A Team Mental Model Perspective of Pre-Quantitative Risk

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Abstract

This study was conducted to better understand how teams conceptualize risk before it can be quantified, and the processes by which a team forms a shared mental model of this pre-quantitative risk. Using an extreme case, this study analyzes seven months of team meeting transcripts, covering the entire lifetime of the team. Through an analysis of team discussions, a rich and varied structural model of risk emerges that goes significantly beyond classical representations of risk as the product of a negative consequence and a probability. In addition to those two fundamental components, the team conceptualization includes the ability to influence outcomes and probabilities, networks of goals, interaction effects, and qualitative judgments about the acceptability of risk, all affected by associated uncertainties. In moving from individual to team mental models, team members employ a number of strategies to gain group recognition of risks and to resolve or accept differences.

1. Introduction

As projects move toward developing increasingly complex, technologically advanced works and attempt to layer additional goals (e.g., green/sustainability in addition to performance, cost, and schedule) project teams must deal with ever increasing levels of risk. As a premier science and engineering organization, the US National Aeronautics and Space Administration (NASA) routinely pushes at the boundaries of technology. In doing so NASA has experienced both phenomenal success (e.g., Mars Pathfinder, Hubble Space Telescope) and catastrophic failures such as the Challenger and Columbia disasters. In-depth inquiries into past failures [5][30] identify socio-technical issues that contributed to an erroneous evaluation of risk. Two independent US government reports published in February 2010 attribute cost and schedule overruns in NASA space missions in part to mishandling risk [1][14]. Even for simple products such as beverage glasses or dog food, the systems for manufacturing, delivering, and ensuring the safety of these products are complex and susceptible to failure [28][37].

The problems we face as a society are multidisciplinary, embedded in complex social systems, and incorporate a variety of technologies. We routinely turn to teams to address these problems because the skills, knowledge and domain expertise required far exceeds the ability of an individual working alone.

Clearly, the many tools and techniques for managing risk are not sufficient because a large number of projects overrun, don't meet schedule, don't perform as expected, suffer from unexpected consequences and in extreme cases, result in catastrophic failures. The problems are not just technical, but rooted in the social structure of the decision-making and design groups [5][30].

To improve our ability to address risk effectively therefore requires a better understanding of it at the conceptual level. This research investigated how team members conceptualized risk and developed a shared mental model of risk over the lifetime of the project. The following sections integrate concepts from the risk and team mental models literature, present the case study, discuss results, and make recommendations for practice and future research.

2. Background

The most basic definition of risk is from models of economic utility, in which risk is the combination of an outcome (assigned a utility value) and the probability that this outcome will occur [9][36]. Although risk can be viewed from multiple perspectives (i.e., domains such as public health, safety, finance, engineering), it is perceived relative to some party's interests; it is not an innate environmental factor that can be studied in isolation or out of context. Human perception of risk can be influenced by emotional [18][24], cognitive [29], and attitudinal [4][21][35] factors. Common to all domains is a general assumption that risk can be managed, and that actions taken by individuals or groups can change risk.

How one addresses risk may depend on one's perspective. For example, risk can be defined in a way that is only negative (e.g., hazards, catastrophes, [27]), either positive or negative (e.g., opportunity/risk, [2]), or both positive and negative (in which one party's gain is another's loss, [3]). The kinds of parties affected by and concerned with a particular risk also differ by domain. Therefore, the language used to convey risk varies among domains, indicating that there is a broader vocabulary to risk than that available in any single domain.

Risk relative to a project team is defined here as *the combination of an outcome of interest and the uncertainty relative to that outcome occurring*. Beyond this definition, which is meant to include both risk (when the uncertain outcome is negative) and opportunity (when the uncertain outcome is positive), however, is the question of how a project team arrives at perceiving something as a risk or opportunity, and what they do about it.

The literature on team mental models (TMM) provides some insights. A team mental model is defined as *emergent characteristics that derive from the cognition of individuals but manifest as collective phenomena* [20] and as *emergent states, representing cognitive "properties of the team that are typically dynamic in nature and vary as a function of team context, inputs, processes and outcomes"* [22][25].

