

A RISK-BASED DECISION SUPPORT TOOL FOR EVALUATING AVIATION TECHNOLOGY INTEGRATION IN THE NATIONAL AIRSPACE SYSTEM

James T. Luxhøj, Ph.D.
Muhammad Jalil, M.S. Candidate
Department of Industrial and Systems Engineering
Rutgers University, Piscataway, NJ

Sharon Monica Jones, M.E.
NASA Langley Research Center
Hampton, VA

ABSTRACT

Commercial aviation, one of the most critical national and international modes of transport, is a highly complex, dynamic domain. From a systems perspective, there are numerous interrelated infrastructural components and stakeholders that challenge analytical modeling. Perhaps more than any other domain, aviation is typically on the forefront of developing and applying new technologies. The *Aviation System Risk Model (ASRM)* is a risk-based decision support system prototype designed to evaluate the impacts of new safety technologies/interventions. The process utilizes an analytic generalization framework to develop an integrated approach to model the complex interactions of causal factors. Bayesian probability theory is being used for model quantification and Bayesian decision theory provides an analytical method to evaluate the possible impacts of new interventions. The entire process is supported by expert judgments. Subsequently, the analytical methodology is encoded as a Probabilistic Decision Support System (PDSS). The resultant PDSS is a risk-informed decision support tool that aids the evaluation of the possible relative impact of single as well as multiple technologies on aviation safety system risk. Presenting a maintenance-related accident scenario provides an illustration of the possible use of the PDSS.

INTRODUCTION

Commercial aviation is a complex mosaic of many varied, yet interrelated human, technical, environmental, and organizational factors that affect system performance.¹ In addition to creating economic investment models, the relative speed with which new technology is

being developed and deployed creates a need to also pursue advanced risk analytics that move beyond the essential identification of risk factors to enhanced system modeling and evaluation of complex accident and incident causality.^{2,3,4,5,6,7,8,9,10,11}

The *Aviation System Risk Model (ASRM)* developed by Luxhøj, et al.^{12,13,14,15} is a risk-based decision support system prototype that is being extended to evaluate the projected system impact of new aviation technologies/interventions. The *ASRM* is both a *process* and a *product*. The *process* uses the combined approach of *analytic generalization*¹⁶ from case studies and knowledge engineering sessions with subject matter experts (SMEs). Using a similar approach, van Vuuren¹⁷ reports on a study of mishaps in the steel industry and medical domain. With the *ASRM*, the underlying analytical method is based on the probabilistic approach of Bayesian Belief Networks (BBNs)^{18,19,20,21,22} to model the complex interactions of causal factors and the possible effect(s) of intervening actions, such as technology insertions. Special considerations with subjective probability elicitations from experts that challenge *ASRM* process development are discussed in Ayyub²³ and Renooij²⁴.

The research *product* is a decision support tool programmed in Visual Basic that facilitates risk-informed decision making for the government and commercial sectors. The *ASRM* is being enhanced to graphically portray a risk metric, termed the *relative risk "intensity"*, to illustrate perturbations from a baseline period.

Aviation Safety Program (AvSP) Products

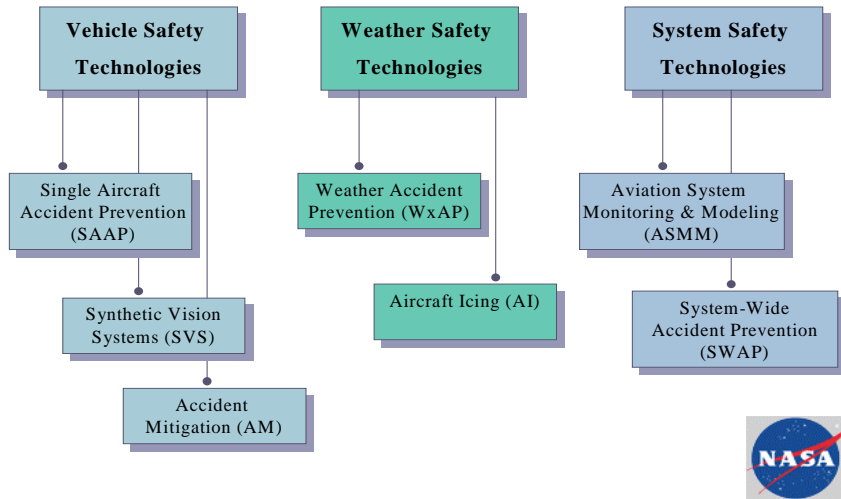


Figure 1. Categorical Overview of NASA Technologies

The NASA Aviation Safety Program (AvSP) Office located at the NASA Langley Research Center is managing the development of 48 new technologies/interventions intended to improve aviation system safety in the National Airspace System (NAS).²⁵ Figure 1 displays the principal categories of the new technologies. Concurrent with the development of the new technologies/interventions is a requirement to develop an analytical method that facilitates assessing the projected impact of the various technologies and/or interventions upon system safety risk reduction.²⁶

METHODOLOGY

The underlying research methodology is comprised of three principal analytical approaches:

- the Human Factors Analysis and Classification System (HFACS)
- Bayesian Belief Networks (BBNs)
- case studies

Luxhoj²⁷ presents a more thorough discussion of the methodology; however, the essential elements are included here.

The Human Factors Analysis and Classification System (HFACS)

The HFACS is an analytical approach for classifying human error that is based on the Reason⁷ framework of system safety theory.

The Reason socio-technical approach models both active and latent pathways from organizational, task/environmental, and individual factors to an accident or incident. While there are numerous contributing factors to aircraft accidents, such as operational, weather, etc., nevertheless, 60%-80% of all accidents are attributed to human error. The HFACS provides a fundamental analytical method for approaching causal modeling factors. Wiegmann and Shappell²⁸ provide a detailed description of the HFACS taxonomy. In this particular study, the Maintenance Extension of HFACS or HFACS-ME²⁹ is used since the case study focuses on a maintenance-related accident.

