order to acquire such data, a meeting with experts from NASA Langley Research Center was held, and opinions were gathered in an informal brainstorming session, and a single point value for each enabler was collected.

Besides the incident/accident related data, current airline and airport financial data are also extracted in order to create a realistic baseline for the gaming activity. For that purpose, the eight largest airports and airline companies are selected, and their financial data are taken as baseline. The airports are selected according to the passenger enplanement in 2009. The hub airports and the financial data are obtained from the FAA Compliance Activity Tracking System (CATS) – Summary Report 127,[28] and the summary is given in Table 4-4. The non-operating revenues and expenses such as interest income, grant receipts and capital expenditures and debts are excluded from the source data.

[28] http://cats.airports.faa.gov/Reports/reports.cfm

Table 4-4 Hub Airports Financial Data

Hub	Aeronautical Revenue	Non-Aeronautical Revenue	Total Revenue	Total Expenses	Operating Income
Hartsfield-Jackson Atlanta Int'l (ATL)	$128,393,480	$261,141,707	$389,535,187	$328,696,000	$60,839,187
Chicago O'Hare Int'l (ORD)	$394,628,018	$229,815,711	$624,443,729	$583,001,760	$41,441,969
Los Angeles Int'l (LAX)	$356,447,720	$322,803,300	$679,251,020	$609,838,347	$69,412,673
Dallas Fort Worth Int'l (DFW)	$214,715,984	$292,003,726	$506,719,710	$565,598,324	-$58,878,614
Denver Int'l (DEN)	$316,559,851	$247,930,260	$564,490,111	$557,099,885	$7,390,226
John F. Kennedy Int'l (JFK)	$572,065,153	$399,901,016	$971,966,169	$824,406,256	$147,559,913
George Bush Intercontinental – Houston (IAH)	$406,284,635	$134,861,967	$541,146,602	$301,177,105	$239,969,497
Las Vegas – McCarran Int'l (LAS)	$162,030,250	$195,450,927	$357,481,177	$317,131,107	$40,350,070
Average	$318,890,636	$260,488,577	$579,379,213	$510,868,598	$68,510,615

Similarly, the airline companies with the highest annual operating revenue are selected and their financial information was obtained from the Research and Innovative Technology Administration (RITA) Bureau of Transportation Statistics (BTS) website[29]. Two separate databases are employed in order to obtain various airline data such as transport revenues (Air Carrier Financial - Schedule P-1.2)[30] and (Air Carrier Financial Schedule P.12)[31] fuel consumption. Schedule P-1.2 database allowed extracting airline specific passenger baggage fees,

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[29] http://www.transtats.bts.gov/databases.asp?Mode_ID=1&Mode_Desc=Aviation&Subject_ID2=0
[30] http://www.transtats.bts.gov/Fields.asp?Table_ID=295
[31] http://www.transtats.bts.gov/Fields.asp?Table_ID=294

transportation fees, reservation cancellation fees and other incomes along with expenses like maintenance, flying operation and maintenance. The schedule P.12 database provided airline specific fuel cost and fuel consumption, leading to average fuel prices for the past 5 years. An overview of the largest air carriers and their financial information is given in Table 4-5. The airlines considered within the simulation are Delta Airlines, Southwest Airlines, United Airlines, U.S. Airways, Northwest Airlines, JetBlue Airways, Continental Airlines, American, Alaska and Airtran Airways. Due to the high volatility in corporate airline finances, non-operating income and expenses including capital gains and losses and interest expenses are excluded from the financial data.

Table 4-5 Airlines Financial Data

Year	Passengers Enplanement	Transport Revenues (Passengers)	Passenger Baggage Fees	Reservation Cancellation Fees	Total Operating Revenues	Total Operating Expenses	Operating Profit or Loss
2009	435,872,373	$76,625,995,190	$2,483,375,320	$2,272,477,940	$107,294,780,070	$107,509,895,540	-$215,115,440
2008	466,135,262	$93,255,623,070	$1,106,215,550	$1,555,489,830	$126,681,047,070	$132,680,337,010	-$5,999,290,950
2007	474,271,862	$87,784,844,810	$444,702,430	$831,832,450	$116,362,119,010	$110,190,954,900	$6,171,164,090
2006	459,673,190	$81,768,216,120	$415,063,060	$824,749,660	$108,841,373,850	$104,771,978,500	$4,069,395,350
2005	460,774,685	$74,428,508,670	$315,147,830	$780,113,770	$97,862,669,110	$99,966,347,780	-$2,103,678,670
Average	459,345,474	$82,772,637,572	$952,900,838	$1,252,932,730	$111,408,397,822	$111,023,902,746	$384,494,876

The ten largest corporate airlines are represented as a single entity for purposes of simplicity. On average, between the years 2005 and 2009, the depicted airlines made up 70% of enplanements in the domestic market. At the time of developing the methodology, 2010 values were not complete. Table 4-6 outlines the specific enplanements for the major airlines and their ratio with respect to the total NAS passenger capacity. The data was obtained from the T-100 Domestic Market (U.S. Carriers)[32] which can be found on the BTS website. The financial data for the airline companies are handled collectively, and their five year averages (2005 – 2009) are adopted as the initial conditions for the gaming exercise.

Table 4-6 Major U.S. Airlines Enplanements

Airline Corporations	2005	2006	2007	2008	2009
AirTran Airways Corporation	16,520,043	19,967,895	23,716,544	24,586,032	23,821,768
Alaska Airlines Inc.	14,603,547	14,916,122	15,328,828	14,864,602	14,060,609
American Airlines Inc.	77,296,967	76,813,449	76,581,414	71,563,663	66,168,794
Continental Air Lines Inc.	32,971,219	35,795,440	37,117,030	34,524,968	31,954,535
Delta Air Lines Inc.	77,581,274	63,495,888	61,599,411	59,375,572	55,708,779
JetBlue Airways	14,462,932	18,098,021	20,527,593	20,517,934	20,022,359
Southwest Airlines Co.	88,435,832	96,330,250	101,947,800	101,965,552	101,374,390
United Air Lines Inc.	55,172,705	57,229,074	56,420,151	51,681,045	45,582,670
US Airways Inc.	37,040,080	31,886,350	37,220,911	48,544,910	44,554,186
Northwest	46,690,086	45,140,701	43,812,180	38,510,984	32,624,283
Select Airlines	460,774,685	459,673,190	474,271,862	466,135,262	435,872,373
Total NAS Enplanements	660,614,523	660,642,163	681,492,975	653,816,163	620,201,000
Ratio of Select Airlines to Total Enplanements	69.75%	69.58%	69.59%	71.29%	70.28%

[32] http://www.transtats.bts.gov/Fields.asp?Table_ID=258

4.5 Assumptions

The risk classification and prioritization methodology presented in Section 3.4.2 consists of accidents occurring in complex industrial systems (handling, storage, and transportation of hazardous materials like flammables, explosives and toxic gases and liquids). The approach within the original methodology is geared towards supporting the upper risk management with system-level risk assessment. For that reason, the probability and consequences calculations contain a large number of assumptions, limiting the methods to be solely risk prioritization for further analysis. The adaption of this approach to the NextGen framework also required a fair amount of simplifications and assumptions in order to focus on the NAS level risk characteristics. Since the timeframe for this method involves over 15 years the technologies, their implications, benefits and costs are mainly provided by the small number of SMEs that took part in the collaboration[33, 34].

4.6 Game Rules

Each serious game is a dedicated simulation gaming exercise, specifically tailored-made and designed for the problem at hand. The actual run of the serious game is a collective and interactive process designed by the very owners of the problem: "Through the unique combination of simulation with role-playing, participants themselves actually create the future that they want to study, rather than it being produced for them as in projects where formal

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[33] The probability number calculation components were collected based on the NextGen JPDO Avionics Roadmap (JPDO, 2008b). The roadmap is constructed by drawing materials from NextGen planning sources in order to communicate the proposed NextGen capabilities and improvements corresponding avionics overtime. The correcting factors located in the probability number calculations are selected upon the Safety Enhancement/Hazard Avoidance and Mitigation section in the roadmap and the general expertise of participating experts related to NextGen safety

[34] In calculating the consequences axis, only fatalities related to FAR Part 121 were taken into consideration. However other consequences like accidents, serious injuries, hull losses and accident related costs were not included since data for a 15-year long timeframe for every future scenario would be burdensome to collect in a meaningful manner. For that reason, consequences were constructed only with fatality data from past 10 years, projected NAS capacity increase, and planned measures to increase survivability rate in case of crashes

simulation models were used" (Geurts, et al., 2007, p. 536). However, unlike in many strategic seminars, serious gaming allows participants to engage by creating and analyzing the results of their decisions in a safe environment. At this point, the laying out of the game rules plays a very important role. Rigid and rule-based gaming works well for well-structured environments like military gaming. This type of gaming is based on specific rule-sets, formalized by mathematical and/or computational methods. The rigid-type rule-sets are successful when the problem at hand is well-defined and understood like oligopolistic market settings.

On the other hand, in social arenas with public and intense stakeholder interactions where firm rules do not exist, free form gaming is more suitable (Mayer, 2009). Free form gaming, initially implemented in the 1950s at the Social Science Division at RAND, is also known as seminar gaming or political-military gaming. During game play, positions, objects and rules can be challenged, modified, and improved by players. The game needs to be carefully monitored by a control team, mostly experts, acting like referees or game directors. This type of gaming requires a high level of subject matter expert input and experienced players within a carefully crafted scenario setting. As stated previously, each game is designed specifically to serve a purpose (solve a problem, provide insights, reach a consensus, etc.) and the gaming rules have to be specifically tailored to this purpose.

Within the scope of this project, the primary goal is to provide insights into future NAS safety and data gathering regarding future systems. For that reason, a combination of rigid and free form gaming rules was employed. However, unlike a traditional policy gaming exercise, the end state of the aviation safety within the NextGen framework is somehow determined, i.e. cutting the aviation fatality risks by 2025 (U.S. Department of Transportation, 2010a). The goal of the serious game is to simulate the aviation safety values within the timeframe while taking into consideration the technological constraints (cost/benefit, feasibility, mixed equipage, etc.)

and behavioral concerns (information overload to pilots, controllers as well as early technology adopters). For that reason, a nominal number of stakeholder rules are determined to help guide the stakeholder interactions (e.g. the FAA mandating Corporate Airlines or Airport Operators to adopt certain technologies, etc.), reflecting real-world relationships. Figure 4-5 provides a basic stakeholder rule schematic outlining the common ground rules regarding engagement rules.

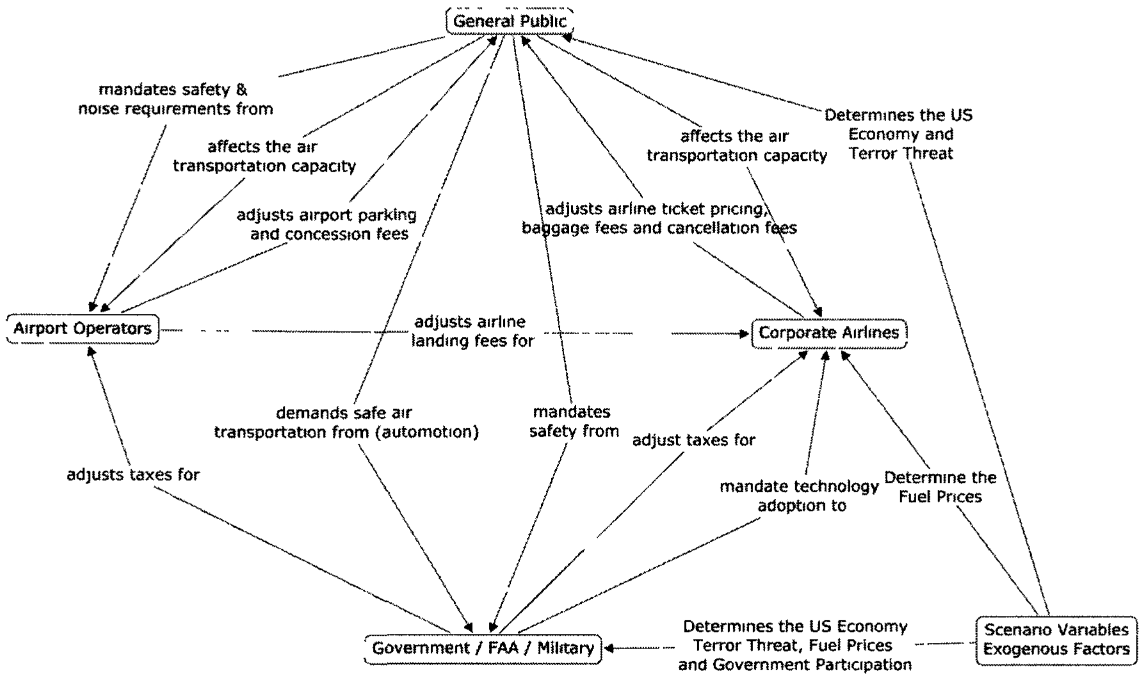

Figure 4-5 Basic Stakeholder Rules

However, in order for experts from various stakeholder groups to reveal hidden complications caused by social factors, the bounding stakeholder rules should be kept to a minimum. Also, due to the nature of the participants, their expertise will help game directors modify certain rules, allowing the serious gaming model to expand and became more realistic after each session.

4.7 Stakeholders

One of the most productive outcomes of the policy gaming exercises is the participants' interaction with the problem at hand. The 'safe' environment allows participants to create and analyze the complexity by communicating various aspects of the issue among the stakeholders. As Duke (1980) argued, real-world complex problems often include a sociopolitical context, created by the idiosyncratic or irrational 'players' present during the decision-making process. Stakeholder identification is crucial to managing projects involving complex technical aspects, and it is also necessary to understand and articulate individual or collective goals along with interaction dynamics before conducting any further research (Faulconbridge & Ryan, 2003). Determining the relevant participants, their value demands and expectations also has to be a part of the equation, especially considering the complexity of the system involving socio-economic, behavioral and human dimension aspects of the problem (Brewer, 2007). Consequently, the large-scale transformation of the NAS also harbors various stakeholders with diverse agendas that can directly or indirectly affect the decision-making process. In order to model such a dynamic environment, a simplified list of involved stakeholders and engagement rules were developed. The interested parties given within Table 4-7 have primary (and often conflicting) goals and resources that will be unfolded throughout the gaming exercise (Sherry, et al., 2005). Each stakeholder group is represented by three experts who determine the strategy that is followed throughout the game. Chytka (2003) argues that adding more experts within each group will not improve efficiency and effectiveness of the data gathered.

Table 4-7 Stakeholders list and their primary objectives

Government, FAA and Military	**Corporate Airlines**
Objective: safety, protect and nurture aviation industry, throughput	**Objective**: Market share, profit, throughput
Airport Operators	**Public**
Objective: throughput, revenue neutral, safety	**Objective**: Affordable and safe transportation

4.7.1 Government, FAA and Military Stakeholder

This stakeholder group represents the "big brother" role over the airports and airlines. The government is responsible for determining tax values for various areas such as income, environmental and security, along with aviation fuel tax. The players representing this stakeholder must behave according to the scenario; however, they are encouraged to take initiatives to promote the acquisition of certain NextGen enablers and overall NAS safety. The FAA's role as the enforcer of aviation safety is also controlled by this stakeholder. By closely monitoring the yearly changes at the Risk Matrix, government/FAA can intervene with airline and airport pricing and acquisition plans. They also have the ability to spare funds for assisting airlines and airports in purchasing large-ticket items such as ADS-B and Data Link enablers. The final task of this stakeholder is to reflect the military agenda based on the scenario presented (i.e. the adjustments required for UAS integration to NAS). It is desirable that this scenario is represented by players with a background in government, the military and FAA certification experience.

4.7.2 Corporate Airlines

The representative group for corporate airlines determines the yearly average ticket prices, the reservation cancellation fees and passenger baggage fees. Their finances are directly affected by the strategies followed by other stakeholders, i.e. airports collect landing fees and the government collects various taxes. Airlines are also affected by the predetermined scenario mandating aircraft jet fuel before taxes or global terrorist threats. Airlines are encouraged to engage in coalitions with other stakeholders and invest funds in NextGen enablers and technologies because they are the primary beneficiaries of the increase in NAS capacity. Corporate airlines are expected to reflect their expenses in passenger ticket prices and fees; however, the general public stakeholder can react to increased ticket prices by choosing other modes of transportation.

4.7.3 Airport Operators

The airport stakeholder represents the main hub airports in the continental U.S.. These airports were listed in Table 4-4. Unlike airline companies, the airport's financial information only reflects the 2009 data, and the averages of 10 airports are taken into consideration as the baseline for the gaming exercise. In other words, the airport operator stakeholder represents only one U.S. hub whereas the corporate airlines represent the ensemble of the eight largest airlines in the United States. Like the airlines stakeholder, airport operators interact with other players in determining their strategies and pricing. Airport authorities decide on aeronautical and non-aeronautical fees. Aeronautical fees include airport landing fees that a passenger facility charges that are billed to airline companies. Non-aeronautical fees include expenses geared towards passengers such as parking fees, concession fees, airport shop rental fees, etc. Airports are bound to pay income and security taxes, as determined by the government stakeholder. Since NextGen enablers allow airports to increase their landing capacities, players representing the airports are inherently motivated to invest in these technologies.

4.7.4 General Public

The general public stakeholder indirectly works with the game master in order to determine the "actual" air transportation capacity. This stakeholder reviews the information available regarding various forms of transportation and determines if he/she agrees with the projected air traffic capacity. The "Public Announcement Dashboard" provides updated information on cost of travel by air, train and car on two pilot routes (Washington, DC to New York, NY and Washington, DC to Boston, MA). At the end of each time step (i.e. simulated year), the public stakeholder decides whether to agree or adjust the projected air transportation capacity from -10% to 10% with 5% intervals. The general public stakeholder can reflect upon the increased the air transportation costs that were decided by airport and airline stakeholders. By modifying that specific year's air transportation capacity, the general public is included in determining the air transportation capacity. The information packages available to the public are U.S. economic competitiveness, threats to global security, transportation costs for the three aforementioned modes, and the evolving transportation environment (introduction of high speed rail systems and other modes). The goal in including the general public in the game is to be able to capture the irrational stakeholder behavior that could be portrayed by the general public.

4.8 Scenarios

The gaming exercise requires a dynamic environment to enable participants (or agents) to interact with each other. The dynamic scenario enables game masters or decision makers to evaluate various scenarios and extract the collective response from all the stakeholders. For gaming purposes, a previous study conducted by the National Research Council (NRC) concerning scenario-based strategic planning is used as a baseline for the required scenarios (National Research Council, 1997). The study involved a workshop performed by NRC to help guide NASA's strategic planning processes. The workshop was organized with the help of NASA's Office of Aeronautics, The Futures Group (TFG) and the Systems Technology Group of Science Applications International Corporation (SAIC). In addition, experts from industry, academia and the military participated in the study to determine five long-term distinguished scenarios. Scenarios are based on economic, social and policy issues and became the dimensions (or attributes) of each scenario. Based upon the NRC study, the following table depicting the scenario environment for each year is determined and tested with the gaming session that took place on February 14th, 2011 (Table 4-8). The scenario is provided as the initial conditions for each year's discussions; however, the final values for the base fuel price or air transportation capacity are determined by the players.

