LEARNING FROM FAILURES: ARCHIVING AND DESIGNING WITH FAILURE AND RISK

Michael Van Wie[1] Matt Bohm[2] Francesca Barrientos[3] Irem Tumer[3] Robert Stone[1]

[1]Department of Basic Engineering, University of Missouri-Rolla, Email: vanwie@umr.edu, rstone@umr.edu
[2]Department of Computer Science, University of Missouri-Rolla, Email: mbohm@umr.edu
[3]Computational Sciences Division, NASA-Ames Research Center, Email: fbarrientos@mail.arc.nasa.gov, itumer@mail.arc.nasa.gov

ABSTRACT: Identifying and mitigating risks during conceptual design remains an ongoing challenge. This work presents the results of collaborative efforts between The University of Missouri-Rolla and NASA Ames Research Center to examine how an early stage mission design team at NASA addresses risk, and, how a computational support tool can assist these designers in their tasks. Results of our observations are given in addition to a brief example of our implementation of a repository based computational tool that allows users to browse and search through archived failure and risk data as related to either physical artifacts or functionality.

KEYWORDS: failure analysis, risk assessment, failure taxonomy, reliability based design

1. INTRODUCTION

A critical application to the success of modern engineering design is the ability of a design team to rapidly produce alternative architectures and technology concepts and effectively perform trade analyses on performance, cost, and risk. This is particularly important with projects involving very high stakes and low margins for error such as space mission design. Innovation in computational design tools that reuse prior design knowledge is a central challenge.

The main goal of this work is to develop a methodology and a computational tool that makes use of past failures to understand failures, risks, and to support the processes used to elicit failures and risks during conceptual design. Examination of past failure data as well as observational studies of designers shows how failures and risks can be archived and subsequently used during conceptual design.

2. BACKGROUND

2.1 Designing with Failure and Risk

The concepts of failure and risk are both indicative of problem areas that require attention during design. Generally a failure refers to a specific event that results in the inability of a system to continue to function in its intended role. Recent work has resulted in the generation of a failure mode taxonomy that incorporates failures in both the mechanical and electrical domains [1-2]. In contrast with the concept of failure, risk refers mainly to three items: what failure may occur, the likelihood of failure, and the consequence of a failure. The problem of accounting for both failure and risk during conceptual design is a fitting opportunity for computational approaches that provide features for archiving and retrieving historical failure and risk data.

Past attempts toward archiving failure and risk data vary widely in the type of data addressed. Applications by the US Department of Transportation and the National Transportation Safety Board included databases for storing large volumes of past accidents involving transportation systems. These databases are not geared directly for designers while others such as the Problem / Failure Report database at NASA are sufficiently detailed to provide specifics of design or operation issues that previously contributed to a failure. In order to examine how a computational tool can be implemented in a conceptual design setting, we focused on an early stage design team at NASA's Jet Propulsion Laboratory (JPL) known as Team X.

2.2 The Team X Early Design Environment

Team X is a 20 member design team that specializes in generating preliminary conceptual designs for space missions in extremely short time frames [3]. Table 1 shows the assigned names of each team member, called a "Chair" by Team X convention. Each Chair is an expert in a particular engineering domain and is responsible for designing that particular aspect of the desired spacecraft. Note that a "Risk" Chair is a recent addition to the design team, dedicated to the task of eliciting, discussing, and documenting risk related issues.

Table 1. Areas of responsibility for Team X Chairs

Cost	Telecom system
Power	Thermal
Structures	Visualization
Configuration	Mission design
Programmatics	Attitude control system
Software	Command and data system
Systems	Instruments
Ground systems	Science
Propulsion	Risk
Telecom hardware	Facilitator

A typical mission design lasts a total of 9 hours that are split into 3 hour sessions on 3 different days. During these sessions, the team members meet in a specially designed room where they have access to custom groupware and can interact face-to-face. This Team X setting is an excellent example of how effectively conceptual design can occur. In our work, we first consider the tool developed as the "Risk Analysis Prototype" (RAP), which is currently used by Team X. RAP is an Excel based application for documenting and communicating risks during a Team X design session as those risks are being identified and discussed [4]. In addition, RAP presents visual feedback for the user by plotting identified risks on a 5x5 matrix known as a "fever chart." And example of a fever chart is shown in Figure 1.