Bayesian Belief Networks (BBNs)

One of the most important factors that should be considered when building models of accident causation is uncertainty. Probability theory derives solutions to the problem of reasoning under uncertainty in the face of limited information. In recent years, Bayesian Belief Networks (BBNs) have been used as the main methodology for numerous tasks that involve reasoning under uncertainty. BBNs provide efficient symbolic representations of probability models, together with the efficient inference algorithms for probabilistic reasoning.^{20,21,22}

Case Studies

The ASRM research uses a case study approach. With a case study approach, statistical generalization is not used. In statistical generalization the samples are chosen randomly

and then generalization is observed as a replication of a specific behavior. However, cases are not random samples and each case study represents a unique portrayal. Rather, with case study research, *analytic generalization*¹⁶ and a replication logic is used to generalize to a theory, in this case, system safety theory. Therefore, multiple case studies can be considered as multiple experiments. If two or more case studies show the same behavior, replication can be claimed; however if contrasting results are produced, there should be predictable reasons for this divergent behavior. While specific case studies are used to initiate a dialogue-based process, the resulting causal influence diagram represents a realistic portrayal of a more generalized model.

Summary of Modeling Approach

The applied approach used in this research is illustrated in Figure 2. It is a systematic, analytical, dialogue-based approach that initiates with discussions of specific accident cases with subject matter experts. The causal factors are identified using an expanded HFACS taxonomy, and then the interactions among the causal

factors are modeled using influence diagrams. After the influence diagrams are constructed and reviewed by subject matter experts, conditional probability tables are elicited from the “beliefs” or value judgments of the subject matter experts, in conjunction with empirical data where available, to create the BBN. Typically, during this step, 2-3 subject matter experts are used. Generally, a consensus-based approach is used during the probability elicitation process, since such an approach encourages the experts to view the final product as a group effort. However, any wide disagreement between the experts is noted for future sensitivity analysis. Then action nodes are added to the BBN to represent the technology/intervention insertions. Additional technologist experts may be included in these discussions. Risk comprises two components – likelihood and severity. The BBN is used to compute likelihood and the severity is based on a numerical score using NTSB data for that accident type as determined by the Volpe National Transportation Systems Center. Finally, the projected risk is displayed relative to a baseline period on the relative risk “intensity” graph.

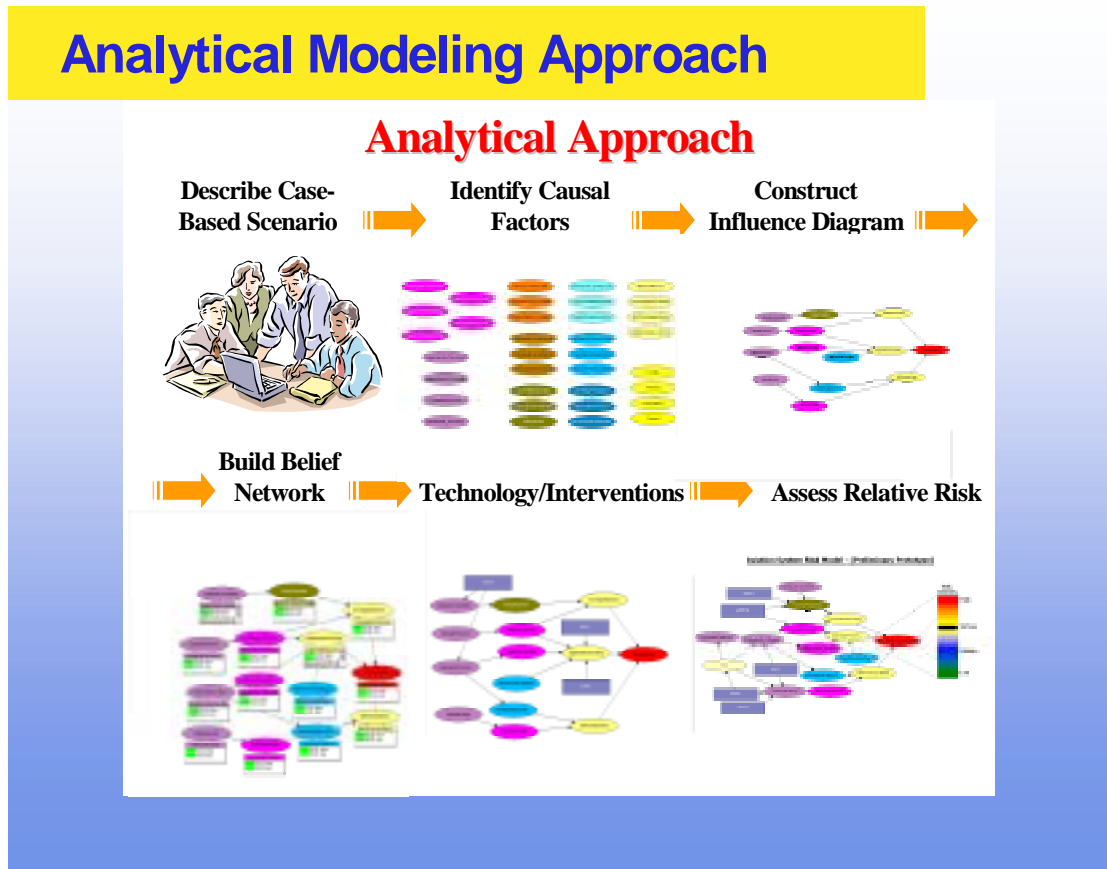


Figure 2. Summary of Modeling Approach

CASE STUDY

This section describes the application of the research methodology to a maintenance-related accident – the United Airlines Flight 811 case.