TMMs enable team members to interpret information, predict future events, and develop cause-effect explanations in a similar way [31]. In their comprehensive review of the TMM literature, Mohammed and colleagues state that TMMs consist of two parts: content, which refers to the "knowledge that comprises cognition" and structure, which addresses "how concepts are organized in the minds of participant" [25: p.884]. In addition, TMMs have two key properties: *similarity* – the degree to which members models are consistent or converge with one another and *accuracy* – the degree to which the TMM reflects the true state of the world [24: p. 879].

In numerous studies of what Sundstrom and colleagues would classify as "action and negotiation" teams such as military units [34], there has been a positive relationship between TMM sharedness and team performance [25]. Although project teams differ in many ways from action teams [10], the robustness of the findings suggest that TMMs could affect project team performance.

Before we can understand the effects of team mental models of risk, we first need to understand what such a model would look like. This research focuses on identifying the underlying *structure* of a team mental model of risk – specifically, what are the components of risk and how do they relate to each other. The question addressed by this research is, therefore, *How does a project team structure and develop a shared mental model of pre-quantitative risk?*

3. Method and Analysis

This research uses a qualitative method which is inherently well suited to understanding the process by which events and actions take place [23]. Among qualitative methods, the research design is based on a descriptive single case study, per [39]. A case study is appropriate because there are a large number of factors that could potentially influence the structure and content of a team mental model of risk Further, descriptive cases are appropriate for answering "how" questions, such as that posed by this study.

The case studied for this research was a new product development project at a national laboratory. The purpose of the project was to propose a mission to Mars: land a spacecraft on the north polar ice cap and deploy a probe that would perform scientific analyses as it melted through the ice [16]. During the project the team was responsible for producing a proposal that defined the concept, demonstrated feasibility, estimated the resources required to proceed to implementation, and identified and developed a plan to manage risk.

This project is relevant for the study of risk in project teams because it represents an extreme case. Extreme cases investigate a phenomenon that is potentially more acutely visible [39] because extreme situations "activate more actors and more basic mechanisms" [13: p.229]. The level of risk for this project was high, as assessed by institutional and NASA peer review processes before, during, and after the project, as well as through evaluation using literature-derived criteria for project risk [6][12][[17][32].

The project team consisted of a core team of 10-12 members from multiple science, engineering, and professional disciplines, as well as over 20 peripheral members providing expertise in a variety of scientific and technical disciplines. Team meetings were generally held twice per week with local attendees meeting in a dedicated conference room and both remote and some local members participating via teleconference. The author was an active member of the core team during the course of this study, with project-specific responsibilities.

As a full-time employee of the laboratory and member of the project team, the author collected the data for this study as a participant-observer, an approach derived from an anthropological perspective [19]. For this study, the method could more accurately be described as "observing participant" because the author's primary involvement was as a member of the team and research responsibilities during team meetings were limited to audio recording the discussion. A "collect-it-all" strategy avoided introducing collection bias [19]. The data for this study are transcripts from thirty-five meetings, totaling just under 4000 minutes (nearly 65 hours), covering a seven-month project period, and fifteen documents project documents.

Data was analyzed using a grounded theory approach, which discovers theory from data that are systematically obtained and analyzed by generating conceptual categories or their properties from evidence [15]. For this study, transcripts and documents provided the "evidence". The conceptual categories and their properties of interest were (1) the language used by individuals to convey aspects of risk and (2) the team processes employed to conceive of and manage risk.

Similar to research by Waller and colleagues [35] and Carley [7], the fundamental premise of this research is that evidence about how team members *think* about risk can be found in how they *talk* about risk. A team conceptualization of risk may therefore be inferred from explicit discussions about risk, uncertainty, or opportunity and implicit cues hinting at the presence of risk, uncertainty, or opportunity during other types of discussion. By studying the language the team used, this research seeks to expose the aspects of pre-quantitative risk that are important to team members, how teams uncover or create relationships among these aspects, and how language may change to reflect changes in the underlying conceptualization of risk.

This study was conducted at the team level of analysis, using data from team discussions, feedback provided to the team, and products produced by the team. The analysis of the data was divided into two parts: a language analysis of the words individuals spoke and a process analysis of the actions taken by the team or its members.

To analyze team language and processes, the author developed "codes" that she used to label segments of text (in documents) or discussion (in transcripts). While initial codes were derived from the literature, the majority of codes were grounded in the data. Each new code was added to a coding dictionary that included the type of code (e.g., language, process), its name, a definition, examples and a detailed description of cues used to recognize the occurrence of this code in the data. Because there was a single coder, the coding dictionary was used to maintain consistency and as a tool to validate code interpretations with key informants on the team.