Table 4-8 Scenario Environment by Year

Year	Scenario Name	U S Economic State	Demand for Aeronautics Services	Global Security Threat	Government Participation	Base Fuel Price	Anticipated Passenger Capacity (%)
2010	Pushing the Envelope	Strong	High Growth	Low	Low	$2.136	100%
2011	Pushing the Envelope	Strong	High Growth	Low	Low	$2.136	120%
2012	Pushing the Envelope	Strong	High Growth	Low	Low	$2 136	135%
2013	Pushing the Envelope	Strong	High Growth	Low	Low	$2.136	150%
2014	Pushing the Envelope	Strong	High Growth	Low	Low	$2 136	165%
2015	Grounded	Strong	Low Growth	High	High	$2 136	50%
2016	Grounded	Strong	Low Growth	High	High	$2.138	60%
2017	Regional Tensions	Weak	High Growth	High	High	$2.140	165%
2018	Regional Tensions	Weak	High Growth	High	High	$2.140	175%
2019	Regional Tensions	Weak	High Growth	High	High	$2.140	185%
2020	Regional Tensions	Weak	High Growth	High	High	$2.140	195%
2021	Regional Tensions	Weak	High Growth	High	High	$2.155	205%
2022	Environmentally Challenged	Weak	Low Growth	High	High	$2 155	215%
2023	Environmentally Challenged	Weak	Low Growth	High	High	$2.170	220%
2024	Environmentally Challenged	Weak	Low Growth	High	High	$2.180	225%
2025	Environmentally Challenged	Weak	Low Growth	High	High	$2.180	230%

4.9 Gaming Sequence

As previously demonstrated in Figure 4-1, gaming takes place in a sequential manner. Stakeholders are given time to evaluate their options by simulating their finances for each time-step. At the end of the short decision making period, the strategies (fees, enabler acquisition and other variables) are revealed in order. Each stakeholder group possesses an Excel spreadsheet enabling it to calculate its budget variables (airline ticket fees, landing fees, etc.) and is required to spare funds for the upcoming NextGen related enabler expenses. On the other hand, since each participant group affects other's finances, a pre-determined amount of time is allowed for groups to discuss and revise their previous assessments and strategies. The following steps are followed during the game.

1. The game master announces the variables of the specific calendar year including the anticipated air transportation capacity, political, economical, social environments and the untaxed fuel price. See Table 4-8 Scenario Environment by Year.

Figure 4-6 Snapshot from a Gaming Exercise

2. According to predictions for the following year, participants experiment with their variables and simulate their budgets using the provided personalized Excel spreadsheets, allowing them to determine the funds that can be used for NextGen enablers.
3. The participants are given 5 minutes to discuss the enabler acquisition strategy and possible coalitions, including the prerequisite enablers like ADS-B or Data Link.

4. The round starts with the government's announcement of taxes for the coming year, in accordance with the political and economic environment (government participation level and U.S. economic state).
5. The participants representing airport authorities announce their landing fees and concession fees, along with the enablers they are willing to purchase this year.
6. The airline stakeholders announce their variables: passenger ticket fees, reservation cancellation fees, baggage fees and the planned NextGen enabler acquisitions
7. Another 5 minutes are allowed for stakeholders to discuss their fees before they are announced to the game master, and the risk values for the specific year are calculated
8. Once the "new air transportation environment" is revealed, the general public stakeholder examines the cost for various modes of transportation along with the safety of air travel and determines the final air transportation capacity by adjusting the previously announced anticipated capacity. Adjustments can be done from -10% to 10% change with 5% increments.
9. With the "actual" passenger capacity determined, stakeholder budgets are adjusted, and the following year's variables are stated by the game master, and another round is initiated beginning with step number 1.

CHAPTER 5

DATA COLLECTION, ANALYSIS AND OBSERVATIONS

5.1 Introduction

Throughout the gaming effort, discussions and possible negotiations within the opposing parties are important findings that can lead to different constructive problem solving approaches. The serious gaming exercise serves both as an individual and collective learning platform for stakeholders, leading to an elevated level of knowledge of the system. Individual learning takes place during the decision making process where each stakeholder group represents its respective point of view. The reflective conversations between participants enable feedback and help participants make informed judgments. Therefore, the presence of realistic interactions among players helps testing and evaluation of NextGen related technologies in the future (Joldersma & Geurts, 1998). Also, besides individual learning, collective learning, or organizational learning provides insight regarding the system at hand (i.e. the NextGen aviation safety values).

One of the most tangible outcomes of the gaming exercise is the 2025 NAS safety values with respect to the FAA's Risk Matrix (Figure 4-4) acceptability measures. Also, the intermediate risk values during the technology implementation phase (for the next 15 years) are also calculated under the same assumptions. The cumulative effect of various safety related technological implementations are examined, enabling decision makers to define technologies or areas that require further analysis and understanding.

There are three venues of data collection throughout the serious gaming exercise. The entire session is video recorded in order to observe discussions that took place between players.

Also, discussions among the stakeholders regarding pricing or behavioral strategies, negotiations and other interactions are followed by the game master and facilitators. Without disturbing the flow of the game, questions originating from the facilitator or the game master regarding certain decisions allow the collection of behavioral information.

The second type of data is the numerical data, originated from the decisions given by the participants regarding NextGen enabler acquisition timeline, coalitions formed, and pricing strategies. This allows the observation of stakeholder reactions through their pricing strategies with respect to the changing scenario. By observing the graphics, it may be possible to single out cause-and-effect relationships to better comprehend the complex decision making environment.

The third and final data source comes from the debriefing and questionnaire section following the gaming exercise. At this point, specially crafted questions are directed to the participants in order to give them the opportunity to express themselves and provide facilitators with the reasoning behind their decisions. Also, data regarding the validation of the methodology is collected via questionnaires.

5.2 Data Collection Mechanism

In order to aggregate and process the data, the *serious gaming platform* presented within the previous chapter is coupled with the *data aggregation platform*, a designated, comprehensive Excel® file assigned to calculate and communicate the dynamic NAS Risk values and other statistics among players, facilitators and game masters. The data aggregation platform contains all the financial relationships, accident statistics and risk assessment model calculations necessary to generate interim safety values and other statistics.

Figure 5-1 provides an overview of the data elicitation mechanism developed within the current research methodology. The serious gaming platform promotes a challenging and engaging environment for discussion and decision making. The discussions and strategic behaviors, along with decisions like pricing, taxation, or enabler acquisitions are followed by game facilitators and recorded on video for further analysis.

Similar to the qualitative data, quantitative data are also collected and recorded via the Excel spreadsheet operated by the game master. The file contains numerous sections including stakeholder tabs (called *dashboards*), a risk calculation (PNM) tab, a technological enablers tab, and the accident database. Each tab is connected to the others; e.g. aircraft landing fees charged by airports are shown as an expense on the corporate airline dashboard, enabler acquisitions provide increased on safety levels on the *Risk Matrix* tab, etc. The developed database stemmed from system variables (NAS capacity, risk, taxation values, budgets, participation, etc.) enables the regeneration of the graphics given within this section.

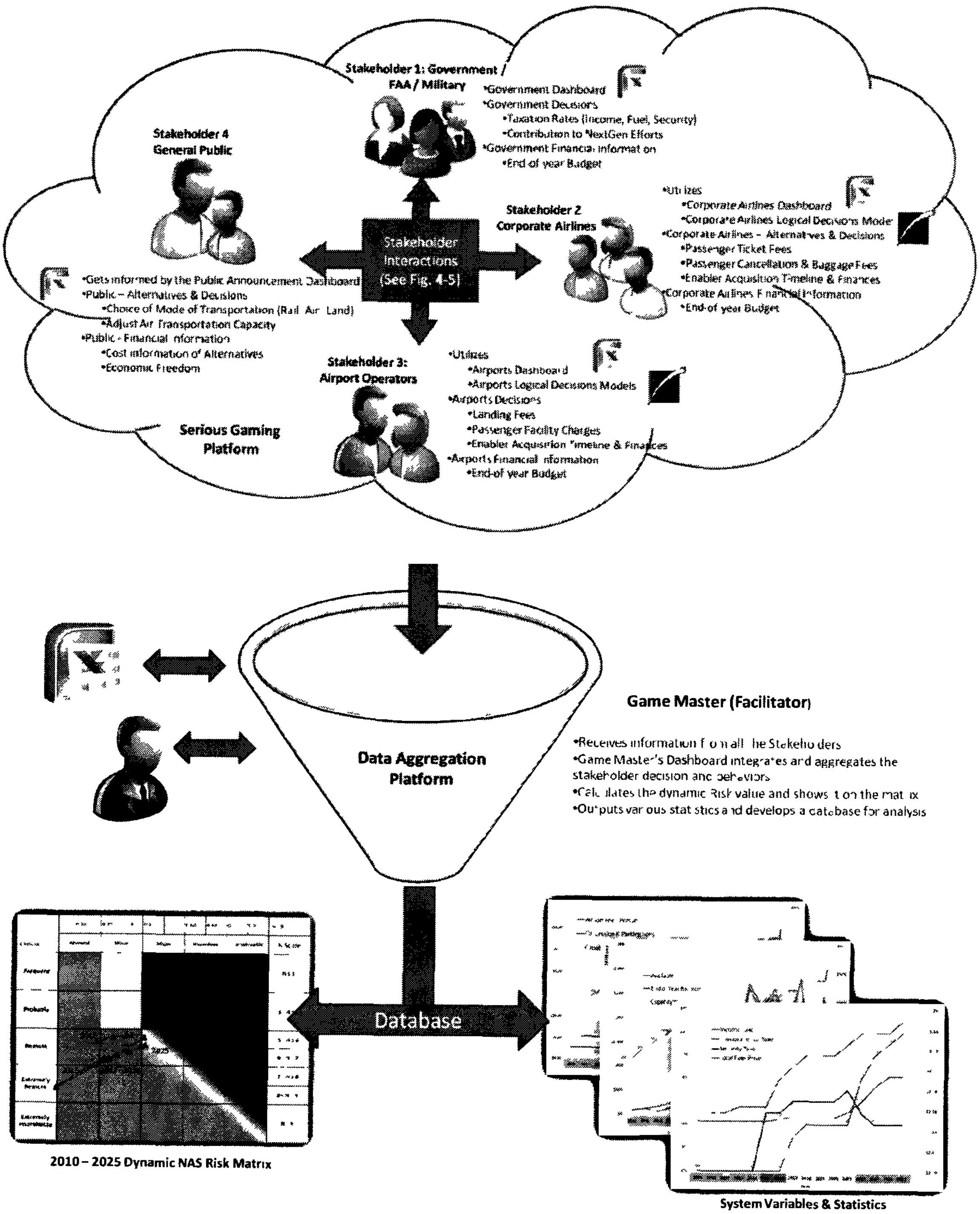

Figure 5-1 Data Elicitation Mechanism

5.3 Sample Data and Generic Scenarios

As previously stated, transactions between players allow numerical data gathering regarding the various variables in the game. Although the participants are bounded to the limits of certain predetermined scenario guidelines, the numerical value for the variables is completely determined throughout the game. For instance, the government stakeholder determines the income, environmental, security and fuel taxes but he/she will only apply, raise or lower these values according to the scenario. That way, it is possible to observe the effects of the scenario among the players. The scenario-sets stated in Table 4-8 are for demonstration purposes only, and they provide a baseline for testing the developed methodology.

5.3.1 "Pushing the Envelope"

One of the most tangible outcomes of the gaming exercise is the simulated NAS safety values for the 15-year time interval from 2010 to 2025. As previously demonstrated, the severity and the likelihood values for the risk construct originate from the PNM approach using the initial conditions obtained from historical data. The modified risk matrix in Figure 5-2 shows the evolution of NAS safety with time. Based upon the assumptions, the 2010 safety level is described with remote accident likelihood and minimal severity. Starting from year 2010, the anticipated air transportation capacity increase takes the accident likelihood towards "probable" where accident severity is also seen with "minor" consequences. This scenario is called "Pushing the Envelope," and the situation reflects the steep increase anticipated by FAA's 2010 Fiscal year. This scenario depicts a continuously growing strong economy and a liberal trade policy environment, allowing stakeholders to regulate the market. During this scenario, stakeholders are required to invest in transportation infrastructure components like ADS-B initiation, Data Link setup and many other enablers to accommodate the anticipated increase in air travel. As expected, several NextGen safety related technologies and management strategies are initiated by stakeholders; however, their benefits don't surface immediately. For that reason, the NAS safety value migrates towards the upper-left corner of the grid.

5.3.2 "Grounded"

In years 2015 and 2016, the air transportation capacity is largely hampered by a scenario-driven series of terrorist attacks. This scenario was generated by the NRC study from 1997, somehow portraying the September 2011 events. Within the NRC study, terrorist attacks are caused by large gap between the income levels and living standard of developed nations compared to second or third world countries. The scenario for these two years is called "Grounded" where air travel is no longer safe, hence the decreased capacity (down to 40% of 2010 values). Decreased NAS capacity results in lower accident risk; yet, random acts of violence against air transportation affects the stakeholders since very expensive security measures are required to encounter the terror threat (Figure 5-2). In addition, the income loss caused by decreased passenger capacity coupled with planned NextGen acquisition costs lead to airport and corporate airline budget deficits that can be observed in the following figures.

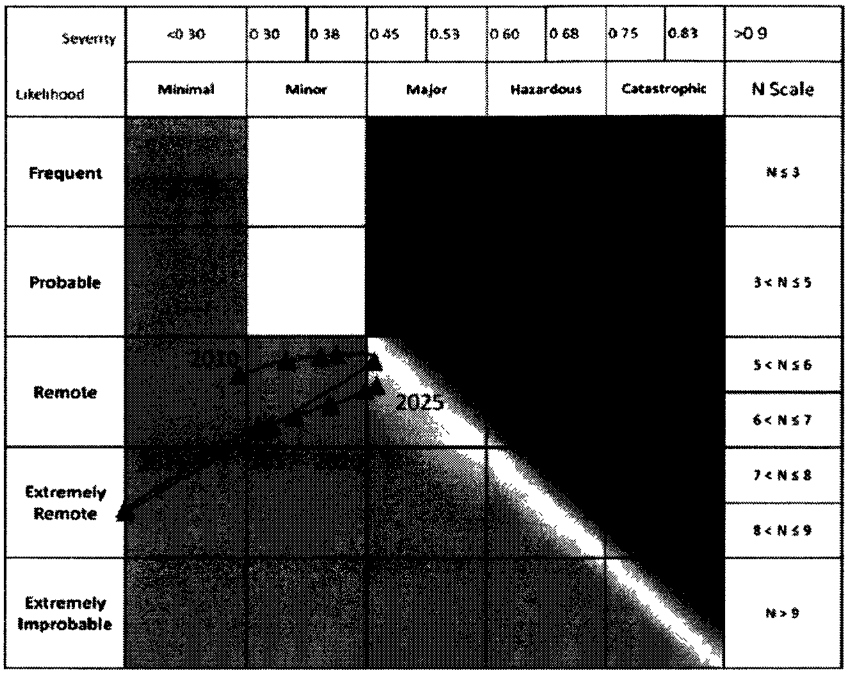

Figure 5-2 Evolution of NAS Safety Values with Time

5.3.3 “Regional Tensions”

The third simulated scenario is called “Regional Tensions” in order to represent a changing global scenario where harmonious globalization is no longer available. Although demand for aeronautics products and services is back up, increased oil cost deeply affects airline companies. Also, stakeholders are obliged to spare funds for military initiated Unmanned Aircraft Systems (UAS) programs, helping to keep the elevated terror level down. Due to the initial NextGen enabler investments, the NAS safety values are better compared to baseline 2010 levels with less likelihood of accident. For the years 2017 to 2020, the increase in air transportation capacity does not deteriorate NAS safety. Even with a considerable terrorist attack risk, air transportation is rather stable and safe (Figure 5-2).

5.3.4 "Environmentally Challenged"

The "Environmentally Challenged" scenario initiated in 2022 simulates a very CO_2 conscious world. At that time, conclusive evidence shows that carbon dioxide harms the planet. For that reason, carbon based fuel usage is very limited and resources are very costly. With their large area and heavy dependency on the use of transportation systems, developed nations face strict regulations. High fuel prices hamper the demand for aerospace products and services where the passenger capacity growth is small. That causes the increased consumer prices for all transportation modes due to higher taxes on fuel. Airline companies tend to acquire larger aircraft with higher load factors while decreasing flight frequency in order to reduce fuel usage. Nevertheless, the NAS safety values start to migrate towards the unacceptable areas due to increased capacity levels, but the unfavorable economic environment prevents further capacity growth, and final air transportation safety values stay within the acceptable limits. At the end of 2025, the likelihood of an accident stays within the "remote" area; however, the consequences of any aircraft related accident are now major due to increased passenger capacity of each aircraft (Figure 5-2).

5.3.5 Stakeholder Specific Variables

5.3.5.1 Government Stakeholder Variables

The government stakeholder fulfills various roles including the military and the Federal Aviation Administration (FAA). The main goal of this stakeholder is to adjust tax values and ensure NAS safety at all times. Also, during the increased terrorist activity levels, the military is intended to take actions and make changes to the existing NAS, causing other stakeholders to cooperate. The FAA (through government funding) can also initiate or mandate the acquisitions of certain enablers if it is deemed necessary by the participants. However, the majority of government stakeholder actions are driven from the NRC scenarios.

The government variables (income tax, environmental tax, security tax, and fuel tax) are given in Figure 5-3. As expected, during the "Pushing the Envelope" era (2010 – 2014), the U.S. economy is strong and tax rates are relatively low, since there are no terrorist or environmental concerns, there is no taxation on these areas. Furthermore, the end of year balance for the government stakeholder shows no significant increase, allowing airports and airlines to invest in NextGen technologies (Figure 5-4). Although the participant representing the government stakeholder did not provide any assistance with ADS-B acquisition, the low tax rates supported the other stakeholders. When asked for the motivation behind this behavior, the participant responded that he/she wanted to see a common initiative from the corporate airlines/airports before supporting the new technology acquisition. During discussions regarding the Data Link enabler acquisition, the participant representing the government stakeholder decided to provide $100 million to assist the corporate airline stakeholder. Both ADS-B and Data Link enabler costs were above the budget limit of any stakeholder, requiring a coalition. The surfaced coalition was between airline/airport and airline/government for ADS-B and Datalink, respectively. The details of the enabler acquisition, timeline and funding are given in Figure 5-3.

