RISK ANALYSIS OF HUMAN PERFORMANCE IN AVIATION MAINTENANCE

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Abstract

The National Airspace System (NAS) in the United States is a complex system involving many interrelated factors and actors. There are a plethora of diverse human, technical, environmental, and organizational factors that affect the performance of the NAS. While numerous methodologies exist for Probabilistic Risk Assessment in complex engineering systems, these specialized tools are somewhat limited in their use for the *integrated modeling* of the technical as well as the human, environmental, and organizational aspects of such systems. While adaptations and modifications can be made, an analytical method that enables a more direct modeling of these various factors is desirable. This paper presents just such an integrated risk analysis framework that focuses on both the individual and collective human performance in the maintenance of complex systems.

Introduction

Aviation safety risk analysis is vital to the effective operation of the National Airspace System. While there may be some differences among practitioners and researchers regarding the terminology used to describe risk, it is generally accepted that risk management is a very systematic process that essentially involves the steps of risk identification, risk modeling, risk evaluation, risk mitigation, and action/surveillance (Haimes, 1998; *CAN/Q850-97*, 1997). *Risk analysis* typically comprises the phases of *risk identification* and *risk modeling*.

While mathematical definitions of risk involve the probability of an event occurrence times the severity of that event, oftentimes this purely quantitative approach fails to capture an inherent part of the existential nature of the notion of risk. What is needed is a more comprehensive, holistic approach to risk analysis that integrates both the *quantitative* and *qualitative* aspects of this natural phenomenon. Developing such holistic risk concepts aim at the interplay between technical content and organizational processes.

Reason has developed a descriptive model of accident causation that integrates individual, task/environmental, and organizational factors (Reason, 1995, 1997). While this model illustrates the complex, multi-faceted nature of accident causality, it cannot be used in a normative way since it is not linked to an underlying analytical methodology.

The Aviation System Risk Model (ASRM) as described in Luxhøj et al. (2001) provides an integrated approach to understanding the complex interactions of multiple risk factors. In the referenced paper, the authors provide a detailed description of the model along with a maintenance case study. The reader is also referred to other risk analysis case studies provided in Luxhøj et al., (1997, 1998, 1999). Accident scenarios, such as loss of control (LOC), have been developed using the combined approach of analytic generalization from case studies and from knowledge engineering sessions with subject matter experts (SMEs).

While previous papers focused on how the ASRM may be used to better understand the role that collective human performance or organizational factors play in aviation safety risk analysis (see also Choopavang, 2000), this paper focuses more on how the ASRM may be used to better understand the risks associated with the human role in aviation maintenance and the importance of defenses in such complex systems.

The Reason Model

The Reason model (1995, 1997) discusses in detail the multiple hierarchical socio-technical elements of accident causation. The *causal chain* starts from organizational processes and continues through task and environmental conditions that establish preconditions for an individual at a workplace. Unfortunately, in some cases the defenses built into the system are breached and an accident occurs. Individuals in the organization may perform these unsafe acts but the preconditions that provoke those acts are sometimes due to faulty management decisions and policies (i.e., latent failures). Figure 1 presents a schematic of the Reason model as used by the Australian Bureau of Air Safety Investigation with the integrated placement of slips, lapses, mistakes, and violations.