To code the data, the author read through each transcript and document to manually identify instances of language, topic and process codes based on the guidelines in the coding dictionary. When a concept related to any of the categories emerged that wasn't in the coding dictionary, a new code was created, the dictionary was updated, and the data set reviewed to check for missed instances of that code. This process repeated until all data was coded for language, topic and (for transcripts only) process. A detailed description of the data analysis process is given in [11]. These three categories of codes formed the basis for further analysis investigating how language, topics, and processes evolved over the course of the project relative.

Section 4 reports the results of the analysis by describing the language components of risk. It then proceeds to identifying the general structure of "pre-quantitative risk." Finally, it proceeds to report how and why team members influenced team perceptions, leading to a team mental model of risk for this project.

4. Results

This section reports the results of the data analysis by addressing the language team members use to convey risk, the structural components of a pre-quantitative model of risk, and social processes by which team members developed a shared mental model of risk for this project.

4.1 The Language of Risk

The team's language depicted many aspects of risk as shown in Table 1. Language related to negative outcomes, uncertainty, and opportunity permeated all team discussions and incorporated terminology from multiple perspectives. Over 10,000 uses of risk-related language occurred during the 65 hours of recorded meetings. Figure 1 shows that the frequency of risk-related language use remained constant over the course of the project, with uncertainty dominating negative outcomes and opportunity.

These results show that regardless of what topic the team was discussing, thoughts related to risk surfaced in the conversation. Further, these results contradict expectations that uncertainty and risk should decrease over time. The steady use of risk-related language could mean that for this extreme case project, the amount of risk far exceeded what could be resolved in the time available. It could also mean that the team primarily chose to discuss areas they considered risky. Both of these suggest that the perception of risk influences what a team addresses as a group. Additionally, the uncertainty component of risk far exceeded the negative outcome component, suggesting that projects, perhaps particularly during early formulation phases, attend to uncertainty, which is present both with and without reference to negative outcomes.

Table 1. Aspects of Risk

Aspect	Sample Vocabulary
Negative Outcome	Concern, damage, danger, failure, threat
Risky	Aggressive, difficult, tricky, unrealistic
Uncertainty	Doubt, maybe, possibility, somehow, unknown
Likely	Likely, probably, pretty sure, confident
Reduce uncertainty	Make certain, be sure, need to know
Perceptions	Believe, feel, seem, think (conversational uncertainty cues)
Not a risk/not risky	Acceptable, comfortable, simple, not a problem
Certain	Absolutely, definitely, zero variance
Opportunity (Positive outcome)	Advantage, nirvana, perfect, success

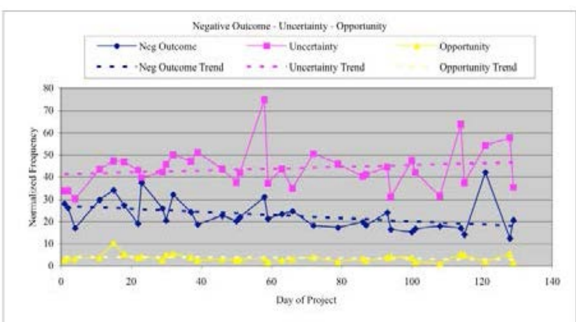

Figure 1. NUO Frequency Counts per Meeting

4.2 Structure of Risk

In forming pre-quantitative conceptualizations of risk, team members combined the classic definition of risk as discussed in the previous section: negative outcomes, opportunities, and uncertainties (represented as the likelihood of a negative outcome). Layered on top of these were two major types of interactions: among different, sometimes contradictory goals and among different elements in the system being design. Goal interactions surfaced when a proposed action to reduce risk relative to one goal, negatively impacted another. For example, during a lengthy debate regarding changing the technology that controls how the spacecraft would land on Mars, team members (TM) discussed interactions between multiple goals and technical elements of the system:

TM1: I wonder how that fits into our risk issue. Where would that put us? Greater risk to retrofit with the [technology] or not?