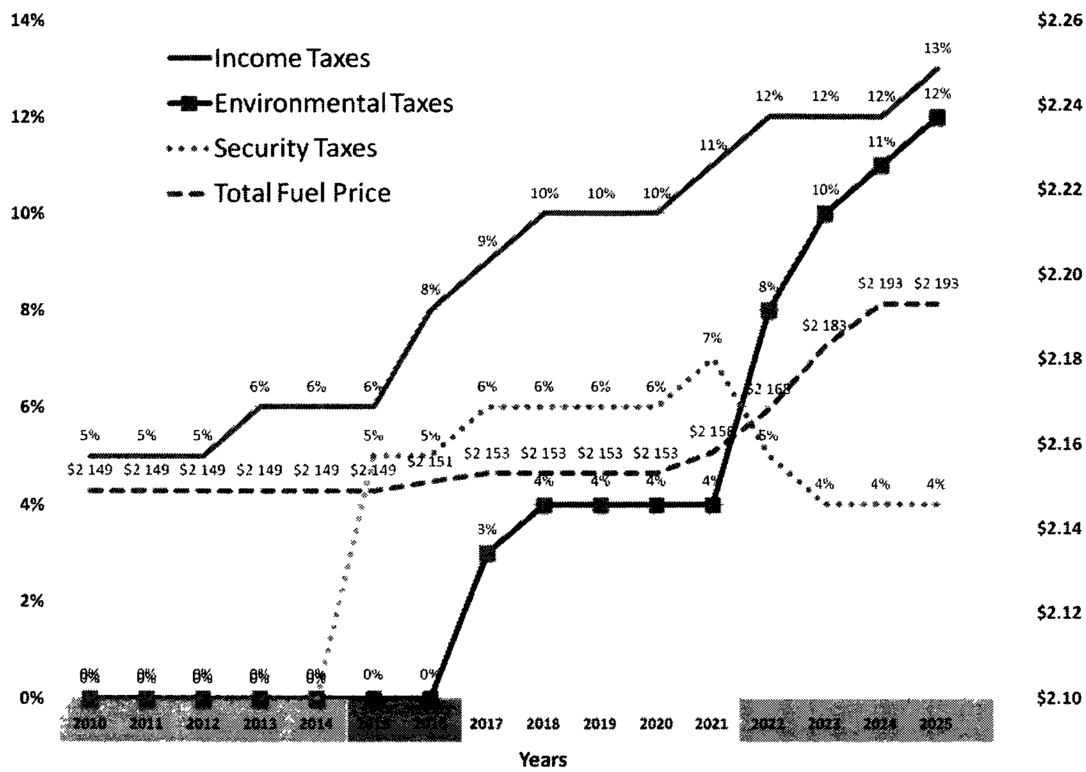

Figure 5-3 Government Variables - Taxes and Total Fuel Price

In the introduction of "Grounded" scenario, the air transportation industry faces a steep increase in security and income taxes in order to compensate for elevated global terror risk and declining economic status. During the "Regional Tensions" era, the security threat remains stable, with constant increase in income taxes and a slight increase in environmental taxes. The fuel tax rate is kept constant since at the time of writing, this tax was planned to be abandoned.

Due to the decline in U.S. economic competitiveness and the disruption of today's global structure, starting from year 2017, the government starts to collect taxes from air transportation stakeholders. Fluctuations in the government end-of-year balance are caused by fluctuations in the income levels of airport and corporate airline stakeholders given in Figure 5-4.

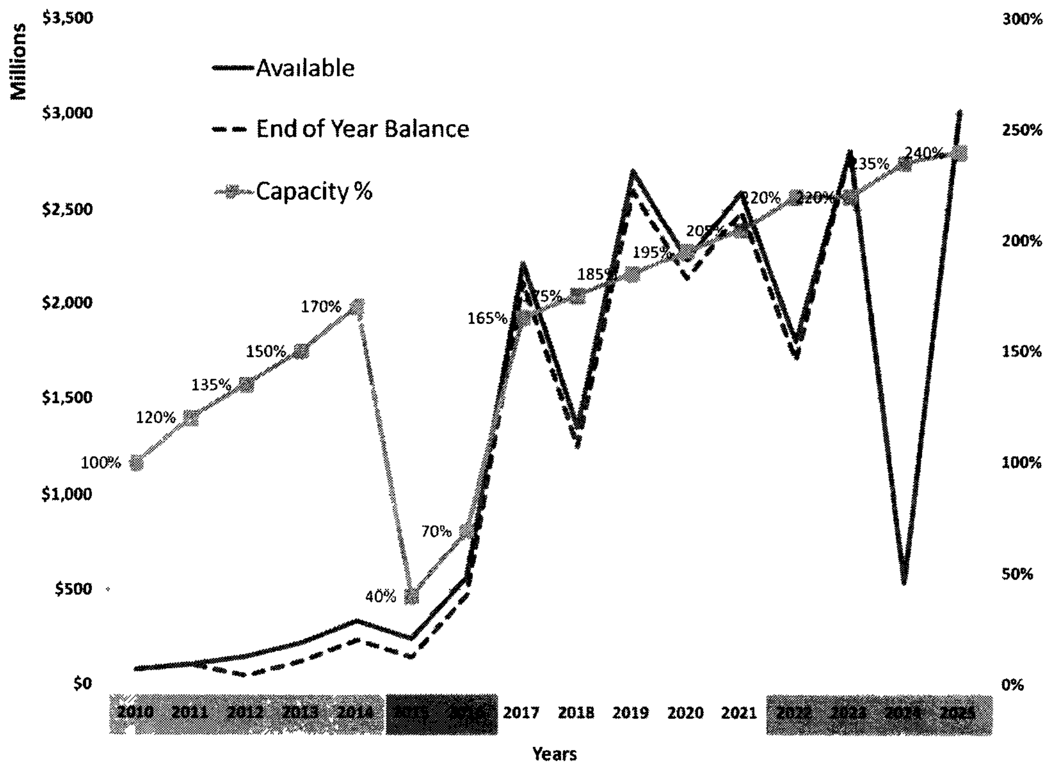

Figure 5-4 Government Financial Data vs. Capacity

5.3.5.2 Airport Stakeholders

Airport stakeholders represent the finances of one large hub airport which is the average of the largest eight airports in the United States. The main operating revenue for the airport operators are aeronautical revenues (passenger airline landing fees, terminal arrival fees, rents and utilities), and non-aeronautical revenues (terminal food and beverage, retail stores and duty free). Operating expenses such as personnel compensation, supplies, and insurance costs were included in the calculations; however, the airport stakeholder does not have any control over these expenses. The operating expenses are assumed proportional to passenger capacity. Figure 5-5 outlines the airport variables and the capacity change. As anticipated, during the competitive air transportation environment (2010 – 2014), airport charges are rather constant, and they are generating low income for airports (Figure 5-6). During the "Grounded" era, the fees climb in order to compensate for increased governmental taxes and increased NextGen related expenses. Starting in 2017 and until 2022, airports raise fees constantly mostly because air transportation remains the main choice of transportation in the United States. During this time, airport and corporate stakeholder representatives exchanged pricing information in order to determine their strategies. Due to the competition between the participants, the airport stakeholder increased the landing fees towards the end of the game when the air transportation capacity reached around 185% of the 2010 values.

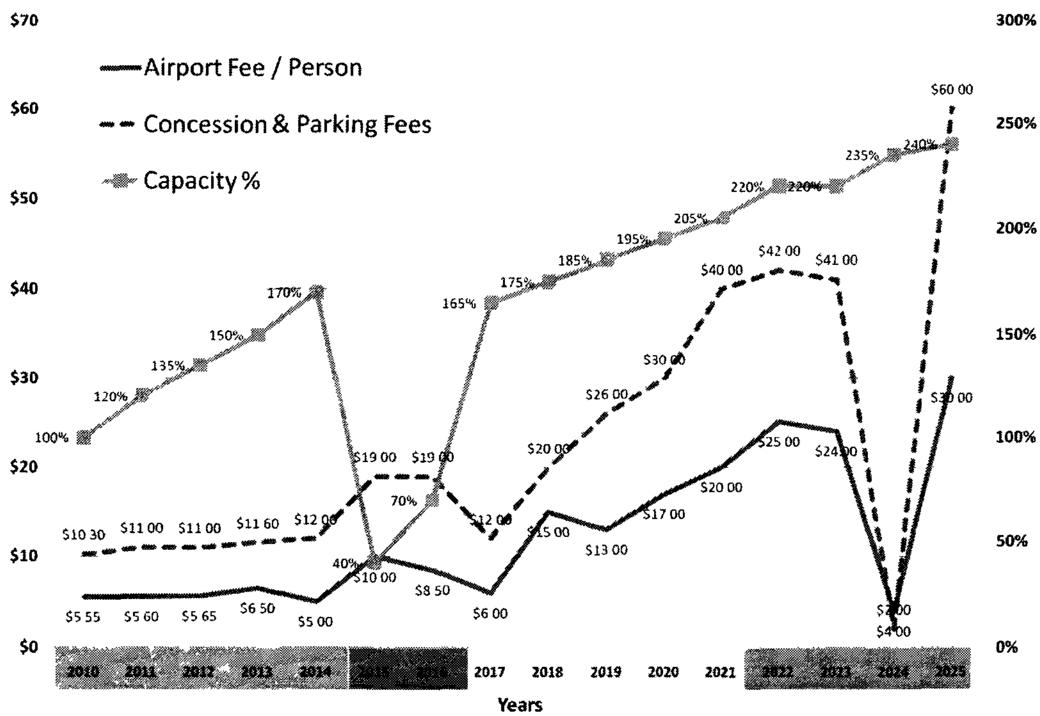

Figure 5-5 Airport Variables - Landing Fees and Concession & Parking Fees vs. Capacity

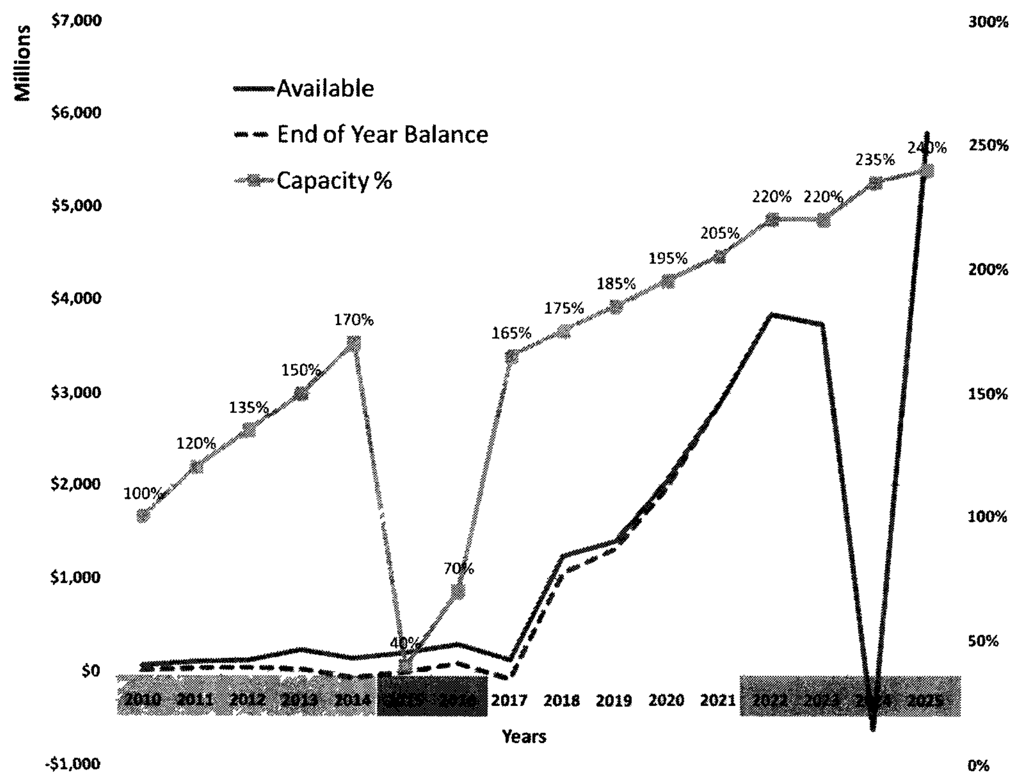

Figure 5-6 Airport Financial Data vs. Capacity

Examining the difference between the available balance and the end-of-year balance, it is understood that the NextGen enabler acquisitions are largely paid-off by the year 2020 and the end of year balance constantly rose until the year 2023 when the general public stakeholder chose to adjust passenger capacity by decreasing it 10%. In order to gain back general public interest, the airport stakeholder dramatically decreased fees resulting in a more than anticipated passenger capacity the next year. In 2024, airports lost close to $500M and re-increased their fees during the last year in order to win the game.

5.3.5.3 Corporate Airlines Stakeholder

The corporate airlines stakeholder was represented by a formal airline employee who was able to provide accurate pricing strategies. In order to afford the large expenses mandated by the FAA, the corporate airlines increased all of their fees throughout the game (Figure 5-7). One prominent observation that surfaced during the gaming exercise was the increase of ticket prices when the airline expenses are elevated. However, even when taxes are back to their normal values, one can see that the airlines did not reflect the relief in their fees, which is in accord with a real-world environment. Like the airports stakeholder, corporate airlines had to decrease their ticket fees when the general public stakeholder reacted and adjusted the passenger capacity. During that time, the raw ticket fee was decreased from $205 to $179; however it climbed back up to $209 once passenger capacity recovered. Throughout the game, passengers experienced a more than $50 increase in ticket prices ($377 compared to $325 in 2010, after the government taxes are reflected). Baggage fees were increased from $25 to $31 while reservation cancellation fees went up from $150 to $198 over the course of 16 years.

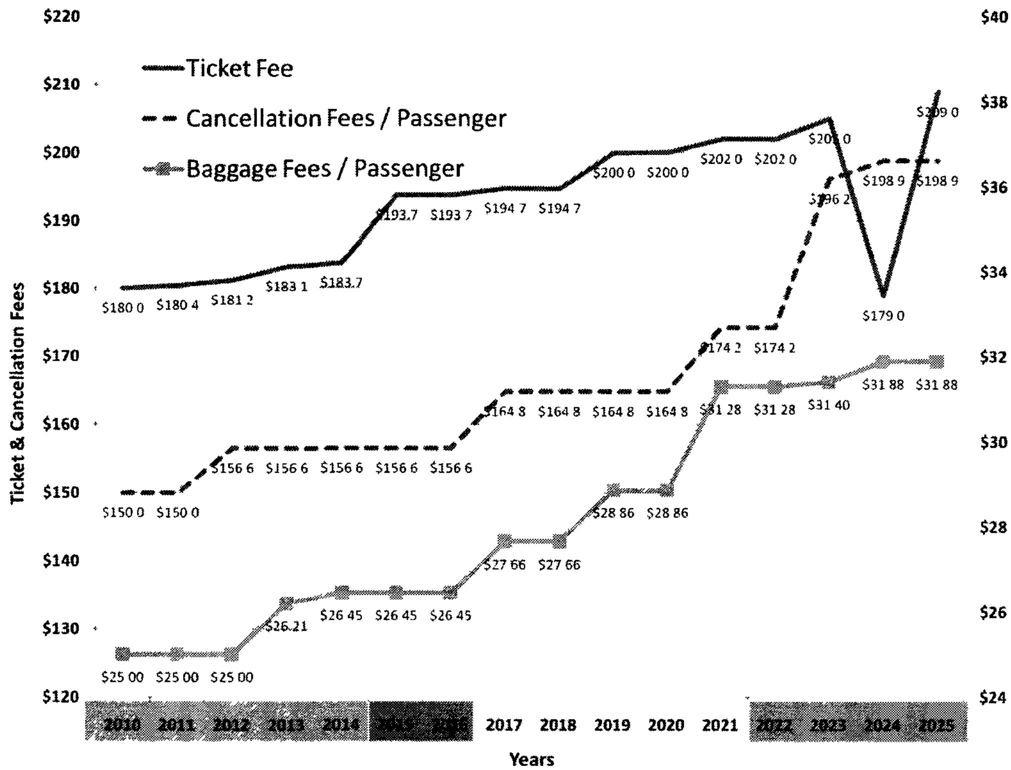

Figure 5-7 Corporate Airlines Variables - Ticket Fees, Cancellation fees, and Baggage Fees

Airline companies are highly susceptible to jet fuel price change due to heavy consumption, especially for the future capacity values reaching almost 3 times the current capacity. Examining Figure 5-8, it is apparent that the corporate airlines managed to keep their end of year balances on the positive. Although passenger capacity reached 240% of 2010 values and ticket prices were increased more than 15%, baggage fees more than 25%, and reservation fees more than 30%, corporate airlines still stayed below the profit margin level experienced at years 2017 and 2019. Fuel prices and increased taxation values are found to be the main reason why airlines couldn't show as much profit as airports declared during the last half of the gaming exercise.

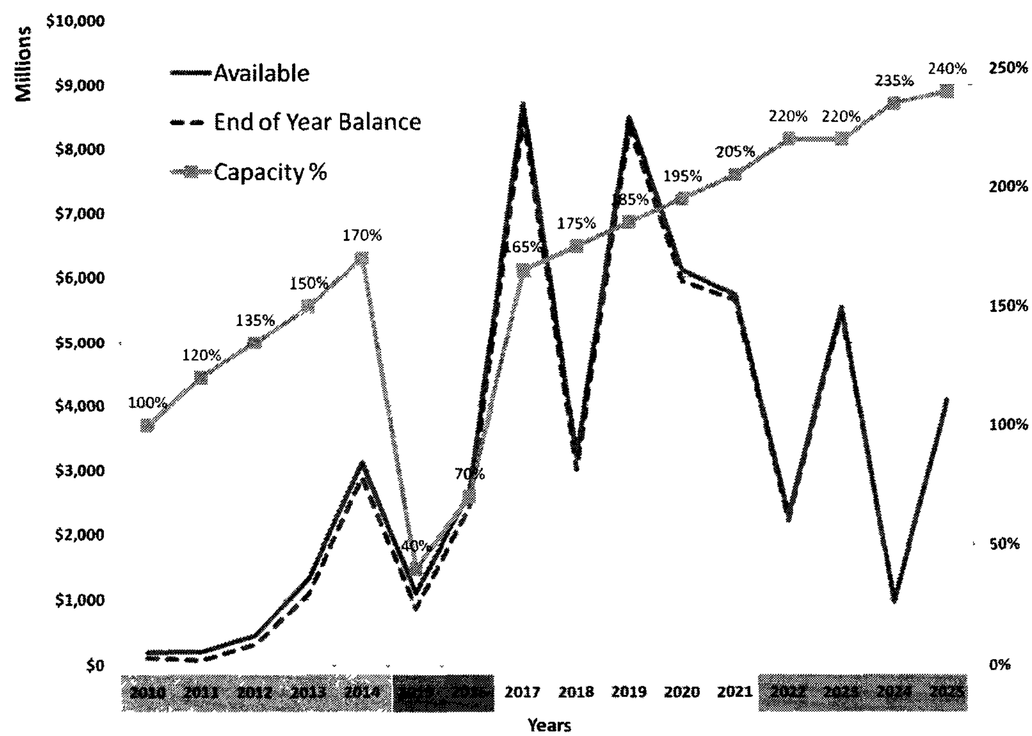

Figure 5-8 Corporate Airlines Financial Data vs. Capacity

5.3.5.4 General Public Stakeholder

As previously stated, the general public indirectly decides air travel passenger capacity at the end of each time-step by comparing the transit time and cost for the two predetermined routes. These one-way routes are the 228-mile Washington, DC (Union Station) to New York, NY (Penn Station) and 437-mile Washington, DC (Union Station) to Boston, MA (South Station) routes. As of March 2011, these two routes are the only two high speed rail routes existing in the United States ("Acela Express" by Amtrak[35]). The three modes of transportation considered are rail, automobile and air transportation. Air transportation values include travel time and costs -estimate of a taxi ride from the airports (Dulles International Airport, John F. Kennedy Airport, and Boston Logan Airport) to the rail stations (Union Station, Penn Station, and South

[35] http://www.amtrak.com/servlet/ContentServer?c=AM_Route_C&pagename=am%2FLayout&cid=1241245664867

Station). Other assumptions can be given as: an automobile with 25mpg, \$3.113/gallon national gas average, arriving early to the departure airport, waiting for baggage at the destination airport and taxi transportation transit times.