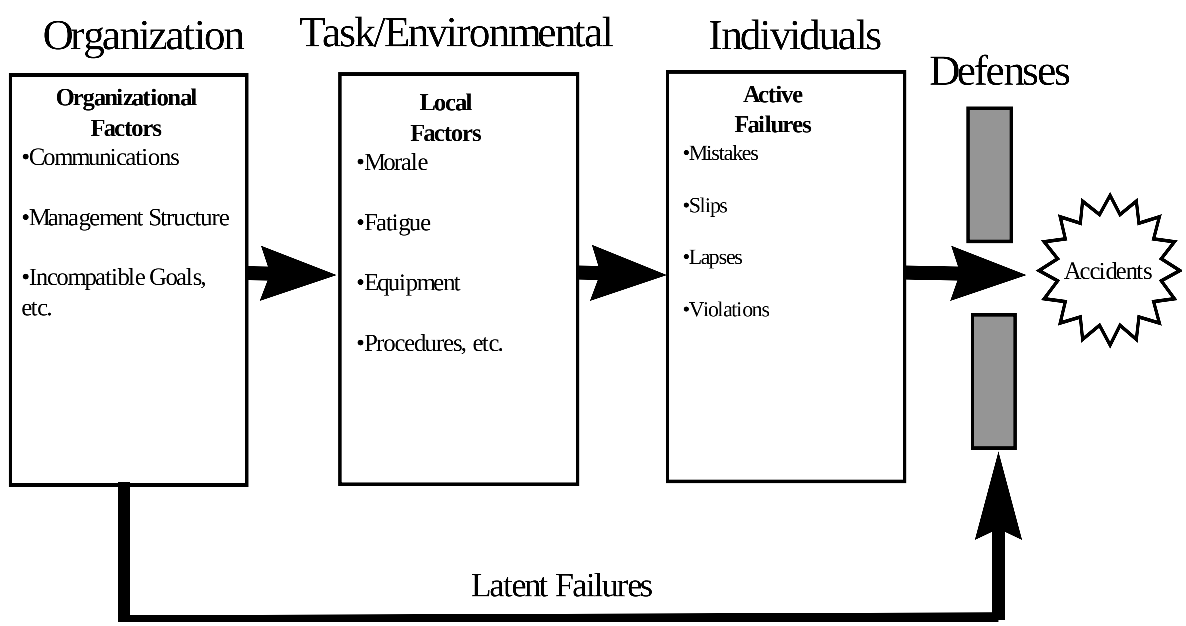

Figure 1. Reason Model of Accident Causation
(<u>Source</u>: Luxhøj et al., 2001)

The Aviation System Risk Model (ASRM)

The ASRM uses the underlying framework of the Reason model coupled with the influence diagram approach of Bayesian Belief Networks (BBNs) (see Jensen, 1993, 1995) to understand the *interrelationships* among causal factors and actors. Organizational factors, along with task/environmental factors and individual factors in this general model were mostly adapted from the NTSB database factor lookup tables. Elements of Nagel's (see Wiener and Nagel, 1988) model of Information-Decision-Action were applied to the individual level. The consequence level was the combination of the United Kingdom's Civil Aviation Authority (UKCAA, 1997) standardized list of consequences and the suggestions of aviation system analysts. The ASRM uses a graphical influence diagram approach to depict the causal relations existing among multiple risk factors. Figure 2 displays a high-level schematic of an influence diagram and the "clustering" of safety risk factors that are consistent with the Reason framework.