Accident Summary

This case study is based on the in-flight accident of United Airlines Flight 811 that occurred on February 24, 1989³⁰. After taking off from Honolulu, Hawaii, and while the aircraft was climbing between 22,000 and 23,000 feet, the Boeing 747-122 experienced explosive decompression. Examination of the aircraft revealed that the forward lower lobe cargo door was separated during the flight damaging the fuselage and adjacent cabin structure to the door. The aircraft was able to land successfully at Honolulu airport. However, nine of the passengers were ejected from the plane and lost at sea.

After a comprehensive search, the cargo door was recovered from the ocean floor. The examination of the door revealed that after the door was closed and locked, the latch cams were driven back from the closed position to a near open position. The lock sectors were deformed; therefore, they failed to prevent the back-driving of the latch cams.

The NTSB investigation of the accident focused on the design and certification of the B-747 cargo doors, operations, and maintenance to assure the continuing airworthiness of the doors, cabin safety, and emergency response. The NTSB determined that the probable cause of the accident was sudden in-flight opening of the forward lower lobe cargo door and subsequent explosive decompression. The door opening resulted due to a faulty switch or wiring in the door control system. Contributing to the accident was a deficiency in the design of the forward lower lobe cargo door that permitted the deformation, allowing the door to unlatch. Another contributing factor as determined by NTSB was that Boeing and the FAA did not take timely corrective actions on the previous cargo door opening incident of Pan-Am B-747.

The NTSB investigation report for United Airlines Flight 811 accident is used to determine possible human, task / environmental and organizational factors for this accident. The HFACS–ME analysis of the United 811 case by

aviation experts at the Navy Safety Center is also used as a primary taxonomic base.²⁹ In this specific case, several organizational entities contributed to the accident. However, HFACS–ME fails to address the differentiation of the several organizational entities and their subsequent contribution to the accident. Therefore, with the assistance of the NTSB error code dictionary and aviation domain experts, the list of contributing factors is extended to address the issue. Table 1 depicts the identified factors in the United Flight 811 case, according to Reason’s framework.

The logical reasoning for the existence of each factor is provided in Jalil³¹. Using the factors identified in Table 1, the ASRM for the United 811 case is developed as depicted in Figure 3. The nodal links are derived using the accident case study report. For example, the link from FAA-Certification to Inadequate Design is derived from the NTSB statement that deficiency in design of the cargo door locking mechanisms should have been discovered during the design approval and certification process. All of the links in the United 811 ASRM as depicted in Figure 3 are verified with experts from the FAA and are reported in Jalil³¹.

It should be noted that the baseline period for the evaluation of AvSP technologies is 1990-96. Therefore, the conditional probabilities in the Conditional Probability Tables (CPTs) correspond to the baseline period of 1990-96. The experts noted that the HFACS–ME framework is consistent with the aviation domain language, and it facilitates accident causal factor modeling.

Candidate Technology Interventions

The description of candidate technologies interventions and their possible links are as follows:

SWAP 6: Maintenance Risk and Task Analysis Tools

Product Form: In some cases, electronic versions of the tools will be developed, otherwise written guidelines.

Product Description: The risk and task analysis tools are based on existing tools in the nuclear power industry. A variety of protocols and processes will be developed for maintenance

Table 1. Case Study Causal Factors

Case-Specific Contributing Factors			
	Organizational	Task / Environmental	Individual
HFACS-ME Factors	<ul style="list-style-type: none"> • Inadequate Documentation • Inadequate Design • Uncorrected Problem • Inadequate Supervision • Judgment / Decision Making 	<ul style="list-style-type: none"> • Training/Preparation • Unavailable / Inappropriate Equipment • Dated / Uncertified Equipment 	<ul style="list-style-type: none"> • Skill / Technique Based
Non- HFACS-ME Factors	<ul style="list-style-type: none"> • FAA-Certification • FAA-Oversight • FAA-Inadequate Resources • UAL-Inappropriate Processes • FAA/Boeing Insufficient timeliness of corrective guidance 		<ul style="list-style-type: none"> • Improper Inspection



Figure 3. Causal Factor Interactions

human factors: (a) risk analysis of procedures to determine appropriate levels of inspection and to streamline inspection and engineering processes; (b) task/risk analysis of procedures to incorporate human factors principles of situational awareness, team coordination, communication, and resource management.

Customers/End Users: Air carrier maintenance departments and NASA.

Targeted Problem: Focus on risk reduction.

SAAP 1: Condition-Based Maintenance Technologies

Product Form: Handbook of guidelines for explanation of condition-based maintenance.

Product Definition: Selection of an aircraft system component (e.g., landing gear), implementation of a prototype condition-based maintenance program, followed by creation of a handbook containing operator guidelines for implementation of a condition-based maintenance program.

Customer/End User: FAA and aviation operators.

Targeted Problem: Component Failures.

SWAP 1: Human Performance Models:

Product Form: Software.

Product Definition: Human performance models that will permit the prediction of human errors due to procedural non-compliance, high workload, poor situational awareness and inadequate crew coordination issues.

Customer/End User: used by aviation product manufacturers and designers during product development.

Targeted Problem: Focus on reducing device susceptibility to human errors.

SWAP 7: Maintenance Resource Management (MRM) Training Program for Maintenance

Product Form: Recommendations, guidelines and lessons learned.

Product Definition: Focus is development of recommendations and guidelines to assist operators in the implementation of MRM principles into their organization. In addition to recommendations and guidelines, assessment tools are developed for the purposes of evaluating MRM skills and training. New assessment techniques incorporating behavioral markers are also being developed and tested.

Customer/End User: Air carrier maintenance, training or safety departments, and contract maintenance operators.

Targeted Problem: Focus on reduction of maintenance errors.

SWAP 9: Human Factors Tools

Product Form: Recommendations, guidance, informative white papers, and research results.