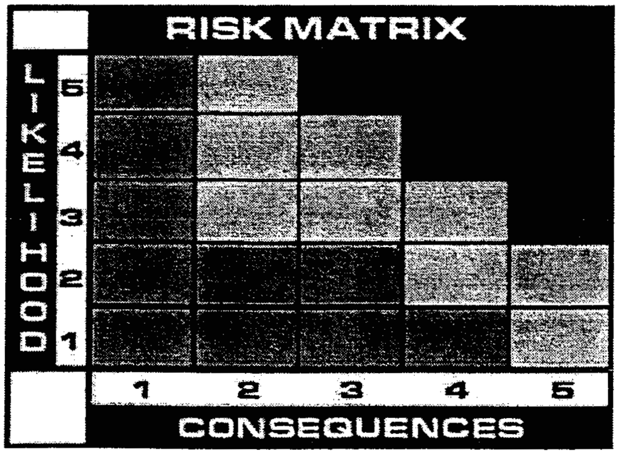


Figure 1. Example of a "fever chart" similar to that used in RAP

The research questions we address in our work are: Do designers use knowledge of potential failures and risks during the design process? How do Team X designers go about the process of eliciting potential failures and risks? How are these risks defined and communicated in the rapid conceptual design tasks during Team X sessions? How can failures and risks be archived in a database with the intention of using such a database during these design sessions to make potential failure and risk identification more effective or efficient? As a starting point, we briefly review previous work on a design repository that serves as a foundation for the features developed in this research.

2.3 Design Repository

Ongoing work at the University of Missouri-Rolla has produced a design tool,. known as the Design Repository, for storing a wide variety of product design information such as component functionality, material description, and manufacturing choice [5]. One principal effort of the repository research has been the development of models for representing design function and for manipulating functional data to support design synthesis. This effort has culminated into a functional basis language that includes a set of terms that span the space of all functions and flows describing the functionality of systems in the electro-mechanical domain [6]. Here a function refers to a transformation operation from input flow to output flow. Functional descriptions are composed in a verb-object format where a function word from the Functional Basis is the verb and a flow word is the object, similar to the Pahl and Beitz [7] description of function.

In addition, a joint effort with NASA Ames Research Center has led to the formulation of mechanical and electrical failure modes of components [2]. The primary level of failures modes is shown in Table 2. The current repository system also includes a description of the failure modes associated with each artifact within the system. This design repository serves as a platform from which to add additional features for addressing failure and risk data for assisting conceptual design tasks in the Team X environment.

Table 2. Mechanical and electrical failure modes (at the primary level of detail)

Mechanical	Electrical
Buckling	Bonding defect
Corrosion	Breakdown
Creep	Contamination
Ductile deformation	Cracking
Fatigue	Diffusion
Fretting	Hot carrier induced degradation
Galling & Seizure	Latch-up
Impact	Mask defects
Radiation	Noise
Rupture	Overstress
Spalling	Punch-through
Wear	Voiding

As a summary of the current implemented design repository system, three modes of use are supported:

browse, search, and process design tool output. In the browse mode, artifacts in the repository can be selected on a left pane and inspected on the right. The search mode allows the user to search for all artifacts that match an input selection based on attributes such as functionality or failure mode. The final mode of operation includes the execution of certain design tools to support design synthesis activities [8].

2.4 Objectives

The purpose of this work is to investigate how designers can utilize knowledge from past failures to better perform design tasks during conceptual design. The first objective is to examine the tasks to determine how a computational tool can be integrated into the design environment. A second objective is to develop new capability into the design repository for handling failure and risk data in a manner that is consistent with findings from the first objective.

3. METHODOLOGY AND RESULTS

The following three sections discuss the steps taken to meet the objectives. First, direct observations of the design team during mission designs are performed in order to analyze the tasks of Team X. Based on data observed and from selected documents from prior Team X design sessions, an analysis of risk data is then performed. Finally, the enhancements to the design repository are presented.