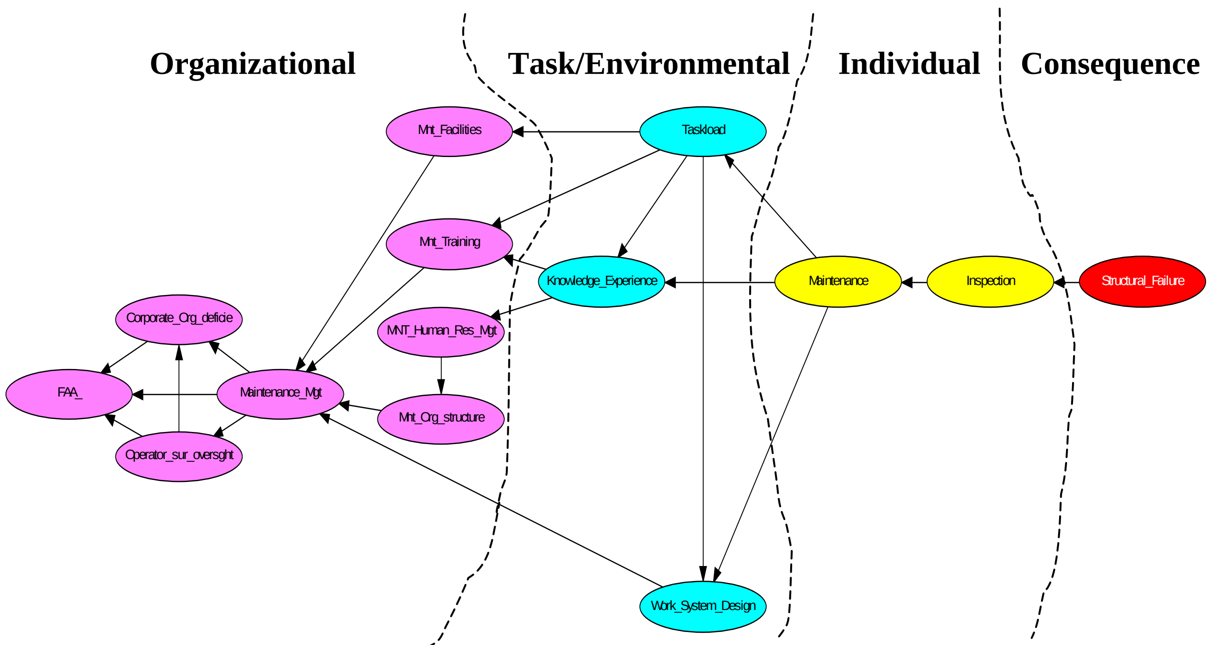

Figure 2. Overview of an Influence Diagram

From a managerial perspective, an influence diagram is useful for graphically depicting and initiating understanding of the *interrelationships* existing among causal factors in an accident. As depicted in Figure 3, such a model enables managers to perform sensitivity analysis or "what-if" analyses to gain an understanding of the effect that, for example, changes in individual maintenance or operations procedures may have on reducing the relative risks associated with certain types of accidents.

By integrating conditional probabilities into the influence diagram, a Bayesian Belief Network (BBN) may be constructed. These influence diagrams graphically portray the complex interrelationships among the various factors (i.e. variables) in the accident chain. The next step involves the determination of various "states" for each factor or variable in the BBN. For example, a "state" may be that maintenance was either proper or improper as a simplification. The third step in BBN construction involves the development of conditional probabilities for the various states. The probabilities quantitatively define the contribution to System Risk where Risk = P(hazard) * P(accident|hazard). Besides indicating interrelationships among the factors in the system, the BBNs may also be used to help identify data requirements. Figures 4-5 display influence diagrams with "states" under each node and probabilities attached to the states.

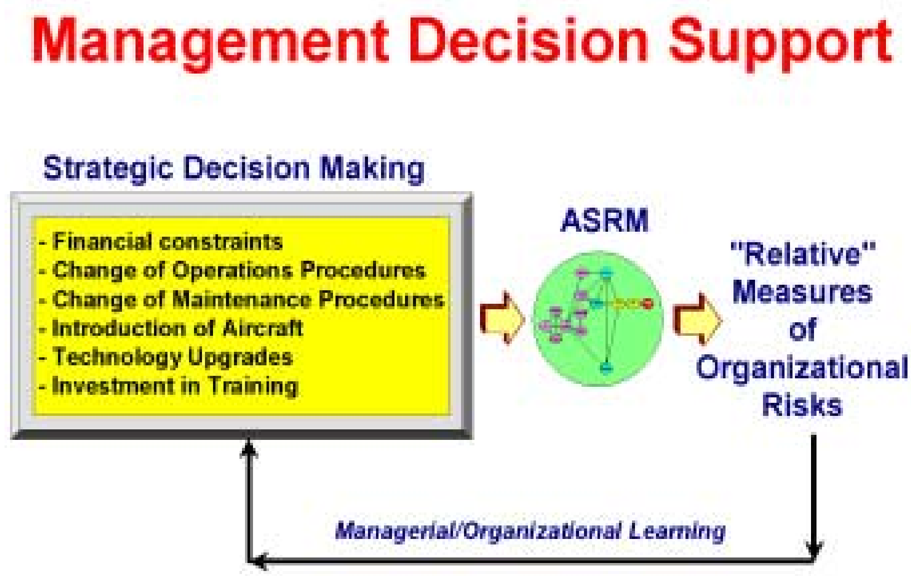

Figure 3. Management Decision Support
(<u>Source</u>: Luxhøj et al., 2001)

