NextGen Future Safety Assessment Game

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Abstract. The successful implementation of the next generation infrastructure systems requires solid understanding of their technical, social, political and economic aspects along with their interactions. The lack of historical data that relate to the long-term planning of complex systems introduces unique challenges for decision makers and involved stakeholders which in turn result in unsustainable systems. Also, the need to understand the infrastructure at the societal level and capture the interaction between multiple stakeholders becomes important. This paper proposes a methodology in order to develop a holistic approach aiming to provide an alternative subject-matter expert (SME) elicitation and data collection method for future sociotechnical systems. The methodology is adapted to Next Generation Air Transportation System (NextGen) decision making environment in order to demonstrate the benefits of this holistic approach.

1.0 INTRODUCTION

The world is heavily dependent on various critical infrastructures in areas like transportation, power, communication, water, energy, etc. Today's critical infrastructures are large-scale socio-technical systems, comprised of multiple components, involving various stakeholders, technologies, policies and social factors [1]. In the recent years, numerous 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" [1]. In other words, the transition includes "a structural change in both technical and social subsystems" [2].

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 became a major challenge for the society [3]. 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 system design due to (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, robust but resistant to change [1, 4]. The lack of empirical data causes decision makers to heavily rely on expert opinions for next generation infrastructure planning.

1.1.1 Lack of Data and Expert Elicitation

The future status of man-made systems like energy, transportation, warfare, agriculture, and other infrastructure cannot be predicted over a prolonged time frame. Large-scale sociotechnical systems are made up of multiple components that involve numerous stakeholders, technologies, policies, and social factors [1]. Decision makers and policy makers often require expert opinion to comprehend the complexity and uncertainties within such systems. Expert elicitation methods typically have been used to obtain the necessary data for reliability and risk studies for these types of technological, environmental, and socioeconomic issues [5, 6]. Furthermore, NextGen will inherently be different from the current system. However, the ability to predict the future remains limited owing to the long-term implementation phase and the large number of uncertainties [5]. "There are no data about the future on which to rely. We are challenged to imagine many different and possible 'futures' as humankind seeks to exert its mastery and control" [7]. The crucial task is to think innovatively and recognize the creative and imaginative capacities of each stakeholder. The overall goal of the methodology is to reduce complexity and uncertainty while inventing the future and analyzing the respective risk for each alternative scenario [7].

1.1.2 Sociotechnical Complexity

The system-wide upgrade of complex systems is a challenging undertaking [8]. The increased complexity adds to the diversity of decision maker's system interpretations that can directly alter the overall system operation and the decision-making processes. Brewer [7] states that real-world problems do not exist independently of their socio-cultural, political, economic, and physiological content, and for that reason, an approach with multiple perspectives and multiple disciplines is necessary to efficiently clarify the matter at hand (which is quite challenging in practice). The presence of multiple actors with frequently divergent and conflicting interests can turn large-scale infrastructure transitions into wicked problems [9]. Traditional policy and market practices have proven ineffective in dealing with problems with a high degree of uncertainty regarding future scenarios and actor interactions [1]. For this reason, creating a methodology that attempts to predict decision pathways for future systems while accounting for the technical, organizational, and contextual complexity of the system is necessary [4, 7].

2.0 TEST CASE

The goal of this research is to develop a methodology that will serve as an aid for decision makers who are responsible for designing and evaluating scenarios for future technological implementations within next generation infrastructure systems. As previously mentioned, the implementation of large system transitions require understanding of the multi-layer complexity and overcoming the lack of experimental data for designing the future phases of the system. In order to demonstrate the proposed methodology, the planning, development, and implementation of the Next Generation Air Transportation System (NextGen) is used as a test case. The following sections will provide insights on NextGen.

2.1 NextGen Overview

The U.S. National Airspace System (NAS) is made up of a number of multifaceted elements, including over 800 billion passengers and input from more than 15,000 air traffic controllers to assist 590,000 pilots onboard 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 [10].