TM2: We discussed that and it depends on who the audience is, I think. If the audience is completely anti-O1, then probably having the [technology] on is a positive thing. If they're completely anti-risk and they believe in the O1, then we probably have to go with the O1. But I'm guessing it's somewhere in-between and we can show them that we're going to use an old technology that is proven and we know works. … and I think that ends up being a positive …

TM2: But then, there's a cost difference too. But it ends up not being such a big cost difference because there's a [test] that has to be performed.

TM3: There has to be significant cost, because the [other technology]… the [other platform] already exists

TM4: sure and you have to interface to the propulsion

TM3: so you got a new propulsion system that you have to retrofit.

TM2: But from what [a team member] says, [the engineer] had done this analysis and the interface was pretty clean, the retrofitting was minimal, structural analysis looked really good

TM4: One thing that I need to follow up on is if presents any problems to [a different subsystem], the amount of ISP, do they have to change…

In this typical exchange, team members explicitly and implicitly addressed three goals: (1) having the proposed mission selected for implementation by NASA Headquarters, (2) landing safely on Mars, and (3) minimizing cost. Also embedded in this discussion were interactions between multiple subsystems, multiple technologies, performance parameters, and the test program. Finally, in Team Member #2's first statement, she voices uncertainty in predicting how "the audience" – meaning NASA HQ will react.

Team member discussion indicated the presence of a second layer to their conception of risk based on the ability to influence outcomes, probabilities, and interactions. Typically, team members would assess an area as easier (i.e., less risky) when they felt they were able to influence the system. These statements followed a general pattern of: "*…I think [this] is easier because all we have to do is…*" The team member would then proceed to outline an approach that would reduce risk. Team members also explicitly stated a cause-effect relationship between being able to influence a problem and a perception of reduced risk, as shown in this statement from a scientist:

My feeling is that ***this is a solvable problem, if and when we do discover that it is a problem****. ... we don't want to solve problems we don't know we have yet.*

Throughout the project, riskiness wasn't calculated, but rather qualitatively assessed based on the degree of control the team felt it had for a given risk relative to the full set of goals, the interactions between system elements, and the degree of uncertainty surrounding the issue. The pre-quantitative conceptualization of risk incorporated judgments assessing the acceptability of aggregated relative levels of risk. Team members continually made judgments whether a proposed approach resulted in more or less risk, without actually quantifying either option. Risks were aggregated not mathematically, but instead by qualitative assessment relative to a perceived target. Team member perceptions of risk were highest when they were least able to impact risk, i.e., when there was high uncertainty (e.g., unknown unknowns) or when many potential risks stacked up or were linked together.

For example, extremely late in the project, the scientists determined that the design did not adequately address an important measurement. In fact, this measurement was judged to be the highest priority and had a cascading effect on multiple design decisions that were made based on a now obsolete prioritization. The team dedicated an entire meeting to debating whether to change the design, and hence the entire proposal. Team members enumerated significant risks to multiple goals, and finally decided by unanimous vote to make the change. At the next team meeting, the Project Manager summed up the following in his status report:

OK, I talked earlier about the fact that we're going to replace the [old laser technology] in the [instrument] with the [new laser technology] which is riskier because it doesn't exist yet. It's under development and that's the reason [the scientists] went to the other laser. But based upon the science meeting they had yesterday, this laser provides additional science and they felt it made a lot of sense to switch to it. ... There shouldn't be any cost impact. There's just a little bit more risk and they're going to address the risk perspective from the point of view that if this is not available, then we're just going to pull back to the previous laser which exists.

The scientists made a judgment call that the extra risk associated with the new technology was acceptable, and that they could mitigate this risk by using the old technology as a backup plan. The project manager accepted that assessment and began efforts to minimize the risk to his deliverable (the proposal) to reflect this significant change.

The structural elements of pre-quantitative risk, as shown in Figure 2, were evident throughout the entire project. At the heart of the conceptualization of risk were negative outcomes and their likelihoods. These traditional elements of quantitative risk were not explicitly quantified, but were influenced by interactions between goals and among system elements. Layered on top of this was the team's perceived ability to influence the preceding items. And further layered on top of all that was uncertainty in many different forms. Finally, all these factors contributed to team judgments regarding the acceptability of risk. These judgments then influenced the team's actions and contributed to an evolving model of risk for this project, as described in the next section.