<u>Organizational</u>

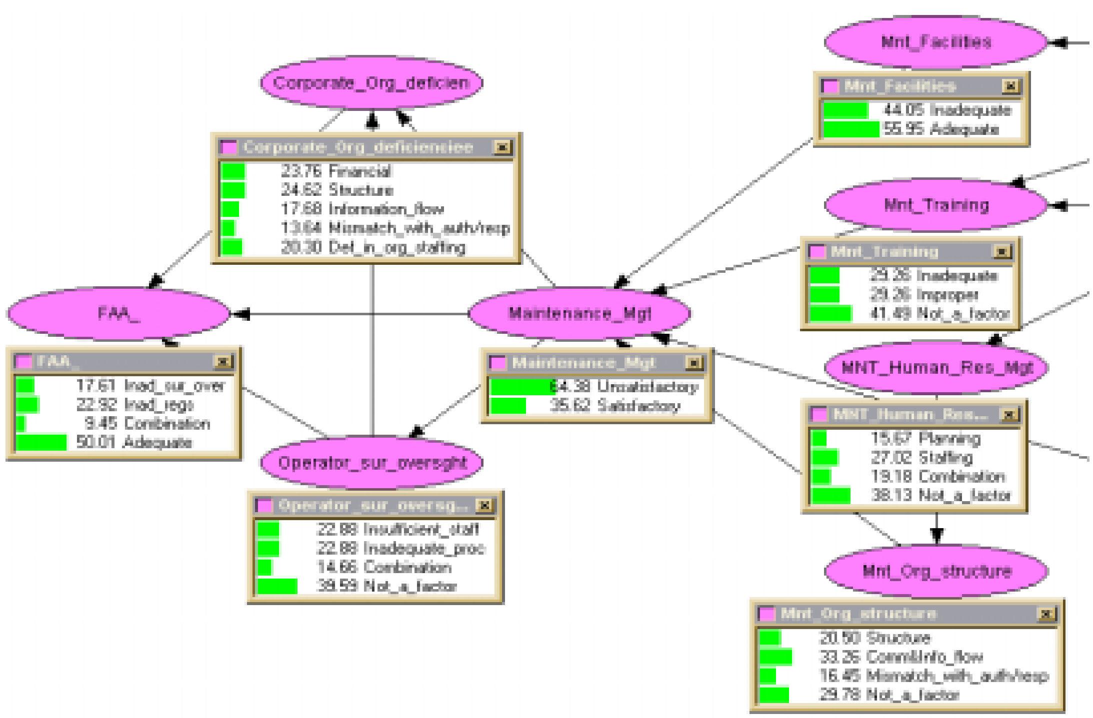

Figure 4. Influence Diagram with Probabilities
(<u>Source</u>: Luxhøj et al., 2001)