The delays that currently impact passenger travel 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 [10].

To respond to this forecasted increase in demand, the Joint Planning and Development Office (JPDO) was formed during the Bush Administration in 2003. This organization is a partnership between public and private stakeholders, including the Federal Aviation Administration (FAA), the Department of Defense (DoD), the Department of Homeland Security (DHS), NASA, and others [11]. The JPDO is charged with developing concepts, architectures, roadmaps, and implementation plans for transforming the current national Air Transportation System (ATS) into NextGen.

“During the next two decades, demand will increase, creating a need for a system that (1) can provide two to three times the current air vehicle operations; (2) is agile enough to accommodate a changing fleet that includes very light jets (VLJs), unmanned aircraft systems (UASs), and space vehicles; (3) addresses security and national defense requirements; and (4) can ensure that aviation remains an economically viable industry” [8].

2.2 NextGen Challenges

The complex nature of the NAS, combined with numerous operational and management challenges, threatens the NextGen efforts. 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 [12]. Uncertainties and a lack of data related to shaping a future aviation system also inhibit the ability to employ formal risk analysis methods. As a result, SME opinion has become the primary source of input for the NextGen scenarios, technologies, and safety.

2.3 Need for a Methodology

In the past, traditional engineering design approaches focused primarily on the technical requirements. Similarly, traditional infrastructure designs were treated like traditional engineering problems, causing them to be brittle and resistant to modernization. However, the next generation infrastructures must be treated differently because of their complex nature [13]. The need to understand the infrastructure at the societal level and capture the interaction between the technical, political, and economic factors becomes more important [4]. Traditional engineering design methods are used in concert with serious gaming approaches to create a holistic decision-making methodology. The goal of the proposed methodology is to enable decision makers and researchers to gather information in regard to NextGen safety values. Toward that purpose, various tools and techniques are employed collectively here to create a methodology that can be used as an alternative to conventional expert elicitation techniques (i.e. Delphi Method, Nominal Group Technique, brainstorming, etc.) for complex systems with multiple stakeholders.

3.0 PROPOSED METHODOLOGY

As discussed above, the methodology for estimating risks within a future system will combine various approaches. Because the air transportation system includes extensive interactions between multiple stakeholders, which can be difficult to track, and because of the lack of historical data, SMEs from diverse backgrounds are the main source of data for this study [6]. Aviation safety within NextGen is measured by using the probability number method. Conventional numerical and qualitative expert elicitation techniques provide the gaming data that are necessary to construct the scenarios, alternatives, attributes, and so on. Commercial-off-the-shelf software packages (i.e., Logical Decisions for Windows® and Precision Tree® by Palisade Corp.) are also used to rank future technologies in order to support SME opinions before and during the gaming cycle. Fig. 1 provides an overview of the methodology. The various tools and techniques are described in more detail in subsequent sections.

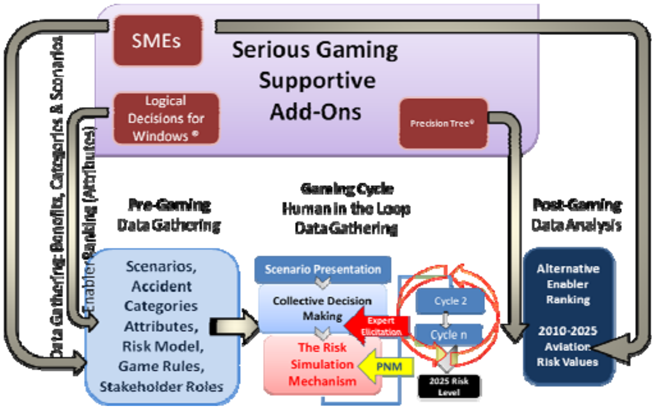


Figure 1. Serious gaming methodology: high-level architecture

3.1 Serious Gaming and Infrastructure Design

The use of gaming and simulation techniques as a formal approach to strategy making has gained wide acceptance, as evidenced by the frequency of occurrence within mainstream strategy literature [14]. Gaming methods (or soft systems thinking) have become an alternative to formal complexity modeling techniques like systems dynamics and operations research. These techniques have been successfully applied to well-structured problems; however, when employed on ambiguous and often ill-structured and complex systems, their contribution has been limited because adequate theory and empirical data were absent [14].