Figure 5-9 shows cost and transit times for the three modes of transportation with respect to the simulation year for the first configuration, from Washington, DC to New York. For this particular trip setup, driving is the lowest cost option; however, it takes over 4 hours and 30 minutes. Flying is the costliest method of all; however, door-to-door transit time is higher than the high speed train option. With the introduction of future high speed rail systems, it is assumed that rail prices will rise in order to compensate for increased infrastructure investments while transit times will reach around 2 hours towards the end of the simulation. Meanwhile, air transportation cost increases throughout the game while transit times vary with the scenario: higher transit times during increased terrorist activities in the "Grounded" scenario and slower travel speeds to abide the tightened CO_2 regulations in the "Environmentally Challenged" scenario. Automobile transit times are assumed to be constant over the next 15 years while costs are slightly increased with higher fuel cost.

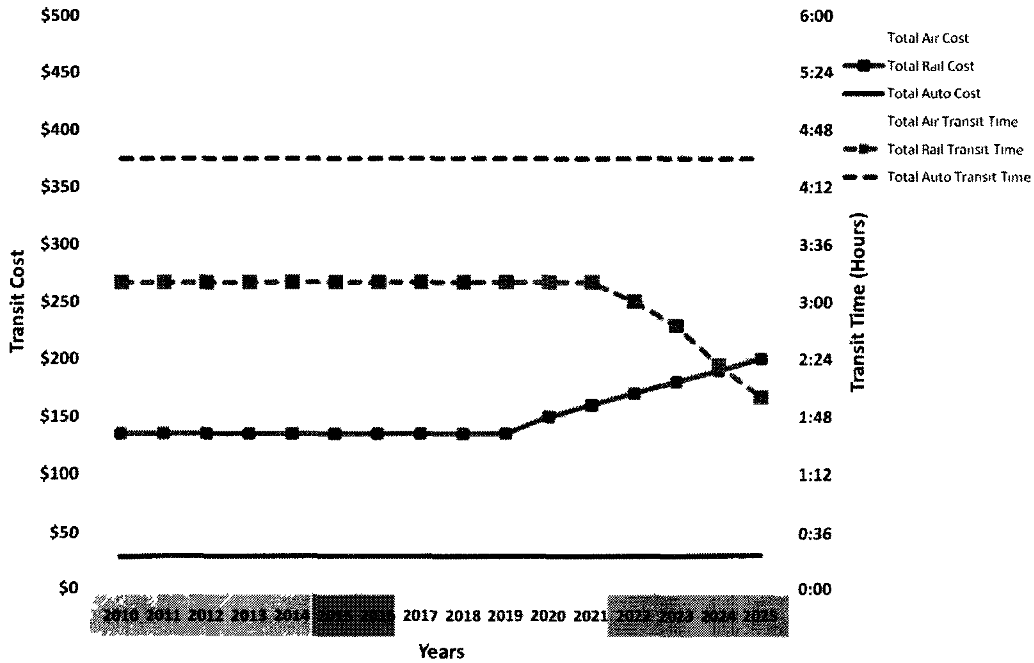

Figure 5-9 General Public Announcement Variables (Configuration 1)

The second configuration variables are given in Figure 5-10. The pilot route for this setup is over 400 miles, rendering the automobile option rather obsolete due to transit times over 9 hours, although the cost associated with automobile transportation is the lowest compared to the remaining two transportation modes. Similarly, due to increased travel distance, the train mode is not considerably cheaper than the air mode, but it is still much slower. The air transportation mode provides the fastest service with the highest cost until around the year 2020 when High Speed Rail infrastructure starts to offer faster service times with increased ticket prices. In year 2023, with increased air transportation fees and the introduction of high speed rail, the general public stakeholder decides to adjust projected passenger capacity by -5% (Table 5-1). By the end of the simulation, transit times for air and train modes of transportation are comparable, and costs for both of the modes are on the rise.

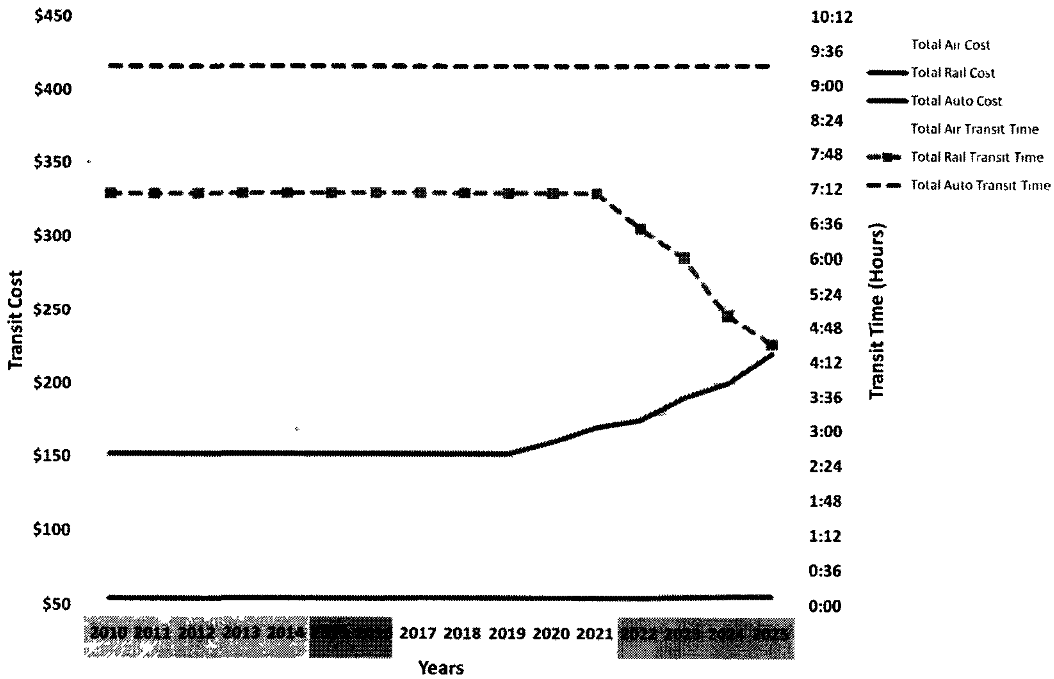

Figure 5-10 General Public Announcement Variables (Configuration 2)

The general public stakeholder participant adjusted air transportation capacity on six occasions throughout the game. These interventions are given in Table 5-1 Public Intervention Values and Provided Reasons. The 2015 terrorist attacks hamper air transportation capacity 10% more than anticipated; however, even with the same terror risk, in the following year, the perceived terror risk is lower than projected. Even with the higher transportation costs and slower travel speeds, the air transportation mode still gets adjusted by the general public stakeholder and reaches 240% of the 2010 passenger capacity. This results in over 1.5 billion passengers in the NAS.

Table 5-1 Public Intervention Values and Provided Reasons

Year / Scenario	Public Intervention Amount	Reason Provided
2014 / Pushing the Envelope	+5%	Strong U.S. Economy + relatively inexpensive air transportation fees
2015 / Grounded	-10%	Perceived terror risk higher than anticipated
2016 / Grounded	+10%	Ongoing perceived terror risk, lower than anticipated
2022 / Environmentally Challenged	+5%	No increase on air transportation fees
2023 / Environmentally Challenged	-5%	With upcoming High Speed Rail effect and the increase air transportation fees
2024 / Environmentally Challenged	+10%	Passenger capacity increase in response to the steep decrease in air transportation fees following year 2023
2025 / Environmentally Challenged	+10%	Continuing satisfaction from air transportation services

5.1 Other Observations

The following figures are plots from various variables, demonstrating the correlation between them. Figure 5-11 shows airline ticket fees versus capacity. The ongoing increase in ticket fees in 2023 resulted in a lack of passenger capacity increase, and the resulting price-cut from the airline companies allowed boosting the passenger capacity back up.

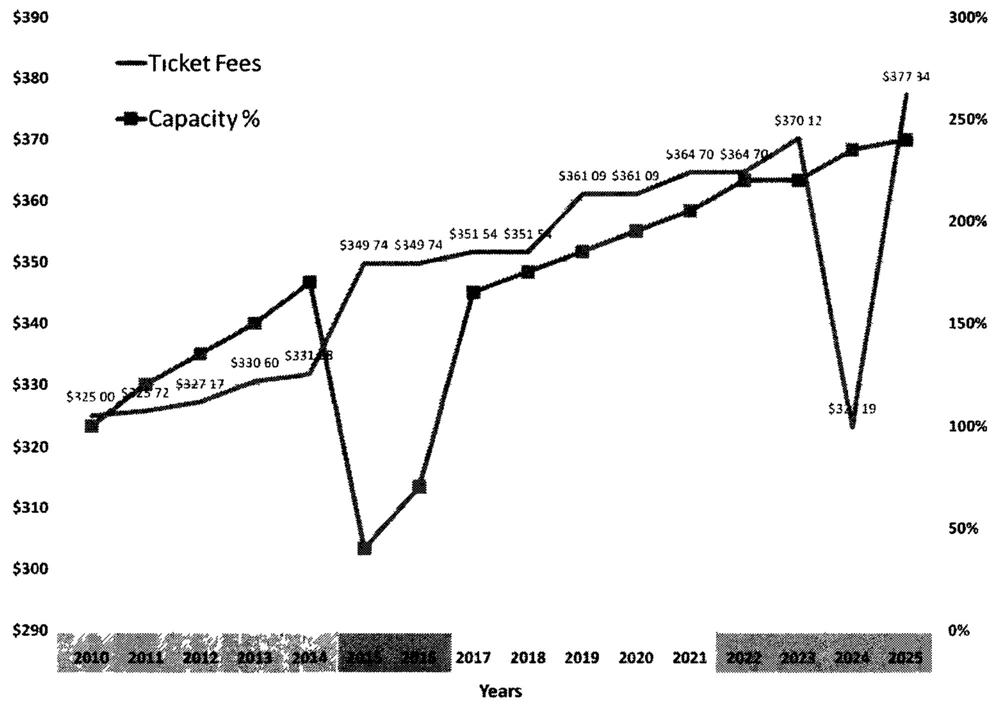

Figure 5-11 Airline Ticket fees vs. Capacity

Figure 5-12 demonstrates the corporate airlines' budget change with respect to airport landing fees. In a majority of the years, these two values are inversely proportional; higher airport landing fees lead to lower airline end of year (or available balance) budget. The two peaks in the corporate airline available funds that can be examined in years 2017 and 2019 can be explained with relatively low airport landing fee charges of $6 and 13$ respectively. Similarly, the lowest airline profit margin was experienced at a very high landing fee of $25. Figure 5-14 shows the corporate airline budget versus ticket prices. Higher ticket prices lead to higher profit margins; however, airline companies are affected by a number of factors such as fuel prices and airport landing fees.

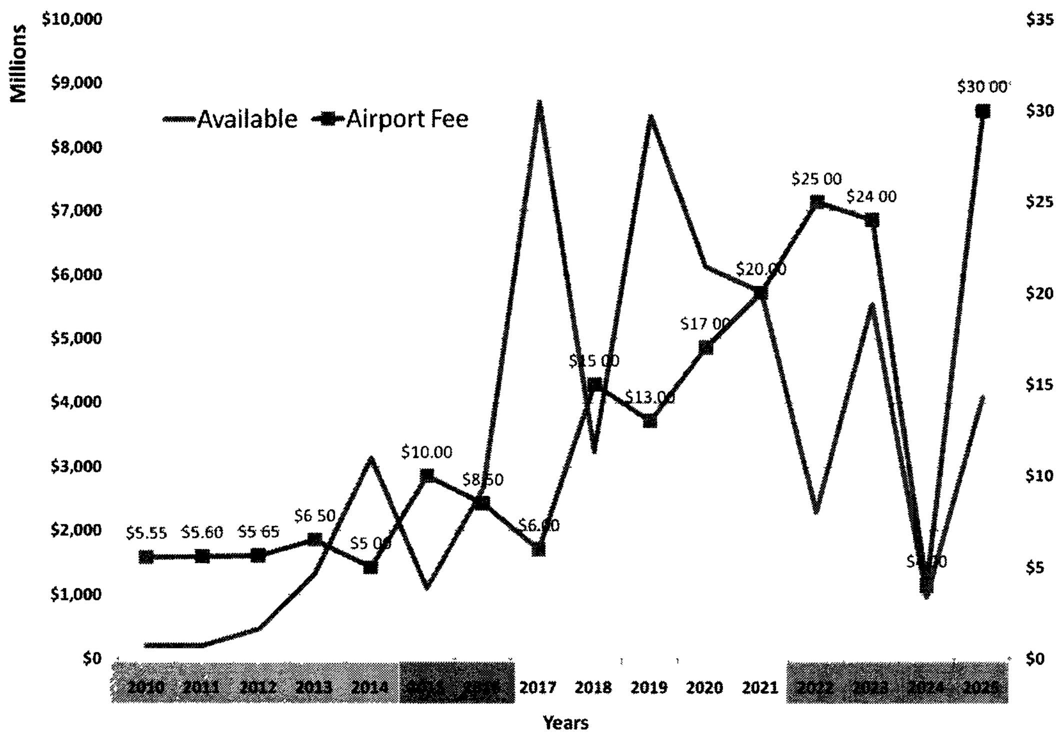

Figure 5-12 Corporate Airlines Budget vs. Airport Landing Fee

Figure 5-13 provides the corporate airline budget with respect to fuel prices. Although fuel prices only fluctuated below 5 cents, increased fuel prices drastically affected the airline budget given the volume of passenger transportation. Even with the elevated ticket prices in 2025, the airline stakeholder profit stayed well below the previous year's values.

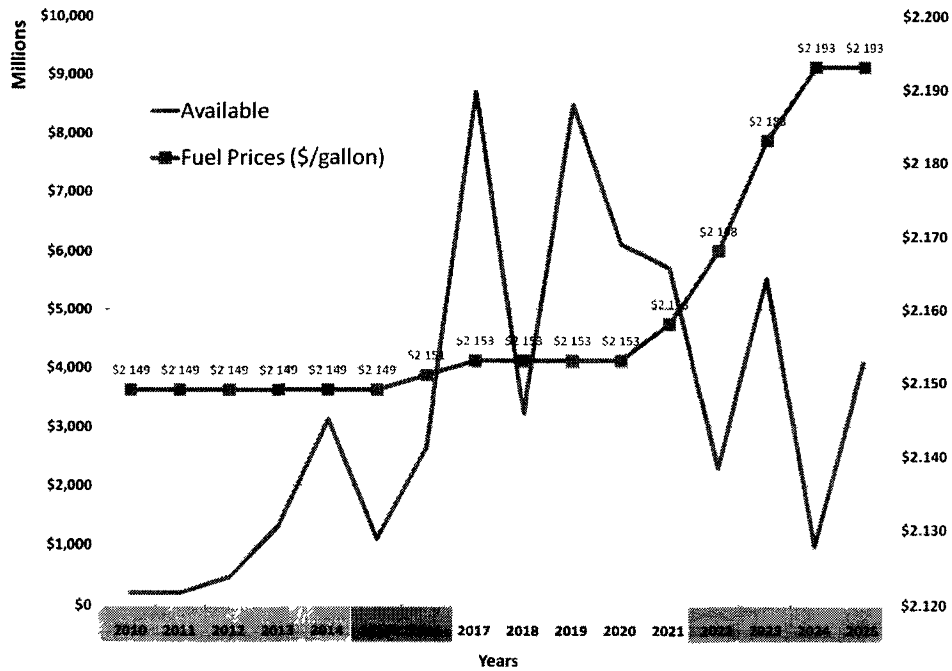

Figure 5-13 Corporate Airlines Budget vs. Fuel Price

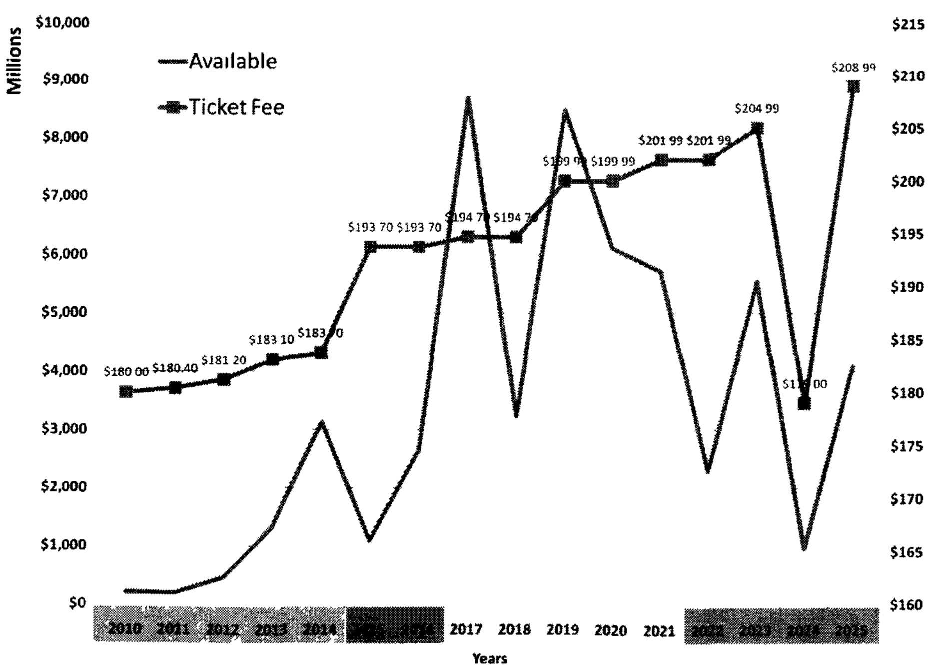

Figure 5-14 Corporate Airlines Budget vs. Ticket Fees

5.2 Enabler Acquisition Timeline and Surfaced Strategies

The selected 18 enablers from 7 different categories are all implemented within the first three years of the game timeline. Since the participants of the game are real stakeholders within the aviation field, they were aware of the necessity of key enablers like ADS-B and Data Link, along with other safety related enablers (Table 5-2). For that reason, all the enabler acquisitions were completed by 2013 unlike other gaming sessions played with non-aviation related participants where the acquisition took place much later in the gaming session. One important outcome of the acquisition strategy was the leadership of the corporate airline participant. He/she was the initiator in purchasing high-dollar items such as ADS-B and Data Link. The cost of such enablers were collected by increased ticket fees and other fees charged by the airline companies. The corporate airline stakeholder compensated for the majority of the widespread application of ADS-B technology which is the main enabler for many NextGen technologies. The airport stakeholder provided a fraction of the technology acquisition (around 0.01%). The Data Link acquisition was realized by the government contribution, around 25% of the Data Link acquisition cost over the 11 years.

Both airports and airlines also contributed to the UAS integration to the National Airspace. According to the scenario, from 2017 to 2021, airlines and airports were obligated to spare $75M and $150M, respectively. Overall, airport authorities spent $1.570B on enablers, $33M on ADS-B and $375M on UAS integration efforts, whereas airline authorities spared $2.316B on enablers, $5.896B on ADS-B and Data Link combined and $750M on UAS integration.

Throughout the gaming activity, participants noted that after infrastructure investments are completed, increased passenger capacity allowed them to obtain large profit margins. However, if non-operational profit/expenses were included in the calculations, their profit would be considerably lower. Examining the past 10 years of aviation data, high fluctuations in the end-of-year balance are apparent due to severe fluctuations primarily in jet fuel prices. For purposes of simplicity, fuel prices were kept rather stable on February 14th, 2011 game (an increase of 4.5 cents).