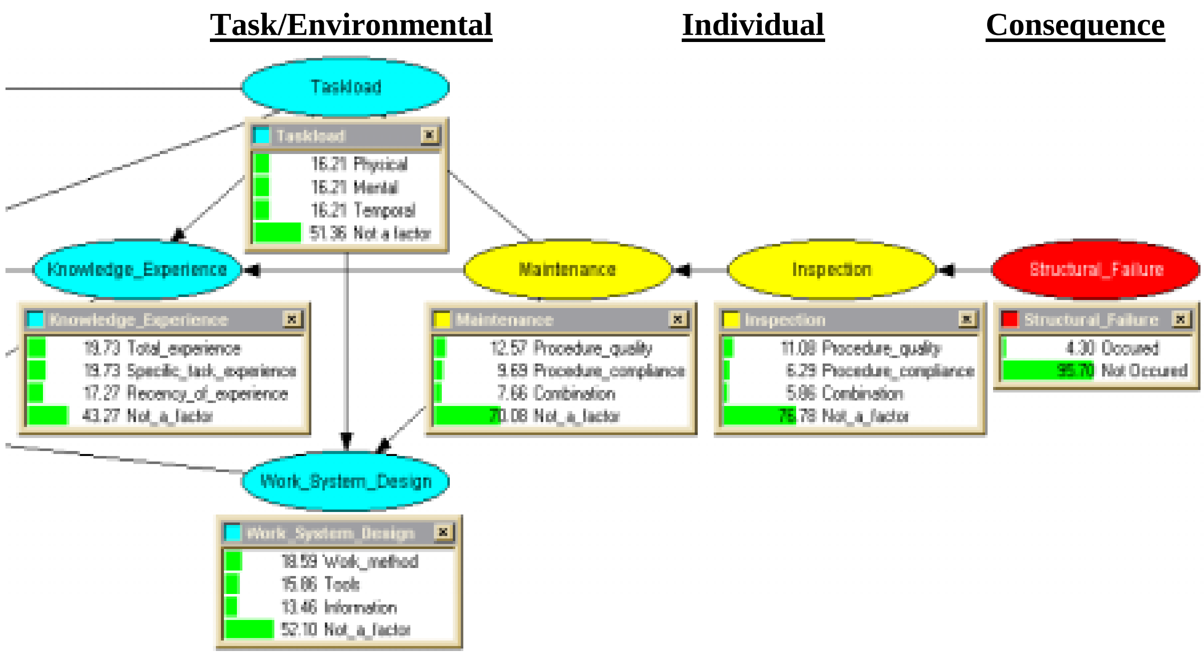

Figure 5. Influence Diagram with Probabilities (Continued)
(<u>Source</u>: Luxhøj et al., 2001)

Once the BBNs have been constructed, scenario analyses may proceed by entering "evidence" into the models. "Evidence" removes the uncertainty of a state and the probability changes to 1.0. This evidence is then propagated through the network through the use of the embedded BBN algorithm. Multiple evidence is possible as displayed in Figure 6.

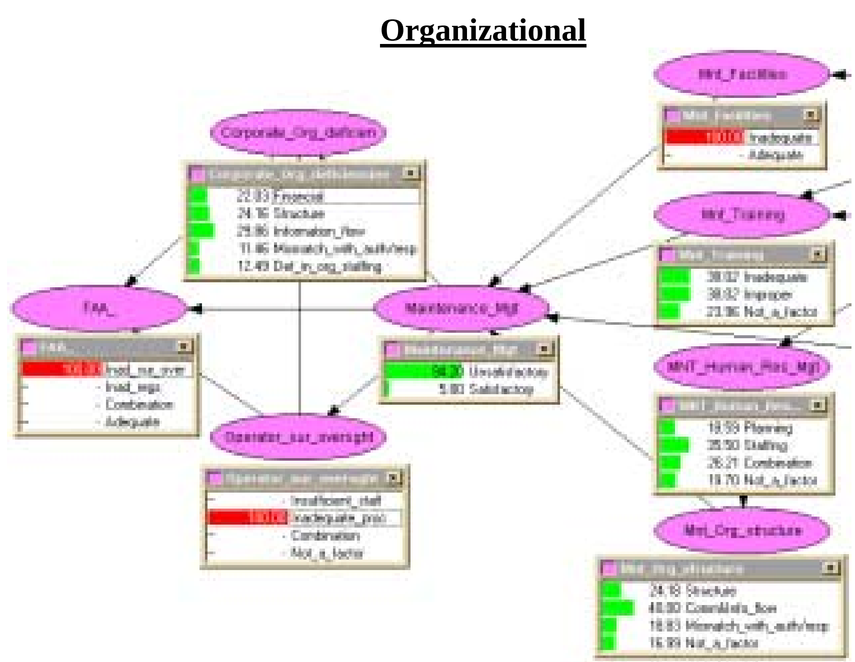

Figure 6. Multiple Evidence
(<u>Source</u>: Luxhøj et al., 2001)

Figure 7 shows a maintenance scenario analysis focusing on human performance the nodes of work systems design and maintenance procedures nodes.