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 [13, 14]. Unlike hard-system methods, the gaming and simulation approach is quite flexible and easily adaptable to other quantitative methods, scenarios, and computer models [16]. 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 [15].

According to Duke [17], a typical complex real-world situation has the following characteristics: it contains numerous variables in interaction; no realistic basis exists for quantification of these variables or their interactions; and no proven conceptual model or precedent exists on which action decisions can be based. Complex systems are also typified by a sociopolitical context of decision-making, where the actions of the various “players” may be idiosyncratic or irrational; furthermore, the decisions are irreversible and the results are not generally fully understood until well into the future [17]. NextGen fits this model, as a complex real-world air-transportation system that will undergo a full-scale transformation and that contains numerous stakeholders with often conflicting agendas, including those of the general public [18]. The gaming context may help capture the organizational and behavioral dynamics of the decision-making process and ultimately yield a more realistic problem solution.

The following section provides insight on the probability number method (PNM), which is used as the backbone for the NextGen risk calculation method.

3.2 Probability Number Method

The PNM was created through a joint effort between the International Atomic Energy Agency (IAEA) and several United Nations organizations. The method was developed as an affordable solution to quickly determine the risks that are associated with handling, storing, processing, and transporting hazardous materials. The methodology is supported by an extensive database that includes the various factors that impact the risks, including types of substances (i.e., flammable, toxic, or explosive gases or liquids), safety precautions, population densities, environmental factors, and so on [19]. The average accident scenario contains only rough estimates because the purpose of the methodology is to serve as a decision-making aid that enables risk ranking and prioritization for further analysis. Dr. Adrian Gheorghe was a part of the development team for the PNM and brings his expertise to decoding, modifying, and adapting the probability number method to the NextGen system.

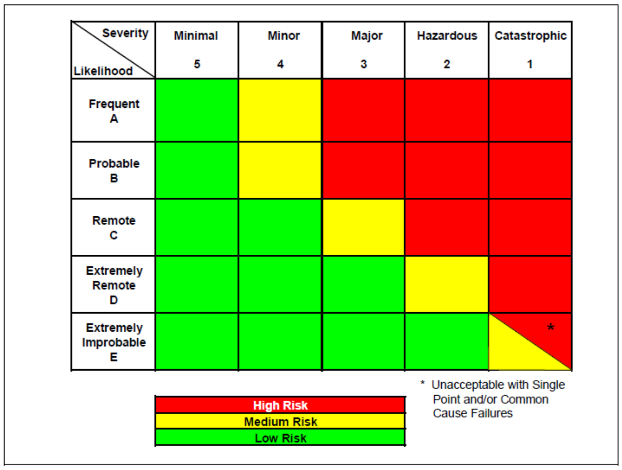
3.2.1 Probability Number

Within the PNM, the probability of the occurrence of a certain accident is calculated via a dimensionless probability number N, which is then transformed into an actual probability. The probability number can be adjusted or updated based on various correcting factors. The risk is defined as the product of the consequences and the probabilities of unwanted outcomes (i.e., hazardous events).

3.2.2 Adapted Consequences and Probabilities

The PNM defines risk as the product of the probability of an accident and its respective consequences, calculated separately. Within the NextGen framework, the consequences are defined as fatal aviation accidents (i.e., accidents per 100,000 flight hours). The probability of an accident that involves a passenger fatality is calculated in the following manner. An average probability number that represents the base assumption is determined; then, this number is adjusted by using correcting factors. These factors represent technological improvements and other enablers that are planned within the NextGen framework, namely, runway safety, aircraft reliability, icing, turbulence mitigation, weather, and airborne collision avoidance. The adjusted accident probability N is then converted into a frequency of occurrence.