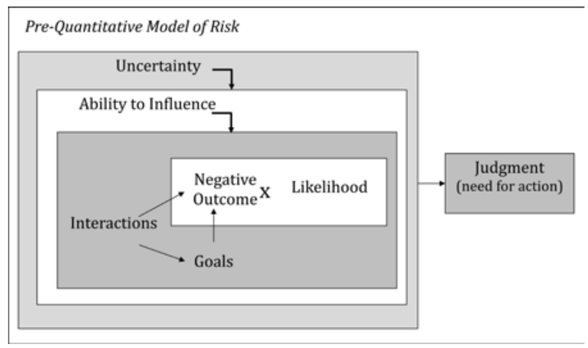

Figure 2. Structure of a Pre-Quantitative Model of Risk

4.3 Evolving Model of Risk

The project team used a variety of strategies to address risk throughout the project lifecycle. These strategies helped the team to conceive and manage risk, for example by resolving uncertainty or focusing the team's attention. The strategies fell into five major categories of actions: (1) engage the team in discussion about the risk; (2) gain a better sense of the factors contributing to negative outcomes, uncertainty, or opportunity, relationships among factors, and the type and significance of consequences; (3) focus the attention of the team to specific risks; (4) resolve uncertainty; and (5) reduce or eliminate risk, mitigate the impact of a risk occurring, or otherwise control risk.

Team members routinely shared their individual perceptions of risk. Beyond simply raising an issue, team members sought to engage teammates in discussion about their concerns. They used techniques that explicitly sought team member feedback (e.g., floating an idea, polling team members for their opinions, challenging team members to find flaws in a design), or invoked the authority or reputation of another person to give their arguments greater credibility, for example:

> *"The more I look at this, I'm ... more concern[ed] that the science is compromised ... and* **a lot of team members** *have expressed concern about that."*

The large number of topics, overall complexity of the product, and the variety of organizational stakeholders meant that team members had a huge number of areas demanding attention at any given time. Both internal and external distractions threatened the ability of the team to complete the project on time. Focusing strategies helped the team put its attention where it was most needed. The focusing strategies at the team level served to move team member attention from external projects to this one, and to select specific areas within this project for concentrated team effort. Focusing strategies at the individual level served to bring risks perceived by an individual to the attention of the team.

To focus attention, team members would ask to have an issue placed on the Project Manager's action item list, so it would be tracked and addressed at each meeting. Team members sparingly, but effectively, used colorful and exaggerated language to grab team attention. When an issue was important, but did not need to be addressed by the whole team, it was often "taken off line" where an individual team member was given responsibility for addressing the issue and reporting back to the team on progress. Finally, if gaining attention was particularly challenging and the member felt strongly enough, he would engage in "persisting." One such example occurred over a two month period, spanning multiple team meetings:

An exploratory discussion on cost estimating triggered a scientist to identify problems related to data processing: the team as a whole failed to account for data processing costs, and failed to create a design that could accommodate the data processing needs for his instrument. After discussion of these problems, the team moved on to other topics. Later in that meeting, the scientist interrupted a discussion about general handling of science data to once again raise the data processing issue. He proceeded to summarize the various options for implementing data processing, and noted that none of the options addressed his "fairly simple but nevertheless essential data processing" requirement. After additional discussion, the issue raised by scientist remained unresolved and the team meeting closed without further mention of this issue.

Six meetings and about three weeks later, the scientist took advantage of a lull in a conversation on another topic to again raise the data processing risk. The team entered into a discussion in which team members suggested different approaches for meeting his unique data processing requirements. Numerous ideas were introduced, but there was no resolution of the specific risk that the scientist had identified. All agreed to continue the discussion outside the meeting, but fell back into discussing details. The instrument lead developer stated his plan for how to remove the risk. The data processing issue ultimately got assigned as an Action Item that the proposal manager tracked.

Nine team meetings and over a month later, the proposal manager asked for status of the data processing issue. The scientist once again expressed concern. The project manager responded by reassuring the scientist that the risk he perceived would be addressed and took an action to follow up with the Deputy PI. The topic did not arise again in subsequent team meetings, but the next draft of the proposal included a statement about how the scientist's data would be processed, and that the appropriate costs were included.

Strategies to facilitate understanding were used to make sense of complex interactions and conflicting information, and to develop a deeper understanding of the risks and uncertainties associated with a given area. These strategies helped the team to develop a richer, shared conception of risk by integrating multiple perspectives and a variety of information and providing a reference framework for future discussions.