3.1 Observations

In the summer of 2004, a research team from NASA Ames Research Center observed Team X during two design sessions on two different days. Our intention was to study the language, tools and design representations used by Team X during the design process in order to better design a computational tool for their use. Prior to our visit to Team X, we prepared a number of questions to focus our observations. Some of these are shown in Table 3. Not all of these questions were answered but the following provides highlights of the main observations of the Team X environment.

Table 3. Questions to focus observations during the Team X visit

What are the kinds of tools, methods and processes they use during their sessions?
What intermediate design representations do they use? Do they make drawings or diagrams?
What verbal representations to they use? – Ideally, we'd like a dictionary of the Team X language.
Does Team X describe functionality, and if so, how?

The most striking feature of the Team X environment is its fast pace. Because all of the team members work together in a single room, each team member can easily confer with other members when a subsystem dependency issue occurs. The pace is prohibitively rapid for any Team X members to perform significant amounts of analysis during a session. In fact, relatively time-consuming analyses are performed offline between sessions. The environment is also noisy and full of potential distractions. The main actions during the session are various trades and negotiations that take place in order to explore the design space. The facilitator verbally prompts and orchestrates team members often on a minute by minute format. Experience of team members is extremely important given that references to prior missions are used to form initial estimates for certain parameters. These mentions of prior missions also provides some indication that risk is implicitly considered by the engineers since a design that was used in a successful mission indicates a less risky option.

Observations of risk assessment and the Risk Chair unveiled several aspects of how risk explicitly is addressed by Team X. The Risk chair performs the function of proactively facilitating increased attention of risks from all of the other Team X chairs. One of tasks we saw the Risk Chair perform was to identify risks associated with the evolving design. First, it appears that there are several sources of design information used by the Risk Chair to identify risks and record those risks using RAP. Documentation provided offline from the customer before design sessions as well as design documents produced by other team members offer one source. Similarly, offline studies provide some risk data. During the sessions, new risks are triggered from announcements by the facilitator, open conversations in the room, and from direct querying of other Chairs during the session.

Considerable risk information is derived by the Risk Chair through eliciting risk information from other Chairs in a direct manner. The Risk Chair speaks to other Chairs when they were not engaged in other conversations. Mental notes are taken as broad questions such as "What are the risks?" and "What are the mitigations?" are asked. Further detail is elicited through probing with narrow questions. For example, the Risk Chair may ask others to explain the current proposed design simply if a particular component might fail or if the technology has previously flown. The Risk Chair continues to probe even when the design engineer says there are no risks.

Given that risk elicitation seems largely experience-based and therefore reliant on memory, we hypothesize that a repository-based risk tool will help augment designer memory.

3.2 Risk Data Analysis

Part of the challenge for developing a computational tool to support conceptual design involves the choice of representation schemes for the desired data, which, in this case is largely centered on risk data. Another challenge in developing a risk and failure analysis tool is providing a means for retrieving the information that is relevant to a particular design. The conceptual design stage presents a particular difficulty because the design is incomplete and described at different levels of detail. One retrieval scheme we are developing is based on indexing risk and failure data by function. In particular we use the functional basis [7] to provide a consistent set of terms. The following presents details of how risk information can be related to other relevant design data for the artifact being designed. Some analysis of a sample set of risk data is also presented to scrutinize and demonstrate notable characteristics of risk data.

3.2.1 Continuity of design detail: mappings among design descriptors

Design descriptors can include a range of aspects from objectives to failure modes. In general, there are potentially several items that are options for representing key aspects of designs from high to low levels of detail. One challenge is to relate risk information to other design descriptors so that cues for risks can be established.

Several triggering events at different levels of detail lead to awareness of risk elements. For example, different levels may include consideration of incomplete information regarding objectives, functionality, technology choices, parameters, etc. This suggests that a repository-based application might be used to return intermediate items such as those on the 'guideline sheets' that the Systems Chair uses in addition to risk elements directly.

3.2.2 Risk Elements

Over 900 risk elements (a risk element is some description of a risk) were provided by JPL for critical review. These risk elements cover 4 mission types: earth orbit, solar orbit, moon, and Mars missions. Generally, the documented risk elements are highly variable in their level of specificity.