Table 5-2 Enabler Acquisition Timeline and Strategies

Enabler Package Definition	Denomina-tion	Enabler Acquisition Planned	Enabler Acquisition Completed	Primary Cost Bearer	Other Cost Bearers	Total Cost	Coalition Surfaced
ADS-B	ADS B	2011	2021	Airline 2,486M	Airports 33M	2,519M	Airport – Airline
Data Link	Data Link	2012	2021	Airline 3,410M	Government 1,100M	4510M	Airline – Government
Capacity/Safety Related Runway Enablers	R1	2012	2019	Airport	N/A	78M	N/A
Runway Visibility	R2	2010	2020	Airport	N/A	452M	N/A
Collision - NMAC	C1	2011	2017	Airport	N/A	98M	N/A
Collision - Loss of Separation	C2	2013	2018	Airport	N/A	570M	N/A
A/C Powerplant	AC1	2010	2023	Airline	N/A	112M	N/A
A/C Structures	AC2	2010	2023	Airline	N/A	112M	N/A
A/C Systems	AC3	2010	2023	Airline	N/A	154M	N/A
Icing - Structures	I1	2010	2023	Airline	N/A	234M	N/A
Icing - Engine	I2	2010	2023	Airline	N/A	392M	N/A
Weather – Thunderstorm	W1	2012	2017	Airline	N/A	60M	N/A
Weather - Visibility	W2	2010	2016	Airline	N/A	70M	N/A
Turbulence - In Flight	T1	2011	2018	Airline	N/A	336M	N/A
Turbulence - Ground Wake	T2	2010	2020	Airport	N/A	132M	N/A
Enhanced Post-impact Fire/Smoke Mitigation	S1	2013	2020	Airline	N/A	400M	N/A
Improved Crash Survivability of Aircraft Structures	S2	2013	2020	Airline	N/A	400M	N/A
Improved Evacuation and Accident Response Procedures	S3	2013	2020	Airport	N/A	240M	N/A

CHAPTER 6

CONCLUSIONS AND DISCUSSIONS

Societies around the world depend on the proper functioning of various infrastructures. However, changes in technology, societal needs and expectations, political shifts, and environmental concerns cause infrastructure systems to underperform, requiring modernization (Roos, et al., 2004). Infrastructure system modernizations are performed to accommodate future capacity levels, address environmental concerns and meet sustainability needs. On the other hand, transformations of large-scale complex infrastructure systems create significant challenges. Their multi-dimensional complexity and increased societal contexts require different approaches to plan, design, and manage such transformations. In order to accurately plan next generation infrastructure systems, understating the interactions between technical, political and economic factors is of paramount importance and obtaining capabilities related to developing, evaluating and evolving infrastructure transformations accurately constitutes a fundamental need.

In order to do so, the current research pursued the development and deployment of a gaming based methodology to serve as a platform to generate, integrate, and evaluate data for next generation infrastructure development efforts. To demonstrate its capabilities, the methodology was applied to the NextGen framework. The multi-dimensional complexity and stakeholder-rich environment of NextGen provided an accurate test bed for the complex socio-technical system transformation. Subject matter expert opinions are used heavily to develop gaming components, constitute participants, and finally, evaluate the validity of the framework.

The questionnaire provided in Appendix C was completed by participants via direct and indirect questions throughout the gaming exercise and debriefing as well as follow up contacts.

6.1 Methodology Outcomes and Contributions

The developed methodology presented in this dissertation allows decision makers to obtain several outcomes. The most important contribution of the methodology is related to the understanding and communication of complexity and interdependencies associated with large-scale system transitions among stakeholders. For the unique cases where the participants are the actual stakeholders, improved knowledge of the system and awareness of its characteristics yields a desirable environment for data elicitation. Coupling gaming with other methods, the methodology can be applied to generate preliminary data regarding the systems' characteristics such as capacity, power generation, throughput, and risk evaluation/acceptance, while using a systemic approach, considering both social and technical aspects of the system. The methodology proposed within this dissertation can help generate and aggregate data for future status and transient phases of the infrastructure system transitions. The developed platform allows decision makers to test and validate scenarios while accommodating on-the-fly changes for adjustment and improvements from participants.

The case study developed within this dissertation allowed decision makers to envisage NAS safety values over a 15-year transition period from the current to the future system visualized by a risk matrix and As Low As Reasonably Achievable (ALARA) principle. The data generation session also revealed potential strategic behavior and pricing strategies.

Although demonstrated using the NextGen transformation, the developed methodology can be applied to any large-scale infrastructure system thanks to its SoS approach and modular structure, allowing planners to employ existing tools and methods to the problem at hand. The gaming based methodology can be successfully adapted to any infrastructure system where large stakeholder interactions, multi-level complexities and high level interdependencies are present (e.g. energy infrastructure, information and telecommunications, emergency services, etc.). Depending on the need, the methodology can be followed to generate an application for scenario testing, preliminary system response predictions, simulating capacity and/or risk levels, prioritizing resources, identifying potential future issues (strategic behavior, public perception, etc.).

6.2 Limitations of the Study

Unlike computer models or other hard-science alternatives, the development, execution and validation phases of the methodology presented within this research require extensive subject matter expert contribution. For that reason, the gaming environment delineates the physical presence of all the prominent stakeholders of that particular infrastructure system on several occasions. It has proven quite difficult to identify, contact, and bring together all the experts and stakeholders under one roof throughout the development of the methodology mainly because of conflicting schedules and cost of travel.

Besides logistics limitations, using serious gaming for academic research raises concerns due to challenges in validating the methodology. The interdisciplinary nature of simulation and gaming, in most cases, limits the use of this approach for educational/training purposes in businesses. Researchers believe that further work must be performed to theorize and establish serious gaming as a field of study; whether simulation and gaming is a beneficial tool or an academic field is still an uncertainty (Shiratori, 2003). However, in a more recent study, Mayer indicates the use of gaming as a serious research method yielding an increasing number of Ph.D. students over the last decade (Mayer, 2009).

Also, the accurate representation of a large and complex system, fusing multiple perspectives and multiple disciplines, has proven challenging in practice (Brewer, 2007). For instance, the selection of scenario elements and the actual composition of the scenario are based primarily on the game developer's perspective and there is no rule for scenario development to guide game builders about what to include and what to omit (deLeon, 1975). Similar to the scenario construct, the abstraction of the elements of the reference system and translating them to the model poses a challenge. At any given time during the game development stage, it is crucial to iteratively check the assumptions against the reference system (Peters, et al., 1998). When developed properly, the plastic nature of gaming, allowing modelers to shape, bend, stretch and adapt to any problem at hand, was proven to be a great way of integrating the technical-physical complexity with social-political complexity, supporting the highly socio-technical and complex environment of next generation infrastructure development (Mayer, 2009).

6.3 Future Work and Methodology Expansion

Due to the characteristics of system-of-systems engineering methodology adopting a modular and flexible modeling environment, the current study has great potential for future expansion. The flexibility associated with the uses of a serious gaming platform enables the introduction of already existing risk assessment, cost analysis or other methodologies in order to investigate different aspects of the problem. For the cases where multi-stakeholder situations and complexity are a prominent part of the problem (which is believed the case on most large scale, complex systems), the developed methodology can be expanded to accommodate such needs.

The future phases of the case study exercise can include other aspects of NextGen related technologies and methodologies besides the safety component. The increased capacity and respective environmental concerns induce more socio-economic problems that require investigation. Although this research adopted the passenger fatality as the primary consequence indicator, other damage factors like accident related costs (damage to the aircraft, legal liabilities, etc.) or loss of reputation can also be included in the consequences scale of the risk definition. Also, additional capabilities can be brought into the data analysis and validation section of the methodology where the generated data can be used as a baseline for computer simulation models. It may be possible to limit dependence on expert and stakeholder participation; however, the feasibility of this approach must be further examined.

Typically, developing a serious game takes one to two years, and there are cases where the game constantly gets updated and enhanced, taking over 6 years (Duke, 1980; Geurts, et al., 2007; Mayer, 2009). Ensuring the seamless integration of the software and techniques covered in this methodology will take additional efforts and serious gaming exercises.

Lastly, the methodology developed within this research can be applied to other large infrastructure transitions or other sociotechnical systems where strong stakeholder interactions occur, e.g. power or telecommunications infrastructures, national security, and healthcare. It is possible to experience and collect information regarding the counter-intuitive behavior of complex systems with methodologies harnessing the capabilities of both classical hard sciences and soft sciences alike, helping plan, develop and manage sustainable systems for generations to come.

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APPENDIX A – UNMANNED AERIAL SYSTEMS INTEGRATION TO NATIONAL AIRSPACE

A.1 Introduction[36]

A.1.1. Overview

Over the past decade, unmanned aerial vehicles (UAVs or unmanned aircraft systems UAS are used interchangeably throughout the text) have proven their values and capabilities via various applications around the globe. Initiated by the military, today UAVs are In high demand since they provide endurances and flight environments beyond the limits of manned systems. Civil government, scientific research institutes and commercial markets have already seized the low-cost, flexible, simple operation opportunities associated with UAV applications. However, barriers like lack of airspace regulations, airworthiness, safety, and standards applying to manned systems still remain the chief issues to address. Various initiatives are brought to life to support the creation and expansion of a civil/commercial UAV market, aiming to integrate unmanned aerial systems (UAS) into the National Airspace System (NAS).

The problems associated with UAS integration into NAS are grouped under five general categories: safety, security, ATM, regulation, and socio-economic factors. Although UAS integration possesses case-specific issues such as public apprehension or consensus on UAS concepts of definitions, some of the technical issues like the lack of information data exchange networks or automated collision avoidance systems are within the NextGen framework. The majority of the NextGen enabling technologies inherently allow the seamless integration of UAS into NAS in the coming years. However, the socio-technical issues including regulations and public perception have to be addressed in order to achieve a fully integrated airspace (DeGarmo, 2004).

A.1.2 Brief History and Integration Issues

Since the 1950's, the U.S. military has spent more than $25 billion on UAS development. The 2006 Department of Defense Budget alone provided $1.7 billion for unmanned vehicles, including ground, underwater, aerial, and combat aerial unmanned vehicles (U.S. Office of Management and Budget, 2006). The U.S. Air Force and Department of Defense employed UAS in various scenarios, including Operation Iraqi Freedom and Enduring Freedom, Afghanistan, and Kosovo (DeGarmo, 2004; The U.S. Air Force, 2005; U.S. Congressional Research Service, 2003; Office of Secretary of Defense, 2005). The U.S. and other foreign armed forces continue to seek a more stable UAS development environment, eventually rendering the UAS one of the vital components of the military. As stated in U.S. Office of Management and Budget (2006), unmanned systems are considered to provide a major advantage to the U.S. forces on the

[36] The goal of this section is to present an object-oriented based software approach to demonstrate the feasibility of accurately addressing the complexity of such an integration plan, while introducing the "business process" concept.

battlefield, while decreasing risks to troops by replacing the pilot with UAS on dull, dirty, or dangerous missions [8]. For these reasons, increased resources are committed to the acquisition and research of related UAS technologies worldwide[37].

Unlike underwater and terrestrial unmanned vehicles, a remotely piloted aircraft's operation area carries a high risk of interference with the National Airspace System (NAS). For this reason, current high altitude long endurance (HALE) UAS are highly restricted as to how, when, and where they can operate within NAS. Remotely operated aircraft (ROA) within the HALE class include Global Hawk, Predator B/Altair, Pathfinder, Helios, etc. and applications such as military reconnaissance, remote sensing, global disaster monitoring are demonstrated by the Department of Defense (DoD), NASA, and Department of Energy (DoE) (Bauer & Dann, 2005; U.S. Government Accountability Office, 2008). Since there is no regulatory or procedural guidance on how the unmanned aircraft operations are executed, these types of missions are considered "one time" events, treated as exceptional, requiring flight authorization on every single mission. Federal Aviation Administration issues a Certificate of Authorization (CoA) for HALE ROA, whose operational environment is similar to manned aircraft in order to maintain safety within NAS. CoA regulates the unmanned aircraft itself, pilot, operating and flight rules (Bauer & Dann, 2005).

Although UAS capabilities have greatly excelled; the lack of UAS classification and standards still constitute the main roadblock before a fully integrated, safely operated National Airspace. Considering the various UAS sizes and configurations from the size of an insect to that of a commercial airliner, determining a universal UAS definition itself poses a great challenge (U.S. Congressional Research Service, 2003). The commercial and civil government market expectations have driven various initiatives, associations, and standard organizations to bring UAS operations inline with the manned operational environment and the ability to withstand any loads created through the commercial and civil government market. Examples of such associations, organizations, and initiatives are the Association for Unmanned Vehicle Systems International (AUVSI), American Institute of Aeronautics and Astronautics (NASA), Unmanned Vehicle Systems (UVS) International, Access 5, and UAS National Industry Team (UNITE) (DeGarmo, 2004; Office of Secretary of Defense, 2007; U.S. Government Accountability Office, 2008).

Potential unmanned systems are prone to bringing more complexity and capacity issues to already saturated commercial airline markets and transportation infrastructure. Caused by

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[37] The opportunities associated with UAVs are not only perceived by the military authorities; many commercial applications are sought, especially in the small aircraft market. Applications such as crop monitoring, communications relay, utility inspection, news and media support, aerial advertising, cargo, commercial imaging, and security, to name a few, are all potential UAV users, more economic and flexible than their space-based or manned aircraft counterfeits (DeGarmo, 2004). The civil government is considered to be one of the primary UAV user, particularly in homeland security. The Department of Homeland Security (DHS) requested $10 million to support the Coast Guard and Border Patrol operations. DHS applications include watching coastal waters, patrol borders, protecting major oil and gas lines, drug surveillance, etc. Other civil applications cover traffic surveillance, emergency response, medical resupply, forest fire monitoring, flood mapping, nuclear/biological/chemical sensing and tracking, land use mapping, etc (DeGarmo, 2004; U.S. Congressional Research Service, 2003)

increased UAS flights, the air traffic will be affected via flight paths, performance criteria, and air services while labor disruptions will be created (DeGarmo, 2004). System interoperability, navigation, communications involving air traffic controllers and UAS are leading issues with air traffic aspects. According to the U.S. Military UAS flight data, unmanned systems have a poor safety record, almost two levels of magnitude (100 times) higher than risks associated with manned aircraft and 50 times higher than F-16 fighters (U.S. Congressional Research Service, 2003). However, the high "mishap" (accident) rates are reconciled with the nature of military uses and low redundancy component failures. One other major concern is the lack of secure communication bandwidths required for UAS applications comprising the vehicle, ground control station, data link infrastructure and security (DeGarmo, 2004). Socio-economic factors including insurance liability, public acceptance, and government investment are other key components that actively drive and restrain future UAS markets.

The undertaken challenges require insuring reliability, security, sustainability and affordability of the transformation and adaptation of the existing unmanned aircraft system (UAS) to NAS. As discussed previously, various initiatives are taken in order to obtain the desired integration state of unmanned aerial vehicles and NAS. DeGarmo (2004) provides an overview of the relevant issues under five main categories: safety, security, air traffic, regulation, socio-economics. This section contains the primary findings of a project where the issues covered by DeGarmo (2004) are adopted and used on object-oriented paradigm based software as an input. The software is called TopEase® and handles problems as "business processes" and provides a desirable end-state of an enterprise, business, or an application while highlighting the gap between the desired and current states. The goal of the project was to demonstrate the preliminary feasibility of applying the UAS-NAS integration plan development to TopEase® environment with limited data on hand (mostly publicly available due to the sensitive material, (Bauer & Dann, 2005; DeGarmo, 2004; The U.S. Air Force, 2005). For this reason, at the time of writing, the results would be the preliminary confirmation from subject-matter experts according to the validity of the application.

A.2 Object-Oriented Programming: An Overview

A.2.1 An Overview

The approach that has been followed during the project was based upon the TopEase® software which runs an object- oriented programming (OOP) paradigm in the background. The OOP paradigm uses "objects" to design applications and computer programs. Object-Oriented Modeling (OOM) may be seen as a collection of cooperating objects, as opposed to a traditional view in which a program may be seen as a list of instructions to the computer. The real system is modeled through the use of classes where each object acts like an independent entity with a distinct role or responsibility. OOP uses several concepts/techniques from previously established paradigms, including inheritance, modularity, polymorphism, and encapsulation supporting the development of efficient class structures. Key concepts are provided in the next section.

A.2.2 Key Concepts

- *Class* defines the abstract characteristics of a thing, including the thing's characteristics (its attributes or properties) and the things it can do (its behaviors or methods).
- *Object* is a particular instance of a class and executable software representations of real-world concepts and is a software package that includes all the necessary data and procedures to represent a real-world object for a specific set of purposes.
- *Message Passing* signifies the objects interacting with each other by sending requests for services known as messages.
- *Encapsulation* is the mechanism by which related data and procedures are bound together within an object. It conceals the exact details of how a particular class works from objects that use its code or send messages to it.
- *Polymorphism* is the behavior that varies depending on the class in which the behavior is invoked; that is, two or more classes can react differently to the same message. The power of polymorphism is that it greatly simplifies the logic of programs by shortening and increasing the execution speed.
- *Inheritance* is the mechanism that allows classes to be defined as special cases, or *subclasses*, of each other (Gossain & Anderson, 1989; Pulfer & Schmid, 2006).

A.2.3 TopEase® Software

Once the OOP paradigm is understood, it is easier to place the objects, classes and message products throughout the software hierarchy. Unmanned aerial system (UAS) integration to NAS creates an interlinked and multidimensional challenge when the highly regulated air transportation infrastructure is taken into account, along with safety, security, air traffic, regulatory, and socio-economic aspects of the problem (DeGarmo, 2004). By defining the stakeholders, systems, subsystems, communications, regulations, processes, activities, etc. it creates a holistic view of the problem, with a structure that allows focusing on the details, limited only by the amount of information provided. TopEase® is commercially available object-oriented-programming based software developed by Pulinco Engineering AG based in Switzerland[38]. The software has been used in various areas like banking, government sectors, solution providers, consulting firms, etc. The main page of the software is given in the following figure (Figure A1).