Three of the most widely used facilitation strategies involved presenting complex information in ways that enabled team members to quickly and easily grasp meaning and significance. These strategies provided a way for a team member to translate their knowledge and experience into a form that facilitated sharing with their teammates and included telling stories, creating analogies, and developing scenarios.

Team members also reframed their ideas to present risks in new ways. One such reframing occurred during a discussion on how to remove contaminants from the robotic probe to meet planetary protection requirements. The probe engineer voiced a concern that components inside the probe would not withstand the high temperatures used for sterilization. Another team member provided specific examples. The risk, as presented, was a "sterilization" problem in which "doing a high temperature bake...is going to kill us." A third team member, however, presented a different interpretation: "this is really an assembly problem – whatever is in the pressure vessel does not need sterilization." He *reframed* the problem based on his understanding of the system implementation, retiring the sterilization risk, but raising others.

Uncertainty permeated all aspects of the project, requiring the team to deal with multiple sources and types of uncertainty throughout the entire lifecycle. The team employed multiple strategies for resolving and working under conditions of uncertainty, which included retrieving information from external sources, working through issues using the whiteboard for sketching or flow-charting, conducting tests or experiments, making simplifying assumptions (which didn't resolve uncertainty, but made it manageable), and "deciding for now" when the team did not have the time or enough information to make a needed decision.

The final strategies were used to modify risk. One approach to modifying risk was to trade risk among different areas. Because they were satisfying multiple goals, the team members could sometimes trade a little risk in one are to gain a significant risk reduction in another, as in this example of a scientist assessing risk relating to a science experiment:

> *The science community will tend to say, "You're going through all this trouble with this experiment and you're not going to do high resolution sampling? You must be nuts!" Versus the engineering community who is going to say "oh my god look at all this risk [for making the probe more complicated]" So we have to balance...the science team...understands the risk posture but they say, "the reviewers are really going to criticize us for not having the vertical resolution." ... from the feedback we've gotten so far, the science in this is such a knockout that we could afford to have a few problems. We're balancing science against risk.*

Other strategies to modify risk included applying operational or physical constraints, introducing a backup plan in the event a risk was realized, and deferring decisions until conditions were more favorable to resolving risk.

4.4 Summary

The team's conceptualization of risk was rich and multi-faceted, flowing into a structure that significantly extended traditional models of risk. The team built a shared mental model of risk through team interactions, incorporating and actively manipulating the different elements in an attempt to reduce the risk of the overall project. While never explicitly referencing a Team Mental Model of risk for the project, team members did, however, actively work to bring their individual perceptions to the attention of the team, influence team processes to modify risk and uncertainty, and act in concert to articulate a design and document that reflected their actions relative to risk. The contributions of these results and their implications for practice and future research are addressed in the next section.

5. Discussion

The primary contribution of this research is the construct of *pre-quantitative* risk, with a structure as shown in Figure 2. Pre-quantitative risk extends traditional concepts of risk as a negative outcome and likelihood [2][38] to incorporate factors that significantly impacted team behavior in this study, specifically: goal and system interactions, ability to influence, multi-dimensional uncertainty, and the

Table 2. Comparison of Quantitative and Pre-Quantitative Conceptualizations of Risk

Element	Quantitative	Pre-Quantitative
Outcomes	Specific negative outcomes, typically measured as cost. May also represent positive risk, but not commonly used. e.g., tornado damages building, cost $2.1 million	Either specific outcomes or general outcomes such as "concern" or "issue." Outcomes are primarily negative, but may also be positive (opportunities) e.g., worried that the power supply may fail
Uncertainty	Multiple individual sources and types of uncertainty condensed into a single numerical probability, e.g. 0.56	Multiple individual sources and types of uncertainty aggregated to provide qualitative assessments of probability in the form of likelihoods, e.g., "could happen" or unknowns, e.g., "I just don't know"
Utility	Arithmetic function of outcome value and uncertainty e.g., $2.1 million x 0.63	Qualitative assessment relative to yardsticks for cost (risk) and value (opportunity) e.g., "that's a big increase in cost for not much gain in science"
Aggregating risks	Arithmetic combination of individual utilities, possibly weighted e.g., U(a) + U(b)	Qualitative judgment based on "stacks" of risk and "links" indicating interactions, e.g., five stacked contributors to power system risk, linked to four other parts of the project
Judgment	Based on numerical values e.g., EU(a) > EU (b)	Based on qualitative assessment relative to thresholds and balancing overall risk, e.g., the extra science value isn't worth the risk
Influencing factors	Risk factors and other characteristics of the project or product that indicate higher risk by their mere presence e.g., increase probability of failure to 0.63 due to large number of interactions	• Ability to influence • Interactions among goals and risks e.g., "we could ask the engineer to develop a back-up supply"

application of judgments of aggregated risk. This research showed that a team operating in an environment of significant risk and uncertainty operated almost entirely without the need to quantify risks. Actions were taken, decisions made, systems designed based on qualitative assessments of *relative* risk and uncertainty.