After a review of the risk elements provided, one decomposition of a risk element can be described by the properties shown in Table 3. P, D, and N respectively refer to Performance, Design, and Noise parameters. For purposes of analysis, the only design parameter considered is that of function. For this work, the primary and secondary functions from the functional basis are used.

Table 3. Risk element properties

Title
Performance parameter (P)
Design parameter (D)
Noise parameter (N)
Scope
Failure modes
Failure scenario
Likelihood of individual failure modes
Impact of individual failure modes
Overall risk likelihood
Overall risk impact
Overall risk
Mitigation
Mitigated likelihood
Mitigated impact

For a portion of the risk elements provided (17 Earth orbit elements and 100 of the moon mission risk elements), each of the risk element parameters shown in Table 2 are identified. Due to the vagueness of some risk elements, these parameters are identified for only a fraction of the total 117 risk elements inspected. The breakdown for the number of parameters identified is shown in Figure 2. One unexpected result is the relatively low number of failure modes that were identified for each risk element. It is also interesting that the risks address secondary functionality more so than primary functionality.

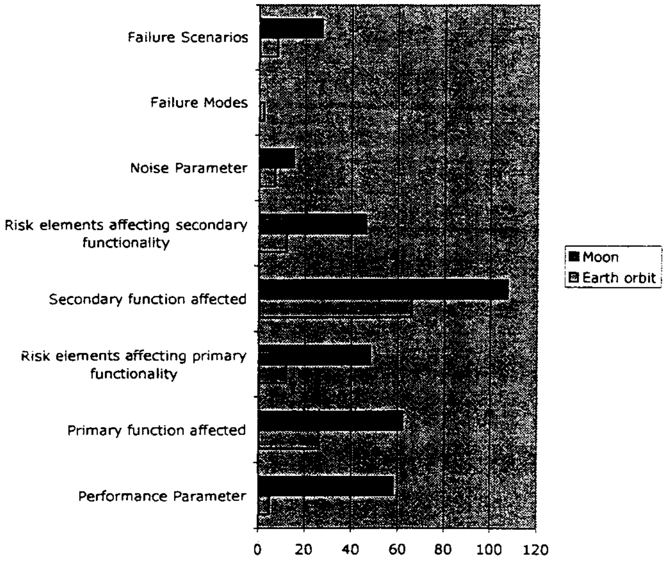


Figure 2. Number of risk element properties identified for 117 risk elements

The overall breakdown of risk elements is shown in Figures 3 and 4. Clearly the Systems chair has the greatest portion of risk that implies that the systems engineer is perhaps a target user of a computational tool for designing with risks.

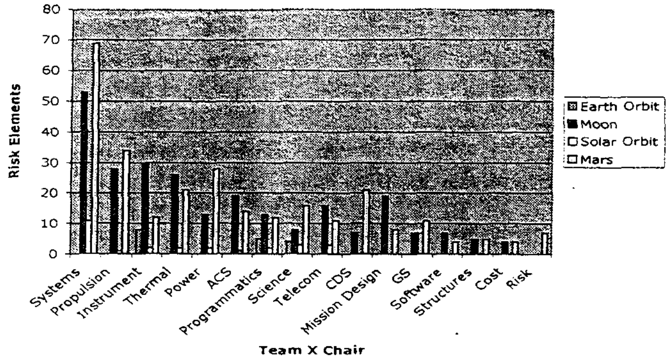


Figure 3. Risk elements according to mission type

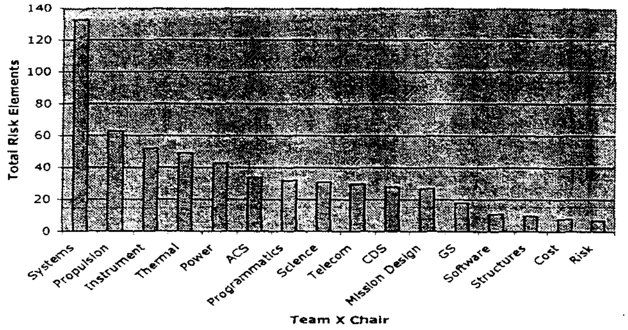


Figure 4. Total risk elements for each Team X chair

The following highlights three risk elements to show the nature of risk element language and information content. Given the lack of specificity for some risk elements, it is difficult in these cases to associate a narrow set of functionality with the risk element. For example the risk of an inaccurate landing is associated with a great number of functions.