The probability of occurrence and the consequence factors are inputted into the FAA's Risk Matrix (Fig. 2). The initial conditions for the risk are determined by the averaged accident data (2000-2009) which are obtained from NTSB website[1]. The average severity of aviation accidents is 0.291 fatalities/100,000 flight-hours or severity classification "Minor, 4"; meanwhile the probability of such an accident is 0.208/100,000 flight-hours, indicating a "Remote, C" likelihood category. Departing from the values above, the current aviation risk is determined as "Low Risk, green".



Severity Likelihood	Minimal 5	Minor 4	Major 3	Hazardous 2	Catastrophic 1
Frequent A	🟩	🟨	🟥	🟥	🟥
Probable B	🟩	🟨	🟥	🟥	🟥
Remote C	🟩	🟩	🟨	🟥	🟥
Extremely Remote D	🟩	🟩	🟩	🟨	🟥
Extremely Improbable E	🟩	🟩	🟩	🟩	🟨🟥 *

🟥 High Risk
🟨 Medium Risk
🟩 Low Risk

* Unacceptable with Single Point and/or Common Cause Failures

Figure 2. FAA risk matrix.

The PNM was chosen to be the backbone for the risk estimation engine in this application as a result of its intuitive structure and ease of expandability. The main components of the PNM, namely, the consequences, probabilities, and risk outcomes, are incorporated into the NextGen Safety Assessment Methodology and fused with the policy gaming effort.

3.3 Software Add-Ons

The selected gaming platform enables the integration of additional methods and techniques, which allows the methodology to remain flexible and expandable. This in turn ensures a more thorough

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[1] http://www.ntsb.gov/aviation/Stats.htm

representation of the air transportation infrastructure. Two commercial-off-the-shelf software solutions have been embedded into the methodology to enhance the ranking and prioritization of enablers and other damage indicators. The Logical Decisions for Windows® software helps the prioritization and ranking of NextGen safety-related technological enablers with respect to their benefits, costs, implementation timelines, and other parameters. The Precision Tree® software is used to collect and further analyze the data that are obtained from the gaming exercise.

4.0 GAMING SEQUENCE

The NextGen safety assessment methodology was developed on a serious gaming platform that was adopted from the play sequence of policy gaming developed by Geurts, Duke, and Vermeulen [14]. An adapted version of the play sequence, which accommodates the NextGen safety framework, is given in Fig. 3. The sequence is initiated by the presentation of the game to the stakeholders; this includes providing the game rules, a general overview of NextGen goals, and the available resources. Stakeholder groups that contain participants from various backgrounds are formed, and their respective goals are established (e.g., the FAA is concerned with safety goals, commercial airlines with economic goals, and so on). The groups are asked to evaluate and select from the list of technological advancements that are related to the improvement of safety. However, the implementation of each of these advancements consumes some of the predetermined limited resources. Stakeholders with conflicting agendas must come to a consensus on certain decisions. Following these discussions, the decisions for each time step are entered into the risk simulation mechanism (based on the PNM) and the updated NAS risk values are calculated iteratively for the next three time steps, until year 2025. The gaming exercise is concluded with the debriefing and discussions in order to create the foundation for the data gathering and analysis.