[38] TopEase was developed as a guide to help the managers understand the current status of the company and to predict its future development. For that reason, TopEase aims to provide the holistic view on the system to manage the complexity and obtain transparency when managing transformation and improvement processes Figure A2 shows TopEase's ability to provide a full-scale view of the system, successfully encompassing the visualization of the system complexity

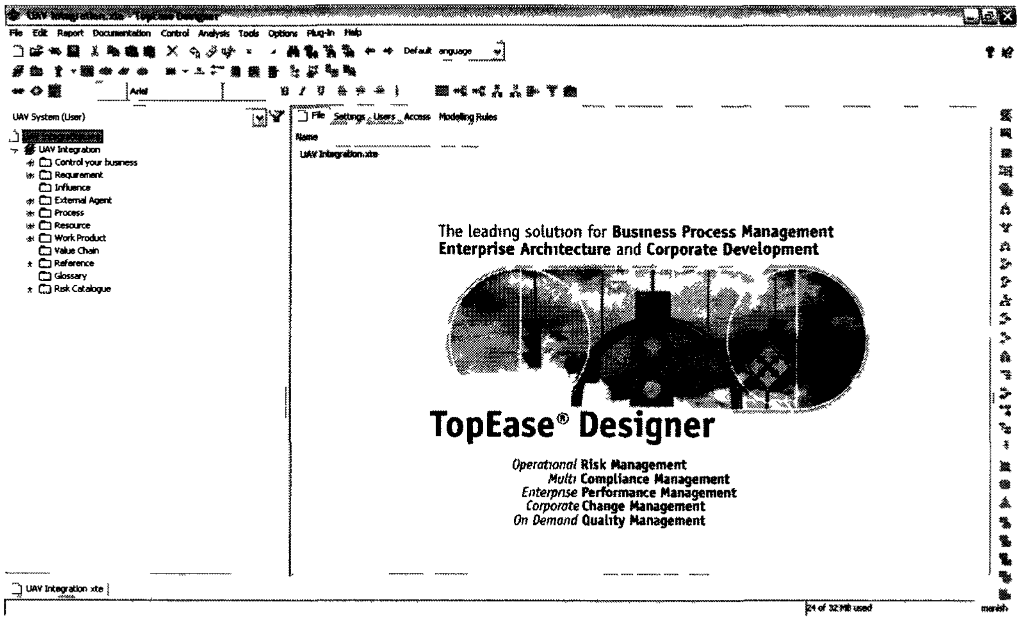

Figure A1 TopEase® Main Screen

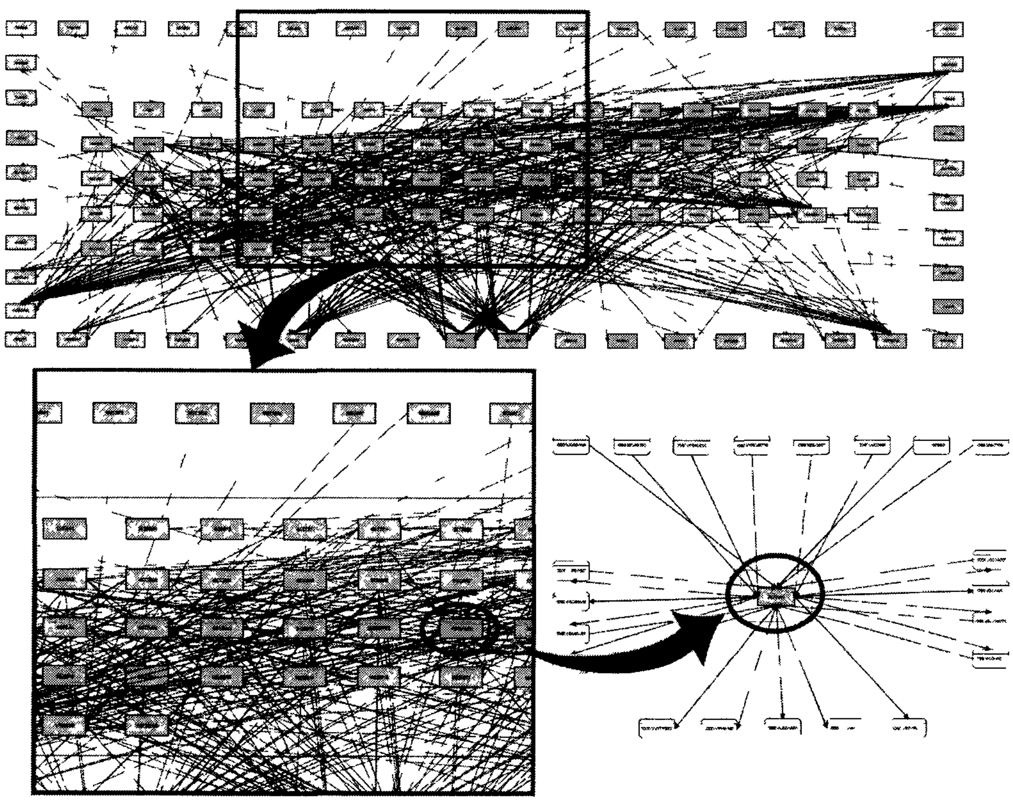

Figure A2 TopEase® providing insights on system complexity

TopEase® software helps manage complex systems in transition from a current paradigm (initial state, or *A*) to an improved future paradigm (end state, or *B*), called Gap Analysis. In the scope of the project, the current UAS operations status and a desirable future where unmanned systems can fly across the nation with similar safety, reliability, and ease to the commercial and military manned aircraft are taken as phases *A* and *B*, respectively.

The Gap Analysis allows tracking of key performance parameters (risk, compliance with regulations, measurements against set goals, etc.) to measure progress. Along the integration, TopEase® keeps track of the current, past and desirable parameter values and monitors risk and other measurements. Since the end state, *B,* is not (cannot be) precisely defined by any authority, the object oriented paradigm behind the software allows flexibility for shaping the desired end-state and related transition states noted as T_1, T_2, etc. (Figure A3)

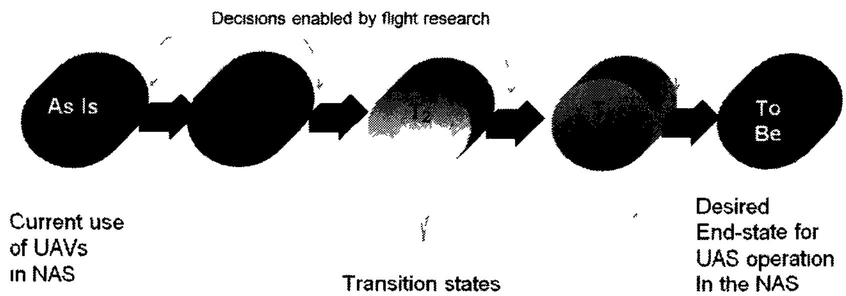

Figure A3 TopEase® handling various transformation phases

A.3 Methodology and Modeling of the Problem

A.3.1 Business Process Approach

TopEase® is largely developed for enterprise modeling, called a *business approach*, where it enables users to model their company/organization including the resource infrastructure, requirements, processes, activities, control flows, information models, etc. while the ultimate goal is to control compliance, improve performance and manage risks (Pulfer & Schmid, 2006). Based on the project definition, the UAS-NAS integration is modeled using limited literature and data coverage, mainly aimed to demonstrate the feasibility of the business process approach application to the matter at hand[39].

The attributes of OOP paradigm differ from any methods and tools in such a way that it allows obtaining descriptions and views (organization, process, workflow, etc.) of an enterprise

[39] The crucial point on using TopEase® is due to its object oriented programming paradigm. The concept of the software is to introduce predefined artifacts to describe the enterprise in a specific time and situation. Each artifact has a behavior and is defined by several attributes which are identified depending on their usability. For example, the "collision avoidance" clause under the *Safety* process is modeled as activities and processes, enabling them to communicate with any other object in the model. On a similar manner, risk is defined as an object, via identifying various risk templates and applying it to any relevant area.

since all the views represent one single view and are not related to each other (Pulfer & Schmid, 2006). TopEase® software enables full visualization of complex systems on one single "Big Picture". To illustrate that concept, a given UAS-NAS integration model can include the information from any physical room within the company infrastructure along with its connected IT network to the performance measurement history against a set of Federal Aviation Administration (FAA) regulations that the company is aiming to comply. This is possible due to the definition of OOP where every artifact is modeled as objects with their own specifications. The originality of this work lies within the application of the project contents to the object-oriented paradigm based business approach.

The processes, risk associated with the processes, organization schemes, compliances with FAA and other regulations, relationships between various processes and stakeholders, organizational departments, regulations, and measurement/risk templates that are modeled within the project are all based upon the literature coverage.

A.3.2 Modeling Assumptions

Due to the limited time and nature of the project, the unmanned aerial system to NAS integration model required some assumptions which will be presented in this section (The author of this dissertation was a prime investigator). *Organizational* structure is adopted from Bauer & Dann, (2005) where Access 5 is considered as the "actual" group dedicated to UAS-NAS integration where it is solely a research project/collaboration and one of the initiatives, involved with NASA and other stakeholders. Since TopEase® models the enterprise and assigns various processes and tasks to departments and personnel, it was necessary to inherit the organizational diagram from the reference to build the backbone of the model. The organization consists of five integrated product teams (IPTs); policy, technology, simulation, implementation, and flight test, forming the system engineering and integration team (SEIT). SEIT and Project control, facilitation and collaboration teams from the Access 5 project which is steered by NASA, DoD, FAA, and UAS National Industry Team and Vehicle Systems Program.

Processes and *activities* are adopted directly from DeGarmo (2004) where safety, security, air traffic, regulation and socio-economic are five main processes, all containing three to nine processes, along with activities. Figure A4 demonstrates the main processes and processes.

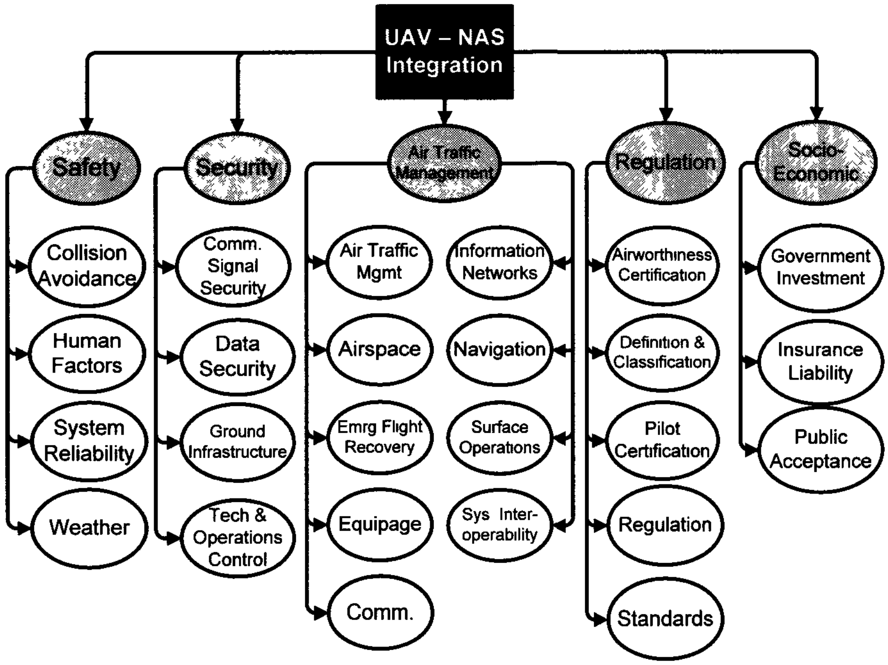

Figure A4 UAV-NAS integration main processes and processes

Risk data is taken from reference (DeGarmo, 2004). However, the information consists of only at the process level. As an example to risk data, the collision avoidance process risk is provided in Table A1. Each process risk is measured upon five criteria: safety criticality, technical complexity, legal complexity, socio-political risk, and economic cost. The five-point Likert scale (low, low-to-medium, medium, medium-to-high, and high) is transformed to TopEase® risk template and applied to all the processes.

Table A1. Process Risk Evaluation Categories (Collision Avoidance)

Issue	Safety Criticality	Technical Complexity	Legal Complexity	Socio-Political Risk	Economic Cost
2.1.1. Collision Avoidance	High	High	Low	Low	Low to High

Considering the project layers, risk information is only available at the process level. Since every process contains various activities, the risk at that level is not provided by the references. Also, risk on a higher level (i.e. safety) is not available. TopEase® does not extrapolate nor calculate the risk on the higher project levels. Risk understanding of TopEase® is mainly for demonstration and tracking purposes, like any other information, risk data needs to be imported to TopEase® using other risk calculation or vulnerability determination engines. At the writing of this paper, TopEase® did not have an interface enabling risk calculation feature.

The *performance criteria*, such as FAA requirements, regulations, or compliance with the socio-economic factors are extracted from reference (DeGarmo, 2004). The process-to-process, activity (process)-to-IPT teams, activity (process) - to - regulations and all other object-to-object interrelationships (named *work products* under TopEase®) are investigated and created within the model, depending on the object's nature.

A.4 The Outcomes

The Big Picture: TopEase® enables users to see the highest-level picture of the meta-system, where every item is linked to lower-level information, only limited with the level of data entered to the model. By creating the diagram below (Figure A5), developers can examine the system and also have the liberty to focus in on any of the components, activities, processes or relationships to gather details regarding every aspect of the transition process.

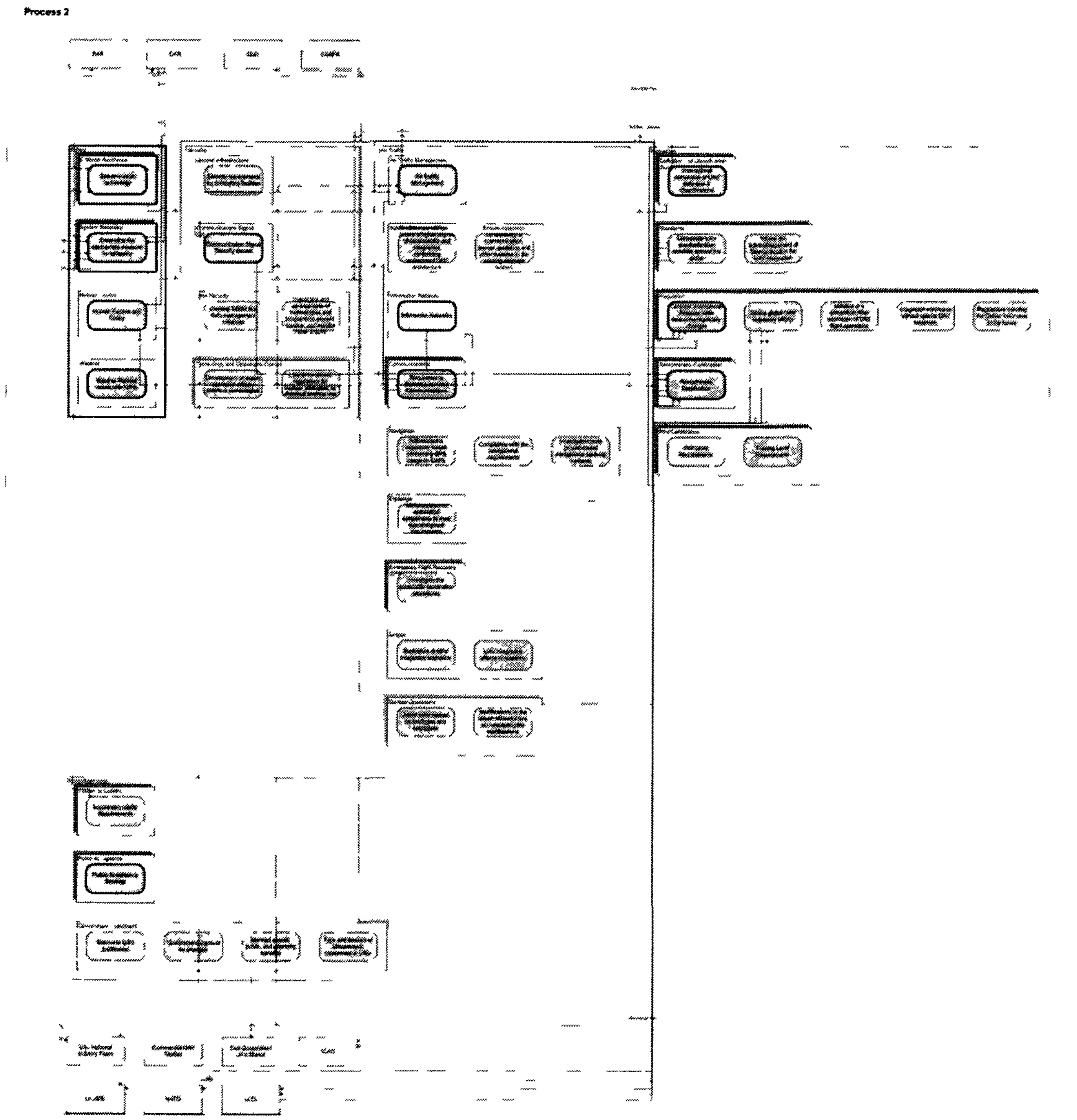

Figure A5 Overview of the High-Level System Interactions

On a lower-level diagram, it is possible to see the interactions, inputs and outputs, work products, overall risk associated with each process (color-coded) and links on the processes to reach activity level information.

A.4.1 Visualization

One of the most significant contributions of OOP based software usage is the modeling ease; however, TopEase® enables users to visualize the whole enterprise (or organization providing the service) from the highest possible project level to the section of a specific regulation including all the relationships within the enterprise. Figure A6 demonstrates the first process under the Air Traffic Management (ATM) main process, which is also called ATM. The level of detail is decreased for the purposes of this section; however, the structure given below can be seen at the highest (or lowest) level desired. The ATM process consists of 5 sub-processes, all containing activities that can be accessed when clicked on the sub-process. The external agents or stakeholders imposing any regulations or requirements are DoD, DARPA, UAV National Industry Team and FAA. The stakeholder relationships are given as work products and are shown with connecting arrows. The diagram is completely interfaced to link at any part of the picture, enabling simple navigation.

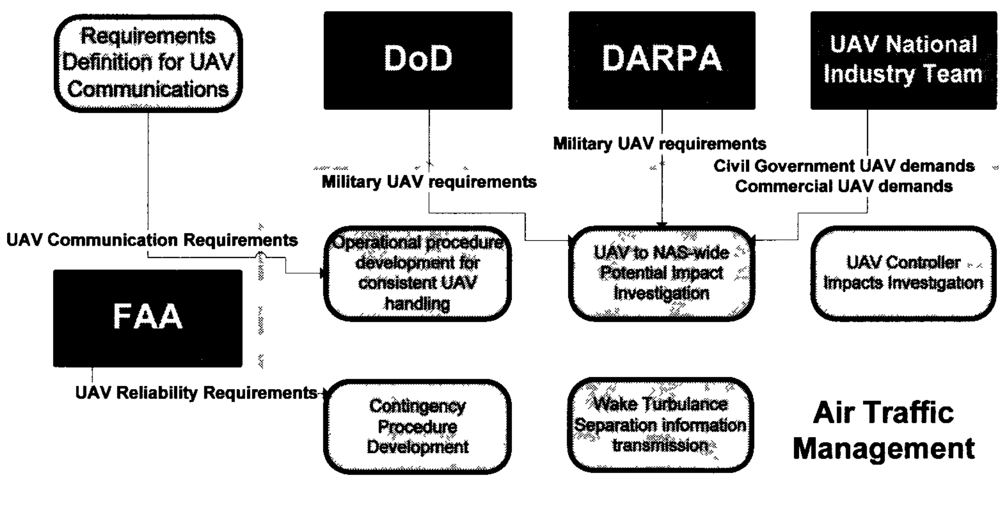

Figure A6 Air Traffic Management process diagram and its interrelations

A.4.2 Measurements

Risk measurement can be documented in various ways. Risk maps, risk scorecards and automatically generated and updated risk documents help to keep track of ongoing risks throughout the big scope of the UAS-NAS integration. In a similar manner, other measurements such as process progress, compliance with regulations and requirements can also be visualized via measurement scorecards and measurement documents (Pulfer & Schmid, 2006).

As the conventional methods and tools provide, the risk maps can be obtained through the TopEase® risk templates, constituting of the product of impact and likelihood. Figure A7 demonstrates the risks associated with ATM processes. Besides the likelihood and impact, risk templates also include risk appetite (introducing the risk perception) and responsible, accountable, concerned, informed (RACI) parties. As all other diagrams, risk maps are hyperlinked to associated objects in the project (Pulfer & Schmid, 2006).