Example risk element #1: "Instruments not able to view sample" In this case it is clear that the performance parameter is "view sample accurately," but there is no hint of exactly what is causing the failure.

Example risk element #2: "Insufficient power for drilling operations" This risk element is somewhat ambiguous. It is not clear if the power source is the problem or a downstream system.

Example risk element #3: "Grounding faults during pyros" This risk element is clear in description of an event, but does not clearly indicate P, D, N, or failure modes. To some degree, the failure scenario is indicated yet the failure is not clear.

The consistency of risk elements can be improved through adoption of a minimal and comprehensive set of risk element attributes such as those found in Table 3. Enforcement of team adherence to these types of properties is necessary for improvement. Adherence to this format involves identifying specific aspects of risk during the risk consideration process. Again, of all the properties for which there is data in Figure 2, the lack of failure mode identification is significant. In addition, the number of risk elements for which affected functionality was identified seems low.

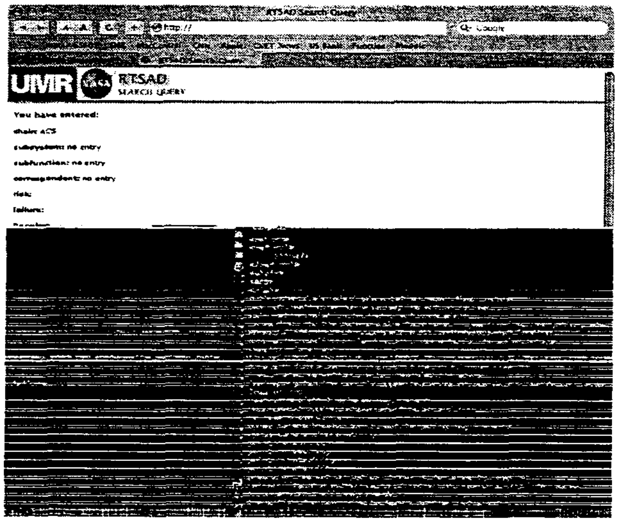
3.3 Design Tool Development

A collaborative effort between the University of Missouri-Rolla and NASA Ames Research Center has been focusing on the development of a function-based failure search and analysis tool, called the Function Failure Design tool, which is built on top of a previously existing artifact based design repository. Artifact based means that attributes (function, failure, material, etc.) are related to individual artifacts. The repository allows for an artifact hierarchy to be established by designating a parent artifact to a given artifact. The Team X hierarchy is categorized by Chairs, followed by Subsystems and then finally artifacts. In order to integrate the Team X hierarchy with the existing repository architecture, Team X Chairs, Subsystems and Artifacts were all designated as artifacts. Because of the parent/child relationship in the repository, Subsystems were populated as children of their corresponding chair. Likewise, artifacts were categorized as children of their corresponding subsystems. This enabled a Team X structure to be created within the repository without drastically altering the repository architecture.

The risk data retrieved from JPL is associated with a particular Team X Chair while Failure data exists at both the Subsystem and artifact levels. The repository already allowed for failure data to be associated with an artifact meaning that the JPL failure data could then directly be associated with their corresponding Subsystems and artifacts. In order to populate the risk elements, a risk table was added to the repository much like the existing failure table. With the risk data table in place, risk elements were populated within the appropriate Team X Chair.

A new repository interface was designed for NASA making use of URL query structures and XML data output. The generic interface allows for multiple NASA design tools to easily access the failure and risk data. Failures can be queried at the Chair, Subsystem and artifact levels. If a failure query at a Chair level is executed, all failures belonging to Subsystems and their artifacts within the specified chair are returned. Risk elements can only be queried at the chair level.