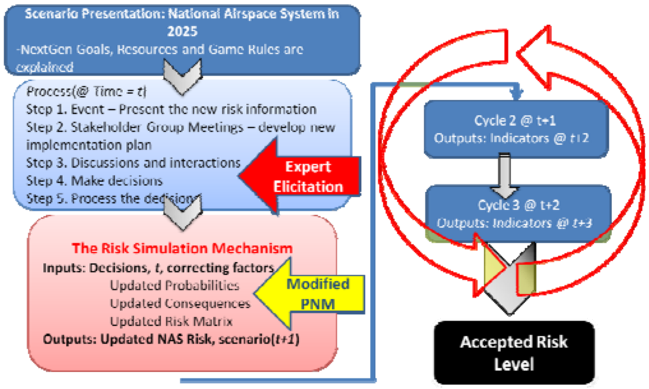

Figure 3. NextGen safety assessment gaming sequence.

4.1 Stakeholders and Game Rules

One of the most productive outcomes of the policy gaming exercise is that the participants are able to interact based on the problem at hand. The "safe" environment allows participants to create and analyze the system complexity while communicating various aspects of the issue among the stakeholders [7]. In order to model such a dynamic environment, a simplified list of involved stakeholders and engagement rules was developed. Stakeholder interactions can be based on rigid rules, free-form rules or combination of the two. Rigid, rule-based gaming is well suited for structured environments, such as military gaming where specific rule sets that can be formalized by mathematical or computational methods are used. However, for social arenas that include both public and intense stakeholder interactions without firm rules, free-form gaming, which relies on game rules, is more suitable. Free-form games enable the participants to challenge, modify, and improve the positions, objects, and rules during the game play. However, the process must be carefully monitored by a control team of experts who act as referees or game directors [16].

Within the scope of this project, the primary goal was to provide insight into the future of NAS safety and data gathering in regard to future systems. Thus, a combination of rigid and free-form gaming rules was employed. The goal of the game was to simulate the aviation safety values within a given time frame, while taking into consideration technological constraints (i.e., cost versus benefit, feasibility, mixed equipage, and so on) and behavioral concerns (i.e., information overload to pilots, controllers, early technology adopters, and so on).

4.2 Outcomes

Throughout the gaming effort, the discussions and negotiations that occurred between participants with opposing agendas were important and can be used to develop different problem-solving approaches. The gaming exercise serves both as an individual and a collective learning platform for the stakeholders, leading to an overall elevated level of knowledge across the system. The individual learning took place during the decision-making process during which each stakeholder group represents their respective point of view. The acquired awareness that was gained in regard to the overall system complexity will ultimately improve the value of the expert elicitation. Furthermore, the presence of realistic interactions among the players yielded data that can be used in the testing and evaluation of NextGen-related technologies in the future [20]. In addition to the individual learning, the collective learning (or the organizational learning) provided valuable insight that relates to the problems that were discussed (i.e., NextGen aviation safety values).

One of the most tangible outcomes of the gaming exercise was the 2025 NAS safety values with respect to the FAA’s Risk Matrix (Fig. 2) acceptability measures. The intermediate risk values that were obtained during the technology implementation phase (i.e., the next 15 years) were elicited under the same assumptions. The cumulative effect of various safety-related technological implementations can be examined, which will enable decision makers to identify technologies or areas that require further analysis and understanding.

5.0 CONCLUSIONS

The planning and implementation of next generation infrastructure transitions are challenging due to their complex nature and the lack of historical data. This paper proposes the use of simulation and gaming methods as a platform for evaluating and generating necessary data for designing future infrastructure systems. The Next Generation Air Transportation System (NextGen) decision making environment is used as a test-bed to demonstrate the developed methodology.

Subject-matter-expert opinions were heavily relied upon to develop the gaming components, to decide on the participants, and finally, to evaluate the validity of the framework. Conventional risk calculation methods and commercial-off-the-shelf software capabilities were integrated to provide system-level overview and risk analysis as a decision-making tool. One of the most prominent contributions of the gaming exercise was its ability to aggregate the perspectives of multiple stakeholders with varying agendas, while calculating the effectiveness of future NextGen safety enablers. The gaming environment promotes individual and collective learning across the system, allowing subject-matter experts to express their opinions for a more thorough and accurate modeling of the future infrastructure.

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