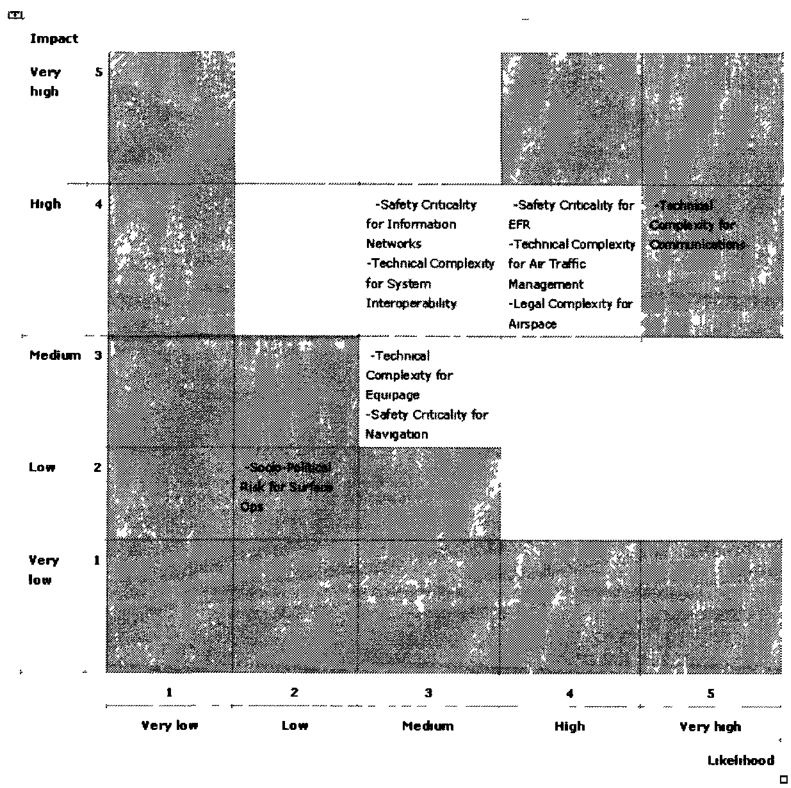

Figure A7 Risk Maps for ATM Processes

Another method of demonstrating risk is through the risk scorecards. Figure A8 shows the risk level for each process under the ATM main process, including the last values. The measurement scorecards are flexible since they are attached to the templates that can be modified in the case where the "to be" description of the dynamic UAS-NAS transformation evolves through time.

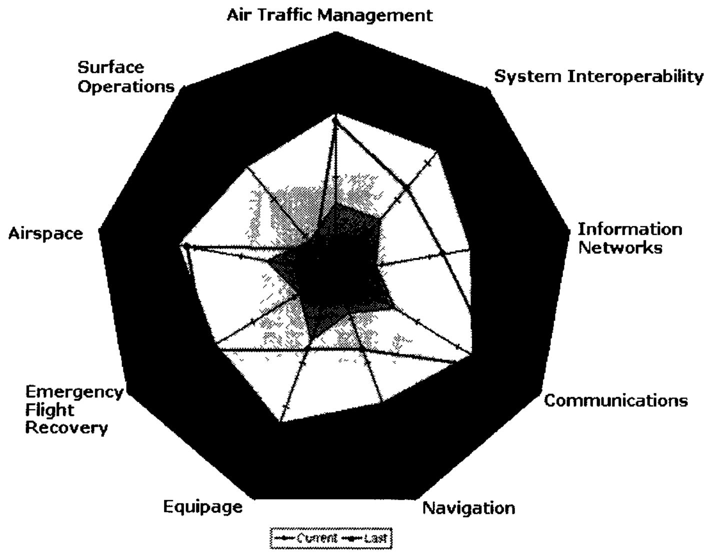

Figure A8 ATM processes risk scorecard

Compliance with the standards and meeting the changing requirements of various stakeholders are visualized with spider-web scorecards that enable past, current and target performance parameters. The business model concept provides strategies and goals for each process (or activity) that can be traced in terms of progress. Figure A9 and Figure A10 provide the overall process progress and risk scorecards for each element given in Figure A3. Various scorecards can be generated for every layer of the UAS-NAS integration plan, however, due to limited information in the scope of the project, only fictitious values are used for limited layers (Pulfer & Schmid, 2006).

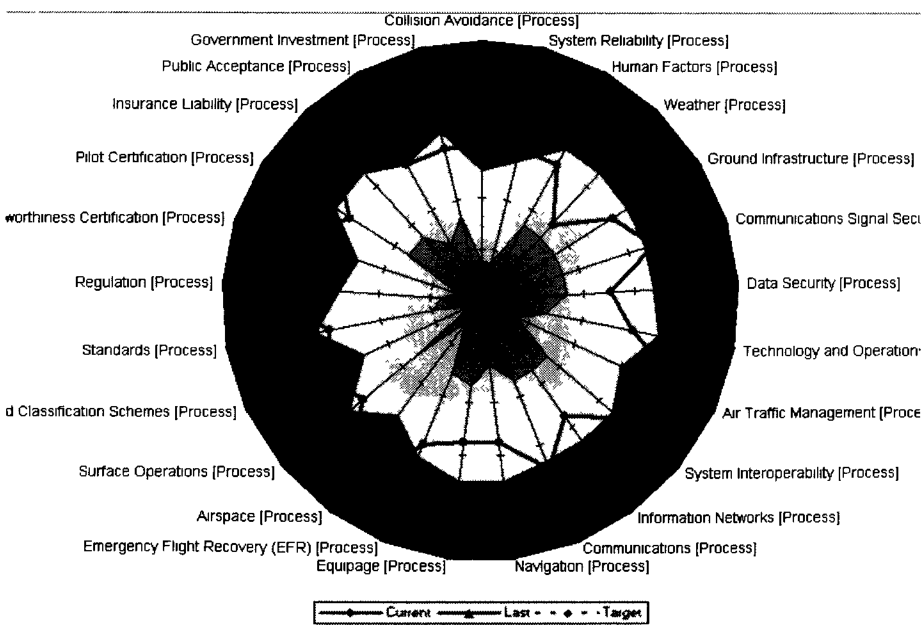

Figure A9 Comprehensive Measurement Scorecard

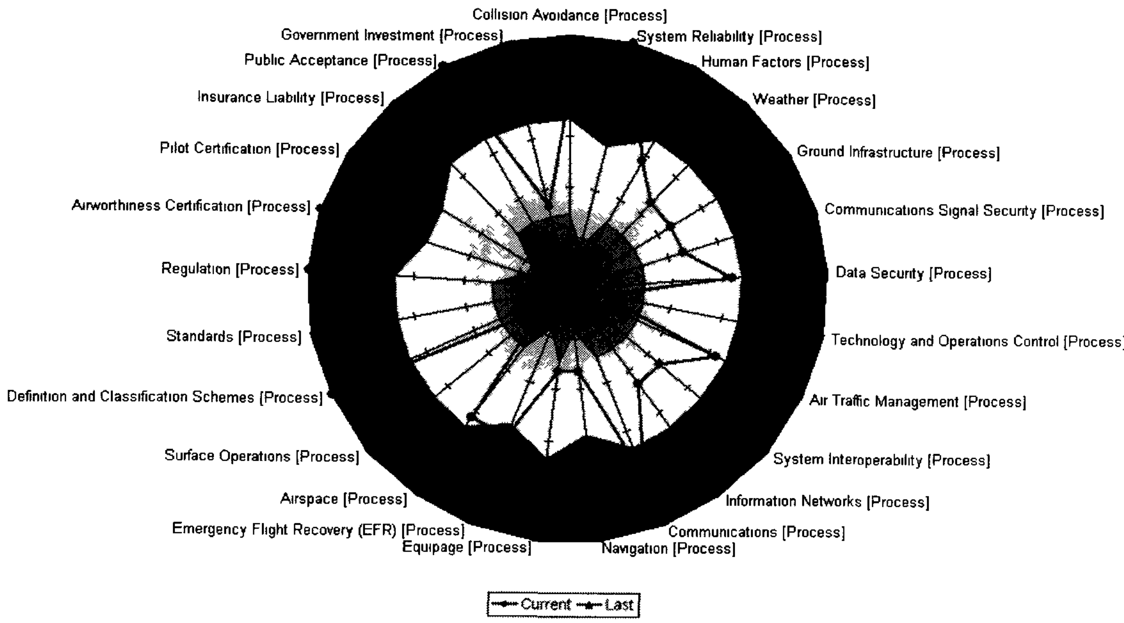

Figure A10 Comprehensive Risk Scorecard

Besides the risk and measurement visualization tools, TopEase® contains extensive reporting capability outputting to Word, Excel, or HTML formats. The responsibility, requirements, processes, and relationships matrices can also be developed. Once the enterprise infrastructure information is input into the model, it is possible to simulate and investigate the cascading effects of a service disruption (i.e. absent enterprise branch/person or non-operational enterprise IT servers). For the UAS-NAS integration model, it is possible to replicate a case where the policy IPT fails to comply with one or multiple FAA regulations and visualize the various effects of the issue on other processes.

A.5 Conclusions

The advantages unmanned aerial systems provide will eventually require a fully integrated manned-unmanned National Airspace in the future. Like in the early ages of aviation, unmanned systems will mature and bring the same or even superior safety features that manned systems offer today. However, replacing pilots and crew on dangerous, dirty, and dull missions will necessitate an intensive planning, execution, and monitoring capability that can ensure a reliable, sustainable and efficient transition. Most of the technical issues associated with UAS-NAS integration are already on the NextGen agenda, and issues associated with poor UAS reliability and lack of UAS classification schemes and definitions will be solved during the NextGen implementation plan.

With limited resources, the UAS-NAS integration project was applied to an object oriented paradigm approach, and results were provided. As the approach taken is a type of "feasibility study" using TopEase®, the sole validation lies within the opinions of air traffic control (ATC) subject matter experts within the university staff. The approach is still under investigation and discussions will determine the possibility of an in-depth application in the future. The technological advances, cost containment, regulatory controls, public acceptance and numerous other factors will determine the direction and strength of the UAS market. Since the prospects for UAS growth look promising, a dynamic, "big-picture" instrument capable of capturing the complexity of the integration is crucial for success.

Future work involving the interfaces of various risk and vulnerability calculation tools will even bring more management and execution support for future efforts in UAS-NAS integration.

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APPENDIX B – RAPID RISK ASSESSMENT MODEL

Risk is defined as the product of the probability of an accident and its respective consequences. The methodology calculates probabilities and consequences separately (See International Atomic Energy Agency, 1996).

B.1 Consequences

The consequences of a certain accident are constructed with respect to the characteristics of the substance and its correcting factors regarding the area, population density, accident geometry, etc.

$$C_{a,s} = A \times \delta \times f_A \times f_d \times f_m$$

$C_{a,s}$ Consequences per accident, and per substance (fatalities/accident)

A The calculated area based on the various inputs based on each class and amount of substance

δ Population density within the impact area

f_A, f_d Correcting factors for the impact area geometry

f_m Correcting factor for the cases if people within the distance have shelter, opportunity to flee, or a way to find out about the event before it happens (e.g. warning from odor, tanks that explode one by one)

Each component of the formula is entered from the existing tables where data is collected from extensive calculations, modeling, and expert opinions. The formula outputs a casualty number for each type of accident which will be matched with its respective probability of occurrence.

B.2 Probabilities

The probability of each substance installation (e.g. flammable liquid stored in a processing plant) is calculated via the following formula. The average probability number (used as a starting point) for each installation is determined by $N^*_{i,s}$ and varies by each type of substance and installation. The rest of the components in the equation are used to adjust this initial estimation in the presence of various correcting factors.

$$N_{i,s} = N^*_{i,s} + n_l + n_f + n_o + n_p$$

$N_{i,s}$ Probability number for an accident to happen for a substance within an installation

$N^*_{i,s}$ Average probability number for the installation and the substance

n_l Correction parameter for the frequency of loading/unloading operations

n_f Correction parameter for the safety systems associated with flammable substances

n_o Correction parameter for the organizational and management safety

n_p Correction parameter for wind direction towards the populated area

Based on the correction factors, the average $N_{t,s}$ value is recalculated and converted back into probability values based on the logarithmic relationship given above. In the same stream of thought, a similar approach is used to estimate the risks of transportation of hazardous substances, $(N_{t,s})$. The formula and description are given below.

$$N_{t,s} = N^*_{t,s} + n_c + n_{t\delta} + n_p$$

$N^*_{t,s}$	Average probability number for the transport of the substance
n_c	Correction parameter for the safety conditions of the transport system
$n_{t\delta}$	Correction parameter for the traffic density
n_p	Correction parameter for wind direction towards the populated area

B.3 Estimation of the Societal Risks

The previous two sections provided calculations of human casualties (fatalities) associated with an accident, along with the probabilities of such accidents occurring. The risk to the public from these activities is estimated by combining these two values.

Consequences are categorized with respect to fatalities, and the probability classes are categorized by one order of magnitude of the number of accidents per year. The results obtained from the consequence and probability calculations are represented on the risk matrix, providing an overall picture of the risk. The interpretation of the risk matrix provides the acceptability criteria for the societal risk. The thresholds for acceptable risks can be based on accident frequency (or probabilities) (Figure B1), consequences (Figure B2), or a combination of both (or ALARA principle) (Figure B3).

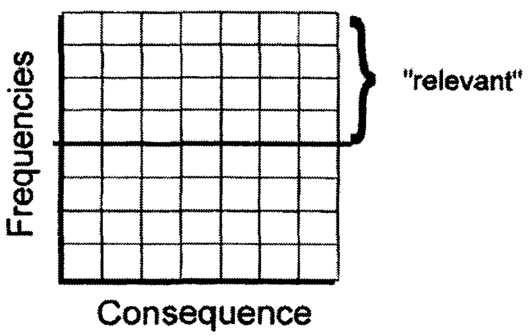

Figure B1 Acceptability determined by frequency

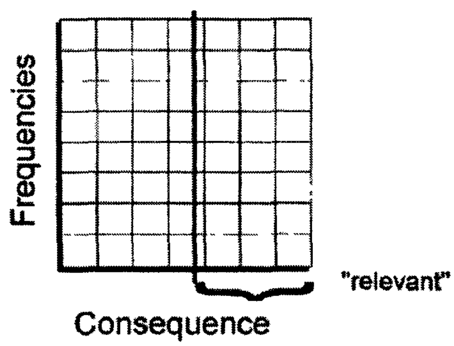

Figure B2 Acceptability determined by consequences

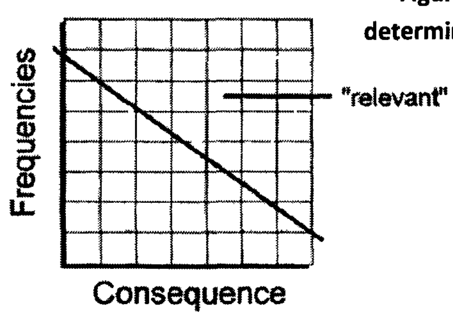

Figure B3 Acceptability determined by both frequency and consequences

APPENDIX C – PARTICIPATION FEEDBACK & VALIDATION

Validation Category	Definitions/ Implications	Ranking				
		1	2	3	4	5
Face Validity						
The game structure or outcomes "seem" to reproduce the reference system	Overall representation of NAS is accurate					
The theory and the assumptions on which the game was built can be shown isomorphic to the reference system	Evaluation and ranking of the validity of the assumptions with respect to NAS					
Actor interactions, information flow, and negotiations are congruent to the reference system	Stakeholder relationships within NAS are comparable to the real world					
Structural Validity						
Individual constructs constituting the methodology	Serious Gaming, Rapid Risk Assessment Model, COTS Software (Logical Decisions)					
Internal consistency of the way the constructs are put together in the method	Contents of High Level Architecture (Figure 3.1)					
Appropriateness of the case study to be used to verify the performance of the method	NAS as a multi-stakeholder and complex sociotechnical system transition platform					
Performance Validity						
The results of the game are comparable to the results in reality	NextGen 2025 Risk Values, Expected NAS future characteristics and stakeholder relationship representations					
The achieved usefulness is linked to applying the methodology	Considering the holistic approach rather than conventional methods					
Usefulness of the method is beyond the case study	Any complex and large-sociotechnical system involving multiple stakeholders					

1- Totally Disagree,
2- Somewhat Disagree
3- Neither Agree or Disagree
4- Somewhat Agree
5- Totally Agree

APPENDIX D – INSTUTIONAL REVIEW BOARD (IRB) APPROVAL DOCUMENTS[40]

INFORMED CONSENT DOCUMENT
OLD DOMINION UNIVERSITY

PROJECT TITLE: Aviation Safety Data Generation and Analysis Using Serious Gaming Methods

INTRODUCTION
The purposes of this form are to give you information that may affect your decision whether to say YES or NO to participation in this research, and to record the consent of those who say YES The research Aviation Safety Data Generation and Analysis Using Serious Gaming Methods' will be conducted in 4111 Monarch Way, Suite 406 in Norfolk, VA

RESEARCHERS
Researchers of this study are Dr Adrian V Gheorghe RPI (Professor Old Dominion University Batten College of Engineering Engineering Management and Systems Engineering Dept), Dr Sharon M Jones (Technical Monitor NASA Langley, Aeronautics Systems Analysis Branch Systems Analysis and Concepts Directorate) and Ersin Ancel, Graduate Research Assistant (Old Dominion University, Batten College of Engineering, Engineering Management and Systems Engineering Dept)

DESCRIPTION OF RESEARCH STUDY
The research study aims to generate data for future aviation systems Conventional expert elicitation methods are found to be successful in generating data for complex technical systems (e g data generation for a conceptual launch vehicle) However, data regarding complex sociotechnical systems with multiple components (e g National Airspace System comprised of technical, political social and organizational aspects) are rather difficult to obtain with the conventional expert elicitation methods (Brainstorming, Delphi Methods, Nominal Group Technique, etc) For that purpose serious gaming methods are proposed to be used in tandem with other conventional techniques to generate data for future systems This research study aims to test the proposed platform and generate initial data for further improvements

If you decide to participate, then you will join a study involving a role-playing environment You will be asked to represent a certain role in the National Airspace System. Your task will be to interact with other players of the game in order to review, discuss and decide on future aviation systems Researchers will contact you within one week of the exercise to provide you with the preliminary results and ask for your input/comments on the research methodology or the results If you say YES, then your participation will last up to 4 hours at Old Dominion University National Centers for System of Systems Engineering (NCSOSE), 4111 Monarch Way Suite 406, Norfolk VA Approximately 20 to 25 participants from various backgrounds will be participating in this study

EXCLUSIONARY CRITERIA
You received the invitation to participate in this study given your current or past experience with aviation in the National Airspace System (e g researcher, pilot, airport operations, etc) or to be representative of the general public You should be over the age of 18 to participate in this study

RISKS AND BENEFITS
RISKS The sole perceivable risk in this study is the loss of confidentiality If you decide to participate in this study, you will be asked to discuss your ideas and engage in conversations with other participants These discussions and outcomes will be noted However in order to minimize the risks, the researchers will remove all linking identifiers from the extracted data Yours and your company s information will not be stored on any database or file cabinet And as with any research there is some possibility that you may be subject to risks that have not yet been identified

Benefits There are no direct benefits to you in participating in this study

COSTS AND PAYMENTS
Your participation in this study is absolutely voluntary. The researchers are unable to give you any payment for participating in this study However snacks and refreshments will be provided throughout the study

NEW INFORMATION
If the researchers find new information during this study that would reasonably change your decision about participating then they will give it to you

CONFIDENTIALITY
The researchers will take reasonable steps to keep private information, such as individual opinions, discussions and personal information related to you or your employer confidential The researchers will remove identifiers from the information store information in a locked filing cabinet and a secure electronic database prior to its processing. The results of this study may be used in reports presentations, and publications but the researcher will not identify you or

[40] The contents of this appendix includes the IRB documents that were generated following the review process, including the Informed consent document and audio/video documentation

your employer. Of course, your records may be subpoenaed by court order or inspected by government bodies with oversight authority.