Product Definition: Human factors knowledge-sharing including issues and priority checklists for Project HF needs, cross-Project integration issues, display intuitiveness checklist, Program relevant bibliography.

Customer/End User: AvSP Projects developing human-centered products

Targeted Problem: Focus on human friendly product design.

AM 4: Next-Generation Crashworthiness Design Guidelines

Product Form: Handbook of materials test results, design and injury criteria and structural design concepts.

Product Definition: Development of a handbook containing test results of materials tested and design guidelines for their use.

Customer/End User: Aircraft seat manufacturers, airframe manufacturers and general aviation and air carrier operators.

Targeted Problem: Reduce design/development time for new products; improve survivability in survivable accidents by minimizing loads and maintaining habitable volumes.

SWAP 8: Augment/Virtual Reality Displays

Product Form: Hardware/software and test results.

Product Definition: a) Image-based communication and advisement system which includes the equipment and human processes involved in an image-based communication system that enables collaborative problem solving, advisement, and documentation. b) Development of a virtual-reality device to train maintenance inspectors and test results. Initial prototype will be a CBT (computer-based training) tool to augment existing classroom and on-the-job inspector training. This product is based on existing virtual-reality hardware that will be upgraded and appropriate software developed.

Customer/End User: Air carrier maintenance department, contract maintenance facilities, FAA, and general aviation fleet operators.

Targeted Problem: Focus on reduction of maintenance and inspection errors.

DECISION SUPPORT TOOL

Figures 4-8 display screens from the *ASRM* decision support tool and illustrate how the integrated interactions of various causal factors may be portrayed. The prototype enables scenario sensitivity analyses for both single- and multiple technology insertions. It is possible that that one technology may impact a single and/or multiple causal factors and that multiple technologies may also impact a single and/or multiple causal factors. A color-coded bar chart displays changes in relative risk “intensity”. Eventually, the Model Library will contain consequence models for Loss of Control (LOC), Maintenance-related, Controlled Flight Into Terrain (CFIT), Runway Incursion (RI), among others.

MODELING RESULTS

As exhibited in Table 2, initial risk assessments of technology insertions by subject matter experts indicate a relative risk reduction of up to 24% for the consequence in some scenarios when compared to a baseline period. The initial findings suggest that the impact of the technologies upon relative risk reduction for the causal factors is even more significant than upon the resultant consequence. For some scenarios in this case, the initial findings indicate that the projected *relative* risk reduction due to certain combinations of technology insertions may be up to 50% for some targeted causal factors.

FURTHER REMARKS

The *ASRM* method and tool are still under development. Future enhancements include enhanced visualization of sensitivity analyses and improved executive summaries. The *ASRM* decision support tool offers a systematic, flexible, adaptable approach to the risk evaluation of emerging technologies, especially when quantitative data may not be readily available.

ACKNOWLEDGEMENTS

Dr. Luxhøj acknowledges the support of the Federal Aviation Administration (FAA) and NASA through FAA grant number 00-G-006 and NASA contract number NAS1-03057. He also acknowledges the contributions of his research team. Dr. Luxhøj and his research team are also grateful to the FAA’s Aviation Safety Inspectors

who served as subject matter experts for this research. This paper is based on the research performed at Rutgers University. The contents of this paper reflect the views of the authors who are solely responsible for the accuracy of the facts, analyses, conclusions, and recommendations represented herein, and do not necessarily reflect the official view or policy of either the Federal Aviation Administration or NASA.

REFERENCES

1. Shappell, S.A. and D.A. Wiegmann (2001), “Applying Reason: The Human Factors Analysis and Classification System (HFACS),” *Human Factors and Aerospace Safety*, 1 (1), 59-86.
2. Leplat, J. (1987), “Occupational Accident Research and Systems Approach,” in *New Technology and Human Error* (J. Rasmussen, K. Duncan, and J. Leplat, eds.) New York: John Wiley and Sons, Inc., 181-191.
3. Pate-Cornell, M.E. (1990), “Organizational Aspects of Engineering System Safety: The Case of Offshore Platforms,” *Science* 250, 1210-1217.
4. Pidgeon, N. and M. O’Leary (1994), “Organizational Safety Culture: Implications for Aviation Practice,” in *Aviation Psychology in Practice* (N. Johnston, N. McDonald, and R. Fuller, eds.), Lawrence Erlbaum, Hove.
5. Maurino, D.E., J. Reason, N. Johnston, and R.B. Lee (1997), *Beyond Aviation Human Factors*, Vermont: Ashgate Publishing Company.
6. Reason, J. (1990), *Human Error*, Cambridge, UK: Cambridge University Press.
7. Reason, J. (1995), “A System Approach to Organizational Error,” *Ergonomics* 38(8), 1708-1721.
8. Reason, J. (1997), *Managing the Risks of Organizational Accidents*. England: Ashgate Publishing Limited.
9. Sarsfield, L.P. (1998), “Aviation in the Next Millennium: A National R&D Plan for Improving Air Transportation Safety and Security in the 21st Century”, Draft, RAND

Science and Technology Policy Institute, October 1.

10. Strauch, B. (2002), *Investigating Human Error: Incidents, Accidents, and Complex Systems*, England: Ashgate Publishing Limited.

11. Leveson, N., "A New Foundation for System Safety" (<http://sunnyday.mit.edu>), 2002.

12. Luxhøj, J.T., A. Choopavang, and D.N. Arendt (2001), "Risk Assessment of Organizational Factors in Aviation Systems," *Air Traffic Control Quarterly*, 9 (3), 135-174. (*Special Issue on Flight Safety*)

13. Luxhøj, J.T., K. Bansal, A. Choopavang, A., T.G. Horton, and D. N. Arendt (1999), "An Aviation System Safety Model for Improved Risk and Management," *Proceedings of the European Safety and Reliability Conference ESREL'99*, Munich, Germany, September 13-17, 1285-1290.