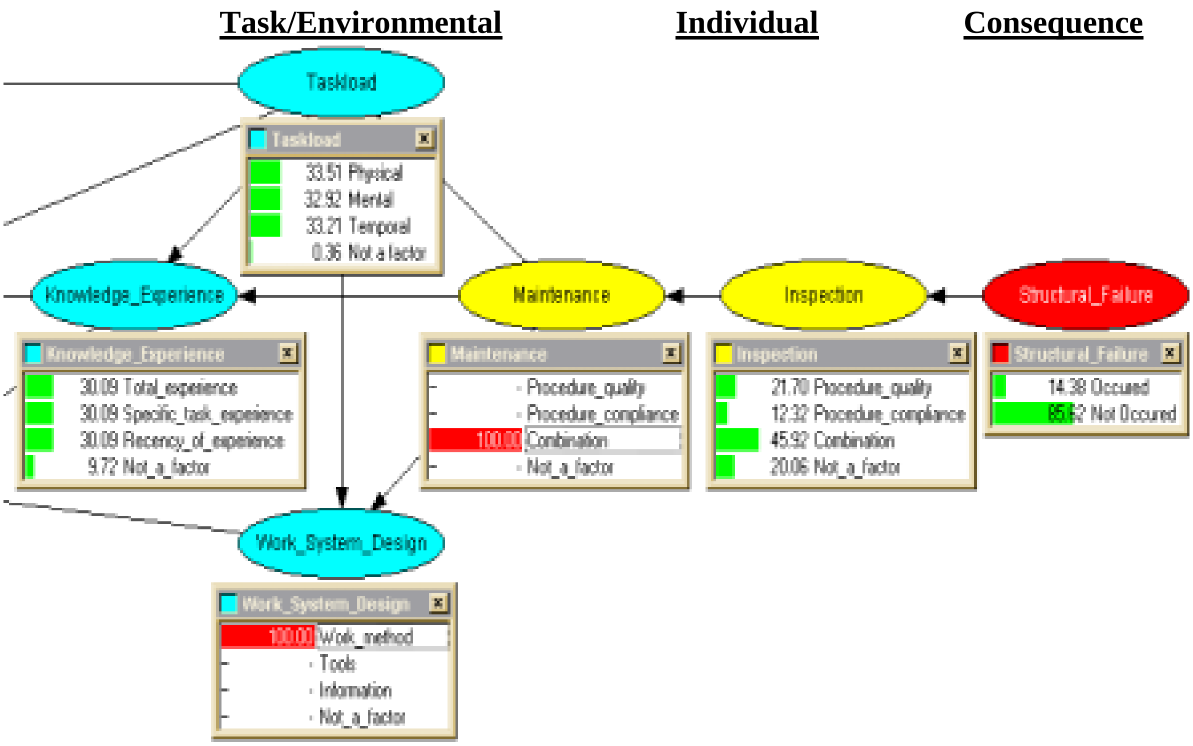

Figure 7. Scenario Analysis with Evidence at the *Maintenance* and *Work System Design* nodes (Source: Luxhøj et al., 2001)

The Role of Defenses

There are numerous ways in which defenses may be applied by either an individual actor and/or an organization. For example, defenses include engineering safety devices and mechanical and electronic devices (e.g., warning signals, shutdown, pressure release valves, ground proximity devices, etc.), management policies and standard procedures, training and briefings, and personal protective gear (e.g., helmets, gas masks, seat belts, etc.).

One of the aviation subject matter experts emphasized that even though a series of unfortunate events may occur through the active error path, layers of a healthy defense system could prevent accidents. Figures 8-10 illustrate, according to the algorithms of Bayesian Belief Networks, that if the state of the defense system is known, and is working properly, then the relationship between the sequence of errors and the accident is blocked. Hence, the accident is not likely to happen from this set of causal factors. Nevertheless, it is possible that some other factors not included in the model, e.g., material failure, as well as maintenance errors may cause an in-flight structural breakup.