WITHDRAWAL PRIVILEGE

It is OK for you to say NO. Even if you say YES now, you are free to say NO later, and walk away or withdraw from the study -- at any time. Your decision will not affect your relationship with Old Dominion University/NASA Langley, or otherwise cause a loss of benefits to which you might otherwise be entitled.

COMPENSATION FOR ILLNESS AND INJURY

If you say YES, then your consent in this document does not waive any of your legal rights. However, in the event of harm arising from this study, neither Old Dominion University nor the researchers are able to give you any money, insurance coverage, free medical care, or any other compensation for such injury. In the event that you suffer injury as a result of participation in any research project, you may contact the responsible principal investigator or investigators at the following phone numbers or Dr. George Maihafer the current IRB chair at 757-683-4520 at Old Dominion University, who will be glad to review the matter with you.

VOLUNTARY CONSENT

By signing this form, you are saying several things. You are saying that you have read this form or have had it read to you, that you are satisfied that you understand this form, the research study, and its risks and benefits. The researchers should have answered any questions you may have had about the research. If you have any questions later on, then the researchers should be able to answer them:

Dr. Adrian Gheorghe (Principal Investigator) 757-277-6280 agheorgh@odu.edu
Dr. Sharon M. Jones (Technical Monitor) 757-864-7642 sharon.m.jones@nasa.gov
Ersin Ancel (Graduate Research Assistant) 757-272-2364 eance001@odu.edu

If at any time you feel pressured to participate, or if you have any questions about your rights or this form, then you should call Dr. George Maihafer, the current IRB chair, at 757-683-4520, or the Old Dominion University Office of Research, at 757-683-3460.

And importantly, by signing below, you are telling the researcher YES, that you agree to participate in this study. The researcher should give you a copy of this form for your records.

Subject's Printed Name & Signature	**Date**

INVESTIGATOR'S STATEMENT

I certify that I have explained to this subject the nature and purpose of this research, including benefits, risks, costs, and any experimental procedures. I have described the rights and protections afforded to human subjects and have done nothing to pressure, coerce, or falsely entice this subject into participating. I am aware of my obligations under state and federal laws, and promise compliance. I have answered the subject's questions and have encouraged him/her to ask additional questions at any time during the course of this study. I have witnessed the above signature(s) on this consent form.

Investigator's Printed Name & Signature	***Date***

TO Adriar Gheorghe PhD
Responsible Project Investigator

FROM George Maihafer PT PhD
Chairperson, IRB

RE Addendum Request to "Using Serious Gaming for Next Generation Infrastructure Data Elicitation (ODU IRB # 10 – 157)

DATE: February 3, 2011

After review of the amended revisions to ODU IRB # 10 – 57 "Using Serious Gaming for Next Generation Infrastructure Data Elicitation", I approve the change in an expedited review manner. The amendment to the methodology of the study is as follows

The addition of a consent for photo/video materials to the study

A Progress report or Close out Report will be required one year from the original approval date (November, 2011) of the study application to the Old Dominion University Institutional Review Board Please let me know if I can be of any further assistance

INFORMED CONSENT DOCUMENT
FOR USE OF PHOTO/VIDEO MATERIALS

STUDY TITLE: Aviation Safety Data Generation and Analysis Using Serious Gaming Methods

DESCRIPTION:
The researchers would also like to take photographs or videotapes of you performing the serious gaming activity in order to illustrate the research in teaching presentations and/or or publications

CONFIDENTIALITY:
The photo/video materials will be used to extract any additional information that reveals during the gaming session All material will be recorded and stored electronically in Old Dominion University's secure servers for a period of 12 months You would not be identified by name in any use of the photographs or videotapes Even if you agree to be in the study no photographs or videotapes will be taken of you unless you specifically agree to this

VOLUNTARY CONSENT
By signing below, you are granting to the researchers the right to use your likeness image appearance and performance - whether recorded on or transferred to videotape film slides photographs - for presenting or publishing this research No use of photos or video images will be made other than for professional presentations or publications The researchers are unable to provide any monetary compensation for use of these materials You can withdraw your voluntary consent at any time

If you have any questions later on then the researchers should be able to answer them

Dr Adrian Gheorghe (Principal Investigator) 757-277-6280 agheorgh@odu edu
Dr Sharon M Jones (Technical Monitor) 757-864-7642 sharon m jones@nasa gov
Ersin Ancel (Graduate Research Assistant) 757-272-2364 eance001@odu edu

If at any time you feel pressured to participate or if you have any questions about your rights or this form, then you should call Dr George Maihafer, the current IRB chair, at 757-683-4520, or the Old Dominion University Office of Research at 757 683 3460

Subject's Printed Name & Signature	Date

APPENDIX E – ENABLER DEFINITIONS, COST, TIMELINE AND BENEFITS

Runway Safety and Collision Avoidance Category

Accident Category (CICTT Occurrence Category)	Enabler	Addresses	Expert Estimated Fully Operational Benefits	Timeline	Costs by Timeline	Enabler Overall Benefit & Probability Number
[R1] Increased Capacity/Safety Related Runway Operations, (RI-VAP,GCOL, RAMP)	ASDE-X, Runway Incursion Reduction Program	Collision with A/C, ground handling caused by increased volume	%90 of all increased capacity induced runway accidents	Level 1: 2017 (JPDO, 2008a, App I-9), Level 2: 2025 (JPDO, 2008A App I-16)	FAA ASDE-X ($4.2M), ADS-B Levels	4.92% (0.279)
[R2] Runway Visibility (Low and near-zero visibility), (RI-VAP/A, GCOL, TAXI)	Runway Status Lights (RWSL), Synthetic Vision (2016), Moving Maps (2018), Terminal Area Hazard Sensor (NASA, 2009 IIFD.SS.3 External Hazard Detection)	Collision with A/C, animal, person, ground handling caused by low visibility	% 80 of All visibility related runway accidents	Level 1 (Low Visibility Surface Ops): 2017 (JPDO, 2008A App I-9) Level 2 (Near Zero Visibility Surface Ops): 2025 (JPDO, 2008A App I-16)	FAA Runway Status Lights [Level 2]($55M), FAA Runway Incursion Program [Level 1] ($5M), Moving Maps ($1.3M FAA FY2011 p.F&E-72)	11.60% (0.659)
Prerequisites	Runway Incursion and ASDE-X require ADS-B (In & Out)					

Aircraft Systems Reliability Category

Accident Category (CICTT Occurrence Category)	Enabler	Addresses	Expert Estimated Fully Operational Benefits	Timeline	Costs by Timeline	Respective Probability Number
[A/C 1] Powerplant related system/ component malfunction or failure [SCF-PP]	Propulsion HMS, Aircraft Catastrophic Failure Research	Powerplant related system, component malfunction or failure, Surface anomaly detection on critical PP components	0-50% of propulsion related accidents	Level 1: 2015, Level 2: 2025, (JPDO, 2008A E-3054,3055 App II-93)	IVHM: $26.4M/yr, A/C Catastrophic Failure Research (FAA FY2011 A11F,$1.1M/yr), Continued Airworthiness: $570,000/yr	1.89% (0.107)
[A/C 2] Airframe related system/ component failure or malfunction [SCF-NP]	Airframe HMS, Continued Airworthiness (Structures)	Airframe related system/ component failure or malfunction, Damage tolerance methods and detection technologies	80% of Airframe related accidents	Level 1: 2015, Level 2: 2025, (JPDO, 2008A E-3054,3055 App II-93)	IVHM: $26.4M/yr, Continued Airworthiness: $3,718,000/yr	0.17% (0.010)
[AC 3] Software and Systems related system/ component failure or malfunction [SCF-NP]	A/C Systems HMS, Software HMS, Digital System Safety	Software and A/C Systems related system/ component failure or malfunction, Develop V&V techniques, software development assurance	80% of all software/systems related accidents	Level 1: 2015, Level 2: 2025, (JPDO, 2008A E-3054,3055 App II-93)	IVHM: $26.4M/yr, Digital System Safety (FAA FY2011 A11D): $2.2M/yr Continued Airworthiness: $1.5M/yr	6.72% (0.382)

Icing

Accident Category (CICTT Occurrence Category)	Enabler	Addresses	Expert Estimated Fully Operational Benefits	Timeline	Costs by Timeline	Respective Probability Number
[I 1] A/C aerodynamics and control surfaces [ICE]	Iced Airframe Aerodynamics Modeling and Prediction Methods (NASA, 2009b, 2.1.3) Atmospheric Hazards – Icing, p.RE&D-30) Icing Remote Sensing & Characterization NASA, 2009a, .SS.4	Aircraft modeling and icing formation related to ice accumulation and its effects on aircraft aerodynamics and control surfaces	70% of A/C icing related accidents	Level 1: 2015 Level 2: 2025, (Airborne icing Related Accident Mitigation JPDO, 2008A EN-3127/28)	Atmospheric Hazards – Icing, US (DoT 2010a ,p.RE&D-30) to Glenn RC ($1,919,000)	0.15% (0.008)
[I 2] Engine Icing [FUEL on icing]	External Hazard – Icing (NASA, 2009a, .SS.3) Engine Icing Modeling (NASA, 2009b 2.2.3) Advanced Sensors and Materials (NASA 2009c, 1.1.1.2)	Engine modeling and icing formation related to ice accumulation and its effects on the powerplant	90% of EI accidents	Level 1: 2015 Level 2: 2025 (Airborne icing Related Accident Mitigation JPDO, 2008a EN-3127/28)	FAA FY2011 A11K, p.RE&D-87 Weather Program ($7.3M)	0.19% (0.011)

Airborne Collision and Loss of Separation

Accident Category (CICTT Occurrence Category)	Enabler	Addresses	Expert Estimated Fully Operational Benefits	Timeline	Costs by Timeline	Respective Probability Number
[C 1] Near Mid-Air Collision / TCAS Alerts	TCAS Enhancements	Risk of Mid-Air Collision, Near Collision, ACAS Alerts	50% of collision related incidents	Operational: 2016 (JPDO, 2008b, V1.0 p.9)	FAA TCAS Enhancements ($2.5M)	1.05% (0.060)
[C 2] Loss of Separation (Separation Assurance)	ADS-B, TIS-B, FIS-B, Wide Area Augmentation System for GPS	Loss of Separation	70% of collision related incidents	2 Levels, 2014 & 2020 (JPDO, 2008a Surveillance Services p.10-3 & E-1023, 1400)	FAA WAAS for GPS ($85M) FAA ADS-B ($176M) (FY2012-15 $969M)	2.50% (0.142)
Prerequisites		Loss of Separation Assurance require ADS-B (In & Out)				

Weather

Accident Category (CICTT Occurrence Category)	Enabler	Addresses	Expert Estimated Fully Operational Benefits	Timeline	Costs by Timeline	Respective Probability Number
[W 1] Thunderstorm / Lightning (WSTRW)	FIS-B, Data Link, (JPDO, 2008a: Weather Forecasts – Consolidated Winter Storm JPDO, 2008A Appendix II – p.82), Integrated Weather in the Cockpit (DoT, 2011a A12E, p. RE&D-134)	Consolidated Winter Storm NextGen initial(1), intermediate (2) and fully operational (3) predictive models and current weather observation information to users via Network Enabled Infrastructure	50% of Thunderstorm related accidents	Level 1(Initial Capability):2013 Level 2 (Adaptive Control/Enhanced Forecast): 2018 Level 3 (Full NextGen): 2022 (JPDO, 2008a Sect. 4.2)	FAA NextGen Network Enabled Weather ($28.25M) (FY2012-15: $145M) FAA Weather in the Cockpit Program ($8,369,000)	0.63% (0.036)
[W 2] CFIT due to Low Visibility	Synthetic Vision Enhancements and Human aspects	Enhanced accuracy of net-enabled deterministic and advanced probabilistic weather forecast information for NAS decision making. Level 2022 integrates weather information from ground, airborne, and satellite sensors broadcast real-time	70% of CFIT due to low visibility	2016 (DoT, 2011a A12D , p.RE&D-121)	$3,162,000 (FAA FY2011 Budget, p.RE&D-128)	0.59% (0.033)
Prerequisites		Network Enabled Infrastructure (DATA Communications) ($153M) (FY2012-15: $1.89B)				

Turbulence

Accident Category (CICTT Occurrence Category)	Enabler	Addresses	Expert Estimated Fully Operational Benefits	Timeline	Costs by Timeline	Respective Probability Number
[T 1] In Flight Turbulence Encounter [TURB]	FLI (Forward Looking Interferometric) [IIFD.SS.1]	Detects clear air turbulence (CAT)	80% reduction in In Flight Turbulence	2011 Feasibility Operational: 2017	$9,517,000 (NextGen Wake Turbulence Avoidance) *IIFD: $16M (See cost assumptions)	18.82% (1.069)
[T 2] Ground Wake Vortices [TURB – ground based]	FLI Aircraft Characteristics Database, Aircraft Wake Database, Wake Transport Model Wake Decay Model Wind Based Wake Procedures	Reduce the impact of wake vortices on operations, allowing more closely spaced arrival and departure operations to maintain airport/runway capacity safely.	90% reduction in Ground Wake related accidents	Level 1: 2015 Level 2: 2020 (JPDO, 2008A App I OI-0400 – 401 – 402 – 403)	$3,000,000 (FAA Wake Turbulence (Re-categorization)) NASA, 2009a – FLI $43M/yr $4.4M Wake Turbulence Mitigation (Arrivals and Departures DoT, 2010a, F&E-74)	0.76% (0.043)

APPENDIX F – CAST/ICAO COMMON TAXONOMY TEAM ACCIDENT CATEGORIES AND DATA

Table F1 outlines the data regarding selected accident categories associated with FAR Part 121 during 1997 and 2006, providing the historical safety risk among large U.S. commercial air carriers. The percentages for each primary accident category are based on the Commercial Aviation Safety Team (CAST) and International Civil Aviation Organization (ICAO) taxonomies. However, regarding the two categories regarding the airborne collision category (C1 and C2), due to the extreme nature of such accidents occurring, incident data were assumed to replace accident data for consistency purposes.

Table-F1 Accident Categories and Respective Data

CICTT Occurrence Category	Respective Methodology Category	Number of Accidents	Percentage
Total Accidents		459	459
Runway Incursion	R2	5	**1.1%**
Ground Collision – Taxi	R1	21	**4.4%**
Ground Collision – Ramp	R2	69	**14.5%**
TCAS Alert	C 1	10 (incidents)	**2.1%**
Loss of Separation (includes NMAC)	C 2	17 (incidents)	**3.6%**
Mid Air Collision	-	0	0.0%
SCF – Powerplant	A/C 1	20	**4.2%**
SCF – Structure	A/C 2	1	**0.2%**
SCF – Systems	A/C 4	40	**8.4%**
Icing - Engine	I 2	1	**0.2%**
Icing - Surface	I 1	1	**0.2%**
Limited Visibility	W2	4	**0.8%**
Turbulence Encounter	T 1	112	**23.5%**
Thunderstorm/Windshear	W1	6	**1.3%**
Wake Turbulence	T 2	4	**0.8%**
Abrupt Maneuver	-	7	1.5%
Abnormal Runway Contact	-	38	8.0%
Aerodrome	-	6	1.3%
Bird Strikes	-	14	2.9%
Cabin Safety	-	5	1.1%
Evacuation	-	6	1.3%
Ground Handling	R2	53	**11.1%**
Low Altitude Operations	-	1	0.2%

Loss of Control – In Flight	-	2	0.4%
Loss of Control – On Ground	-	3	0.6%
Loss of Engine Power	A/C 1	2	**0.4%**
Runway Excursion		22	4.6%
Security Related	-	4	0.8%
Unknown		2	0.4%

Table F2 provides the NTSB accident data for the past 10 years, (2000 – 2009)[41]. The average accident values (0.208 Accidents/100,000FH) and average fatalities (0.291 Fatalities/100,000FH) are used as the baseline values for probability and consequences baselines within the probability number method. The 2001 values are adjusted in order to exclude the 9/11 terrorist attacks. The terrorist attacks resulted in 4 fatal accidents with 246 casualties, and these values are subtracted from the original accident data values. The original (adjusted) values are as follows: 46 (42), 6 (2), 525 (279).

Table-F2 NTSB Accident Data for FAR Part 121

Year	All Accidents	Fatal Accidents	Aboard Fatalities	Flight Hours	Accidents/ 100KFH	Fatal Accidents /100FH	Fatalities/ 100KFH
2000	56	3	92	18,299,257	0.306	0.016	0.503
2001*	42	2	279	17,814,191	0.236	0.011	1.566
2002	41	0	0	17,290,198	0.237	0.000	0.000
2003	54	2	21	17,467,700	0.309	0.011	0.120
2004	30	2	14	18,882,503	0.159	0.011	0.074
2005	40	3	20	19,390,029	0.206	0.015	0.103
2006	33	2	49	19,263,209	0.171	0.010	0.254
2007	28	1	1	19,637,322	0.143	0.005	0.005
2008	28	2	1	19,097,962	0.147	0.010	0.005
2009	30	2	51	18,001,000	0.167	0.011	0.283
				Average	**0.208**	**0.010**	**0.291**

Table 3 above provides the accident categories that are covered within the probability number method, and it totals 76.5% of the accidents given in the table. The total actual accident reduction in each category (assumed the respective technologies are fully implemented) reaches 61.45% of the total accidents covered within the 6 major categories.

[41] http://www.ntsb.gov/aviation/Table5.htm

Table F3 Accident Percentages, Categories and Respective N numbers

Category	Accidents	Enabler Contribution	Actual Reduction of Accident	Respective N
R1	4.4%	0.9	3.97%	0.225603022
R2	26.7%	0.9	24.01%	1.364361136
C1	2.1%	0.5	1.05%	0.059683339
C2	3.6%	0.7	2.50%	0.142046347
A/C1	4.2%	0.5	1.89%	0.107430011
A/C2	0.2%	0.8	0.17%	0.009549334
A/C4	8.4%	0.8	6.72%	0.381973371
I1	0.2%	0.7	0.15%	0.008355667
I2	0.2%	0.9	0.19%	0.010743001
W1	1.3%	0.5	0.63%	0.035810004
W2	0.8%	0.7	0.59%	0.03342267
T1	23.5%	0.8	18.82%	1.06952544
T2	0.8%	0.9	0.76%	0.042972004

VITA

Ersin Ancel

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Ersin Ancel received his Master of Science degree in Aerospace Engineering from Old Dominion University in Norfolk, VA. in 2007 and his Bachelor's Degree in Astronautics Engineering from Istanbul Technical University in 2005. He worked as a graduate research assistant for both the Aerospace Engineering and Engineering Management Departments at Old Dominion University during his M.S. and Ph.D. studies where he contributed to two ODU Sounding Rocket payload developments projects and two NASA funded studies involving Unmanned Aircraft Systems integration to the National Airspace System and Next Generation Air Transportation System (NextGen) safety. His research interests are focused on Aviation, Aerospace and National Airspace System Safety.