14. Luxhøj, J.T., D.N. Arendt, and T.G. Horton (1998), "An Intelligent Computer-Based Tool for Evaluating Aircraft Accident Causation," *Proceedings of European Safety and Reliability International Conference ESREL '98*, Trondheim, Norway, June 17-19, 839-846.

15. Luxhøj, J.T., D.N. Arendt, T.P. Williams, and T.G. Horton (1997), "An Application of Advanced Information Technology for Assessing Aircraft Accident Causation," *Proceedings of International Society of Air Safety Investigators*, Anchorage, Alaska, September 29 - October 3.

16. Yin, R. (2003), *Case Study Research: Design and Methods*, 3rd ed., London: Sage Publications.

17. van Vuuren, W. (1998), *Organizational Failure: An Exploratory Study in the Steel Industry and Medical Domain*, Institute of Business Engineering and Technology Application, Eindhoven University of Technology, Eindhoven, Netherlands.

18. Andersen, S.K., F.V. Jensen, and K.G. Olesen (1987), "The HUGIN Core – Preliminary Considerations on Systems for Fast Manipulation of Probabilities," in *Proceedings of Workshop on Inductive Reasoning: Managing Empirical Information in AI-Systems*, Risø National Laboratory, Roskilde, Denmark, April.

19. Andersen, S.K., K.G. Olesen, F.V. Jensen, and F. Jensen (1989), "HUGIN - A Shell for Building Bayesian Belief Universes for Expert Systems," in *Proceedings of the Eleventh International Joint Conference on Artificial Intelligence*, Detroit, Michigan, 1080-1085, August 20-25.

20. Pearl, J. (1988), *Probabilistic Reasoning in Intelligent Systems: Networks of Plausible Inference*, San Francisco: Morgan Kaufmann.

21. Jensen, F.V., S.L. Lauritzen, and K.G. Olesen (1990), "Bayesian Updating in Causal Probabilistic Networks by Local Computations," *Computational Statistics Quarterly*, 4, 327-352.

22. Jensen, F.V. (1996), *Introduction to Bayesian Networks*, New York: Springer-Verlag.

23. Ayyub, B.M. (2001), *Elicitation of Expert Opinions for Uncertainty and Risks*, New York, CRC Press.

24. Renooij, S. (2001), "Probability Elicitation for Belief Networks: Issues to Consider," *The Knowledge Engineering Review*, 16(3), 255-269.

25. NASA Aviation Safety Program (AvSP) Product Dictionary (2002), February.

26. NASA Aviation Safety Program (AvSP) Commitment Agreement (2000), July.

27. Luxhøj, J.T. (2003), "Probabilistic Causal Analysis for Safety Risk Assessments in Commercial Air Transport," *Workshop on Investigating and Reporting of Incidents and Accidents (IRIA)*, September 16-19, 2003, Williamsburg, VA.

28. Wiegmann, D.A. and S.A. Shappell (2003), *A Human Error Approach to Aviation Accident Analysis: The Human Factors Analysis and Classification System*, England: Ashgate Publishing Limited.

29. Schmidt, J., Figlock, R., and Lawson, D. (2000), *Human Factors Analysis, and Classification System—Maintenance Extension (HFACS – ME) Review of Selected NTSB Maintenance Mishaps: An Update* Naval Safety Center, US Navy, Norfolk, VA.

30. The National Transportation Safety Board, Accident Report No. AAR-92-02, Washington, DC, 1992.

31. Jalil, M. (2003), *A Probabilistic Decision Support System for Evaluating the Impact of Technology Insertion on Aviation Safety Risk*, M.S. Thesis, Department of Industrial and Systems Engineering, Rutgers University.