For example, a query of the ACS Chair for failures and risks would return all of the risks associated with the ACS Chair level. Failure modes are not associated with a Chair, however, the ACS Chair contains the Star Scanner Subsystem. No failure modes are denoted at the Star Scanner Subsystem levels, thus no failure modes are returned at the Subsystem level. The Star Scanner Subsystem contains 7 artifact groupings. The artifact groupings within the Star Scanner do have associated failure modes and are listed as failure modes for the Star Scanner Subsystem. Figure 5 shows a snippet of the returned risks for the ACS chair and Figure 6 shows the returned failure modes for the same chair.



You have entered:

chair: ACS

subsystem: no entry

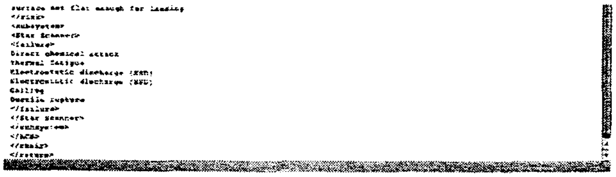
subfunction: no entry

correspondent: no entry

risk:

failure:

Figure 5. Risk query return for ACS Chair



```
surface not flat enough for landing
</risk>
<subsystem>
<Star Scanner>
<failure>
Direct chemical attack
Thermal fatigue
Electrostatic discharge (ESD)
Electrostatic discharge (ESD)
Galling
Ductile rupture
</failure>
</Star Scanner>
</subsystem>
</ACS>
</chair>
</return>
```

Figure 6. Failure query return for ACS Chair

4. CONCLUSION

It is clear from the examination of risk data in this work that there is a great amount of variation exhibited in the verbal descriptions and references to failures where these variations propagate to variations in how failures and risks are formally documented and reported. By adopting a structured functional language (the functional basis), a consistent taxonomy of failures, and inclusion of risk data (in the form of risk elements), this work demonstrates that archived failure and risk data can be stored and accessed in a manner suited for conceptual design given that both browse and search capabilities are implemented. Beyond tool development, this work shows that during conceptual design, failures are addressed at multiple levels of abstraction depending on the problem being solved. The variations found in the references to failure and risk information during conceptual design suggest that despite an existing failure taxonomy, designers could still benefit from advanced failure and risk tools for conceptual design activities. An ongoing challenge is to define a workable interface that increases designer awareness of potential failures while minimizing the workload and training curve associated with any new failure based design methods [9-10] or tools. We also hope to better characterize the ways in which failure and risk analyses impact the conceptual design process.

REFERENCES

[1] Tumer, I., Stone, R., and Bell, D., 2003, "Requirements for a Failure Mode Taxonomy for Use in Conceptual Design," *Proceedings of the International Conference on Engineering Design, ICED 2003 – paper 1612.*

[2] Uder, S., Stone, R., Tumer, I., 2004, "Failure Analysis in Subsystem Design for Space Missions," *Design Engineering Technical Conference DETC2004 DTM-57338.*

[3] Mark, G., "Extreme Collaboration," *Communications of the ACM,* **45**(6):June 2002.

[4] Meshkat, L., Cornford, S., Moran, T., 2003, "Risk Based Decision Tool for Space Exploration Missions," *American Institute of Aeronautics and Astronautics Space Conference and Exhibition, AIAA 2003-6377.*

[5] Bohm, M. and Stone, R., 2004, "Product Design Support: Exploring a Design Repository System," *ASME International Mechanical Engineering Congress IMECE 2004-61746.*

[6] Hirtz, J., Stone, R., McAdams, D., Szykman, S. and Wood, K., 2002, "A Functional Basis for Engineering Design: Reconciling and Evolving Previous Efforts," *Research in Engineering Design* 13(2):65-82.

[7] Pahl and Beitz, 1988, *Engineering Design – A Systematic Approach*, Springer.

[8] Bohm, M., Stone, R. and Szykman, S., 2005, "Enhancing Virtual Product Representations for Advanced Design Repository Systems," Journal of Computer Information Science in Engineering. [in press]

[9] Stone, R., Tumer, I., Van Wie, M., 2005, "The Function-Failure Design Method," *Journal of Mechanical Design* [in press]

[10] Tumer, I. Stone, R. 2003, "Mapping function to failure mode during component development," *Research in Engineering Design*, **14** (1):25-33.