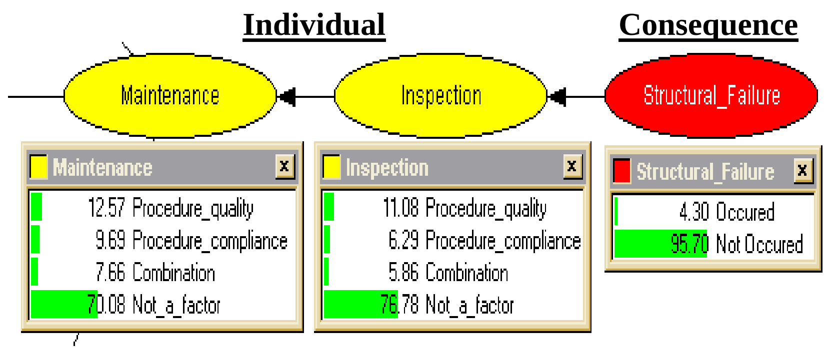

Figure 8. Unperturbed Probability
(<u>Source</u>: Luxhøj et al., 2001)

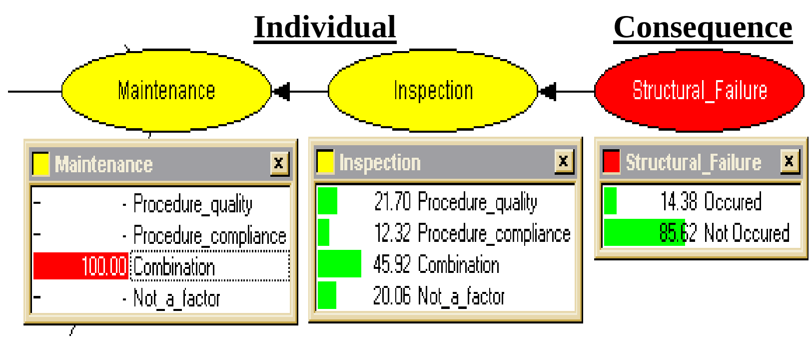

Figure 9. Updated Probability After Evidence Enters at the *Maintenance* node
(<u>Source</u>: Luxhøj et al., 2001)

Figure 10 shows that proper human performance of inspection procedures could act as a strong defense against the combination of poor quality of maintenance procedures and improper compliance with maintenance procedures. The relative probability of the structural failure is significantly reduced.

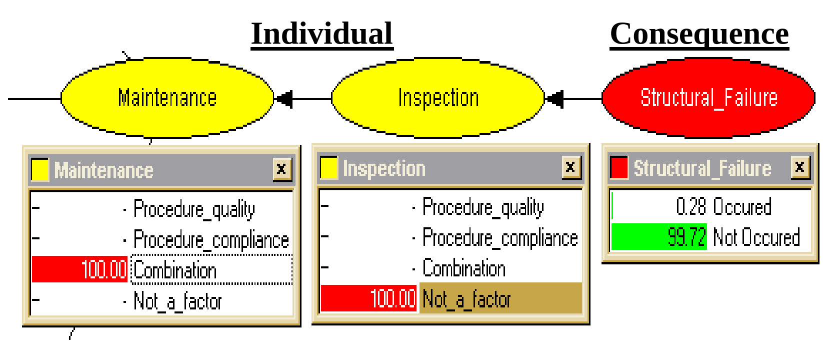

Figure 10. Updated Probability After "Positive" Evidence Enters at the *Inspection* node
(<u>Source</u>: Luxhøj et al., 2001)

Conclusions

This paper presents an alternative approach to the *integrated* modeling of both quantitative and qualitative risk factors in modeling human performance in complex systems. The Aviation System Risk Model, with its underlying framework of the Reason model of accident causation and the use of Bayesian Belief Network algorithms provides a flexible, systematic approach to understanding the interplay of technical content and organizational and human performance in aviation maintenance. Future research involves the development of a common terminology with perhaps the Human Factors Analysis and Classification System (HFACS) (see Shappell and Wiegmann, 2001), building and validation of more accident scenarios, and refinement of a tool to assess both human and organizational factors as well as the impact of technology insertion upon the performance of aviation maintenance.

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