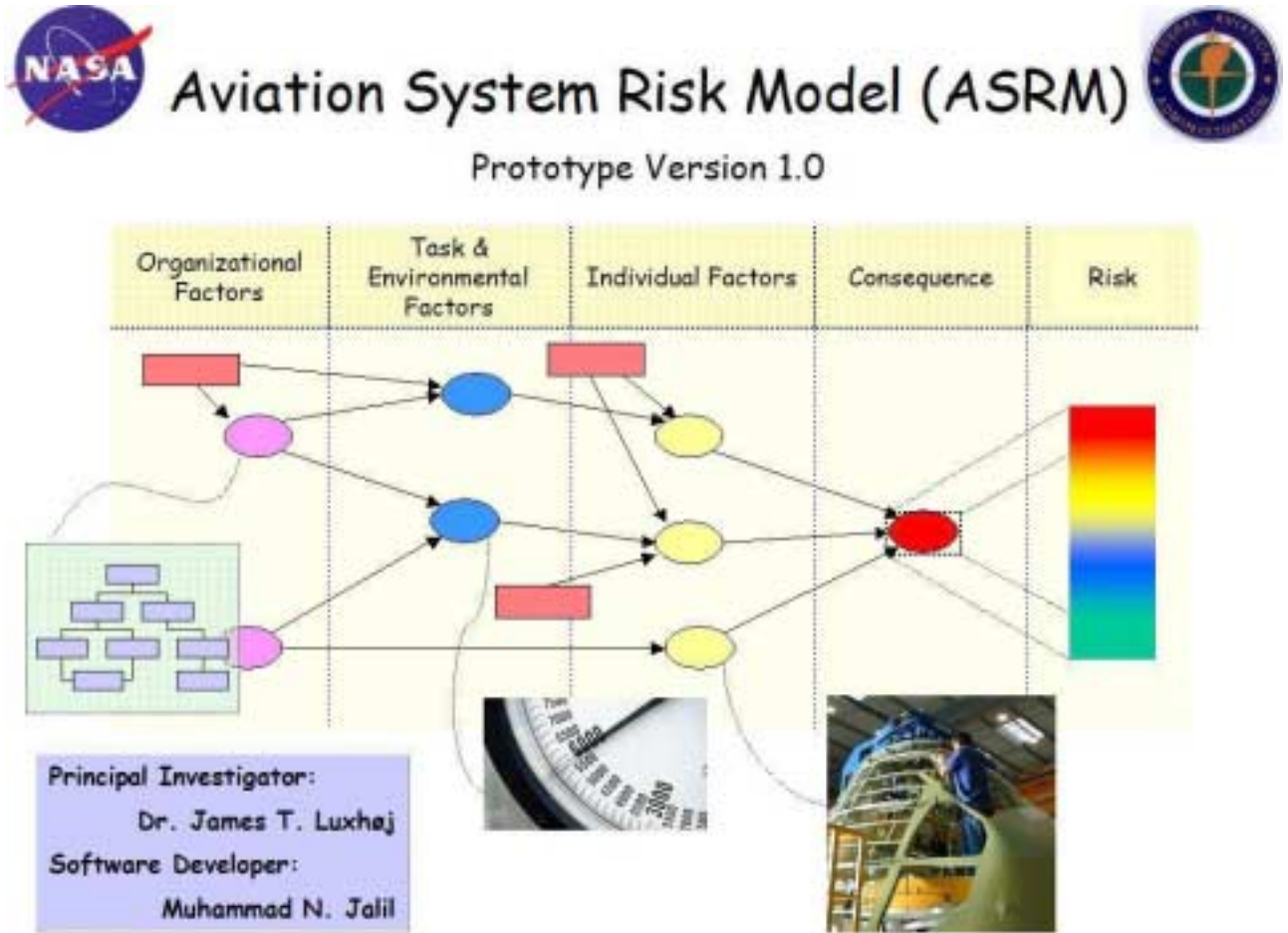


Figure 4. ASRM Initial Screen

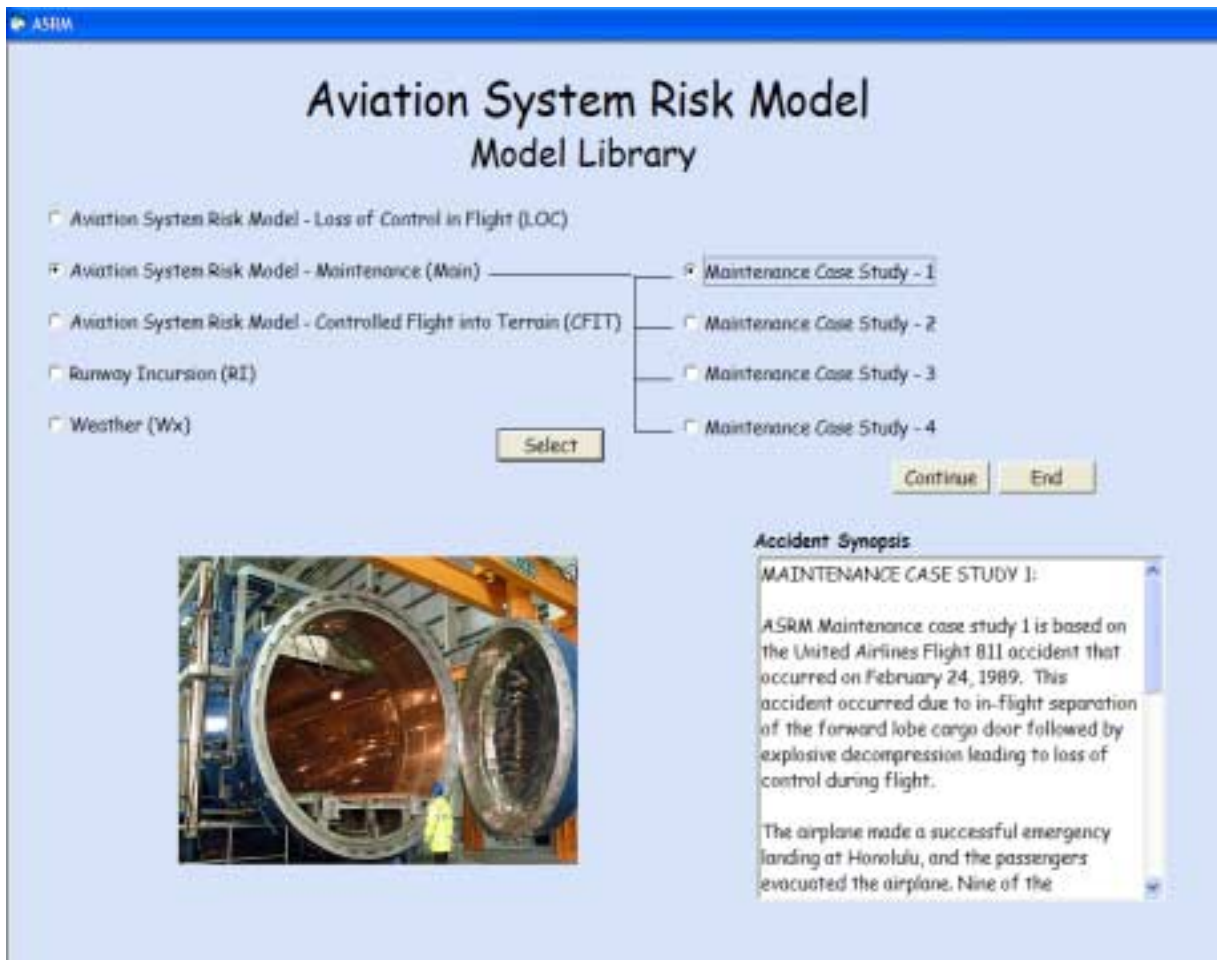


Figure 5. ASRM Model Library

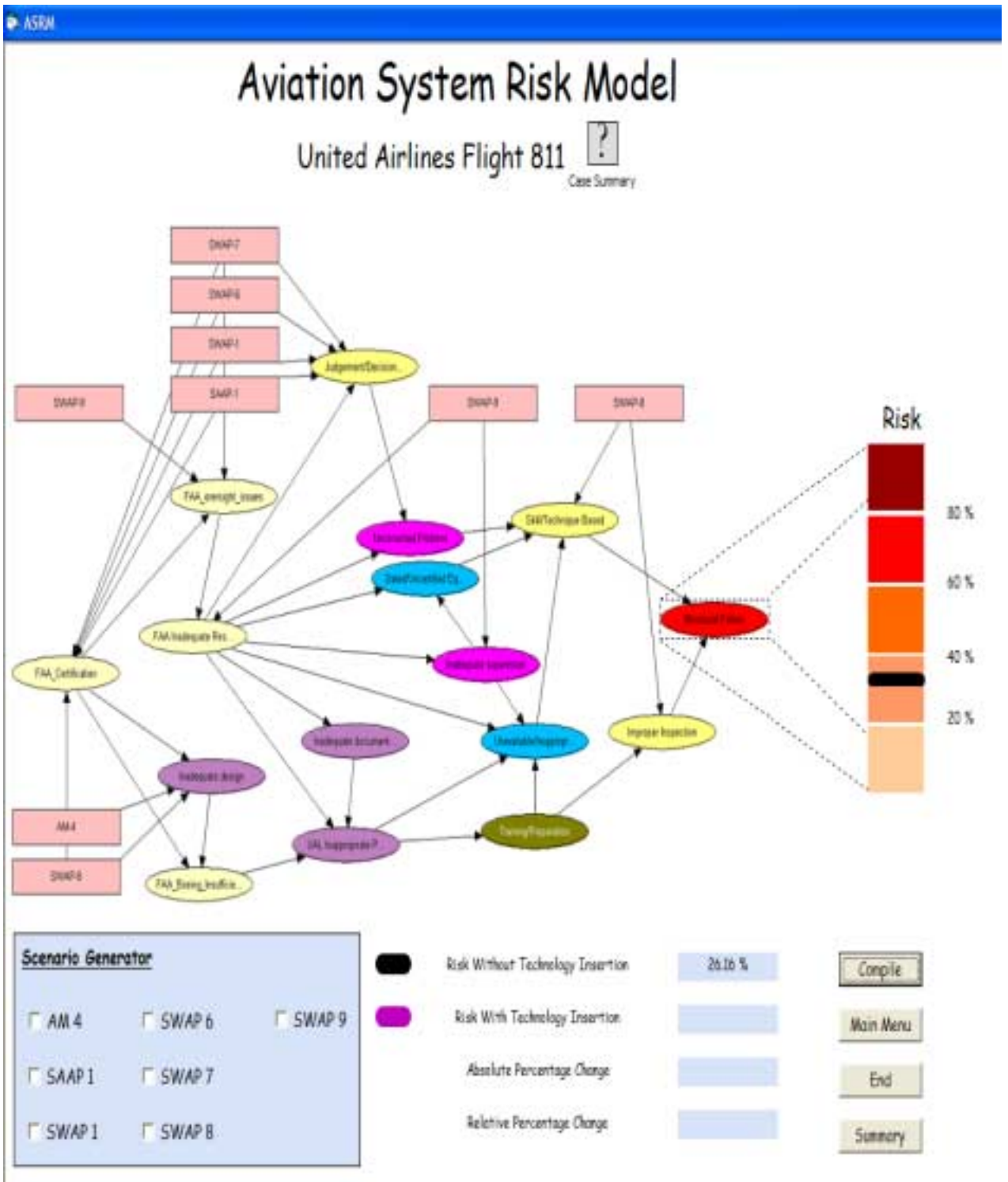


Figure 6. ASRM Baseline Screen

Aviation System Risk Model

United Airlines Flight 811 ?
Case Summary

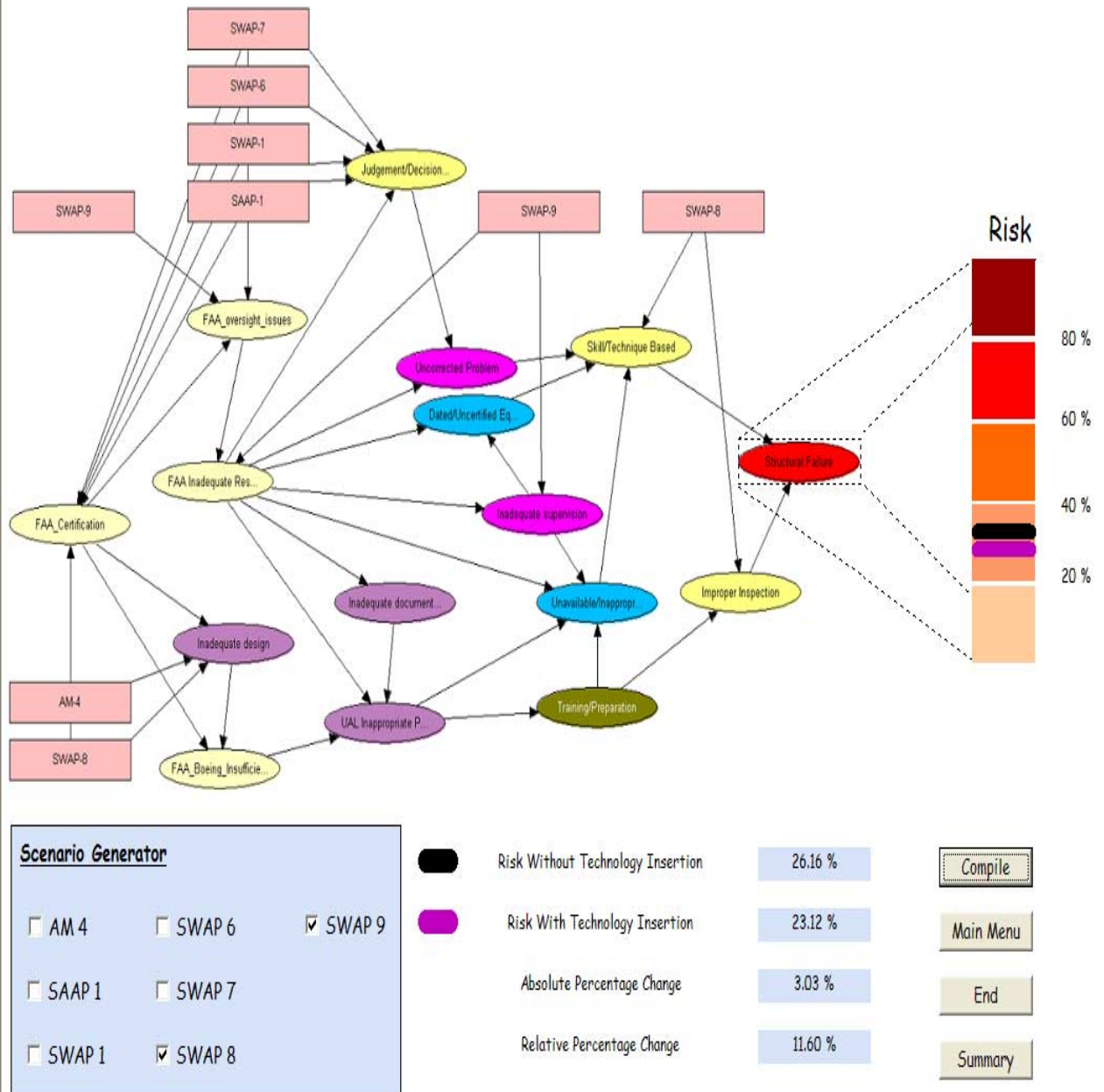


Figure 7. ASRM with Technology Insertions

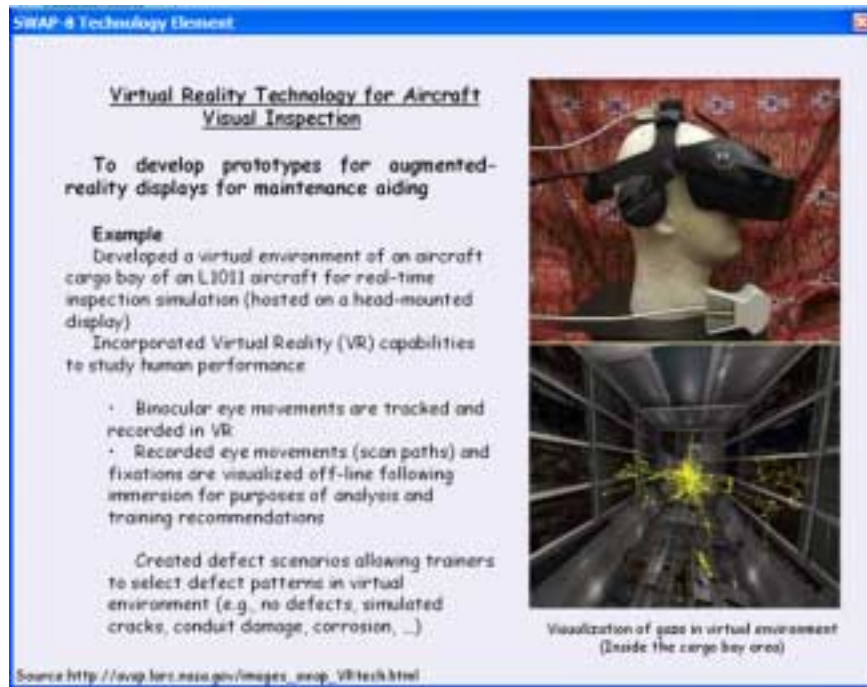


Figure 8. AvSP Technology Information Screen for SWAP 8 (included in the ASRM tool)

Table 2. Preliminary Results of Relative Risk Assessments

Scenario Description	Targeted Causal Factor(s)	Technology Element(s) Inserted	Risk (Factors)	Relative % Decrease or (Increase) on Factors	Risk (Consequence)	Relative % Decrease or (Increase) on Consequence
Base Line Scenario	-	None	-	-	26.16%	
Maintenance Scenario No. 1	Inadequate Design	AM-4	13.76%	49.41%	23.39%	10.58%
	FAA Certification	SWAP- 1	14.72%	48.89%		
	FAA Oversight	SWAP- 8	21.53%	21.02%		
	Judgment Decision Making		21.99%	16.72%		
Maintenance Scenario No. 3	FAA Certification	SWAP - 1	21.12%	26.67%	23.01%	12.04%
	FAA Oversight	SWAP - 9	18.84%	30.88%		
	Judgment Decision Making	SWAP - 8	21.01%	20.45%		
	Inadequate Supervision		16.76%	37.03%		
	FAA Inadequate Resources		20.71%	25.01%		
	Inadequate Design		20.16%	25.88%		
	Skill / Technique Based		17.08%	41.48%		
Improper Inspection		21.85%	14.81%			
Maintenance Scenario No. 5	FAA Certification	SWAP - 8	19.52%	32.22%	23.40%	10.54%
	FAA Oversight	SAAP - 1	21.11%	22.55%		
	Judgment Decision Making		18.77%	28.91%		
	Inadequate Design		19.36%	28.82%		
	Skill / Technique Based		18.93%	35.15%		
Improper Inspection		22.18%	13.54%			