In general, this research suggests that for certain classes of projects, at significant points in their lifecycle, risk and uncertainty don't need to be measured; it is enough for the team to know if risk or uncertainty was increasing or decreasing. Table 2 compares quantitative and pre-quantitative conceptualizations of risk. The differences suggest that research on risk in project teams needs to expand to investigate how to make product and project interdependencies explicit, how to better identify and characterize unknowns, and how to improve judgments based on relative assessments of risk.

The pre-quantitative conceptualization of risk has profound implications for both practice and research. First, this research challenges risk management practices that attempt to prematurely quantify risks. For example, projects often are required to convert their risks to quantized elements on a matrix representing probability and impact, commonly referred to as 5x5 risk matrices [8][26]. Teams expend significant effort estimating probabilities and assigning consequence levels when they naturally confound those and other concepts into a single qualitative assessment of overall riskiness. The process of converting their natural mental model structure to this matrix representation essentially requires teams to convolve a multi-factor pre-quantitative conception into a simplistic 2-factor measurement. In doing so, teams often subvert the process by determining the placement first and then assigning values to the factors to ensure correct placement.

Second, this research suggests that the squares in the 5x5 risk matrix may be more effectively replaced with bands associated with the matrix's red-yellow-green color coding. These bands can represent the team's assessment of overall riskiness in steps progressing from acceptable to too-risky. Further, the dynamic nature of risk can be captured in a meaningful way in terms of how vulnerable a particular risk is to changing to a different band. In essence, teams could record their simple assessment of risk rather than their attempts to select a combination of numbers in a way that produces the desired assessment. By simplifying the overall representation, teams and their organizations can then focus on the most critical aspects of those risks.

The 5x5 risk matrix is one of many risk management tools used by projects. Even projects that are mandated to use current risk management tools, however, experience significant problems [1][14]. This research suggests that one possible reason is the mismatch between how tools represent risk and how team members think about it. The previous discussion suggests one way in which a risk management tool can be modified to make it more user-natural. Areas ripe for both future research and practice are creating new and modifying existing tools to leverage the more natural pre-quantitative model of risk.

This research does *not* suggest that projects should abandon *all* efforts to quantify risk. Instead, it suggests that quantification may be over-used and counter-productive when assessments of risk are based on *judgments.* When assessments of risk can be based solely on measurable, physical characteristics, then it is appropriate to use of quantitative techniques such as probabilistic risk assessments and reliability analyses. Further, the results of these quantitative analyses can become important components of larger, pre-quantitative assessments because they have the potential to significantly reduce different types of uncertainty. Monte Carlo simulations, for example, can reduce uncertainty about probability distributions while failure modes and effects analysis can reduce uncertainty about low level system interactions.

This research investigated how one project team conceived of and managed risk on a project considered high risk. There are two major dimensions that affect the generalizability of this study: project phase and product characteristics. The project was in an early formulation phase during this study (it was not selected to proceed into implementation). Early formulation phases often experience changes to requirements and other sources of uncertainty that occur much less often in later phases. This level of uncertainty contributed to the overall risk of the project, but also provided the flexibility needed for the project to respond to opportunities. One avenue for future research is therefore to assess the impact of project phase on conceiving and managing risk.

Product characteristics can vary greatly from project to project. Rather than make comparisons based on the specifics of this project (a project to melt a robot through the polar ice cap of another planet would be considered unique by almost all standards), the author used prior research to establish a standard basis of comparison. This basis of comparison used literature-defined characteristics of "risky" projects, which in turn were based on characteristics of the product. Using this standard, the results of this research should inform similar projects, i.e., those that exhibit some or all of the following characteristics: high cost, low product volume, high degree of technological novelty, large number of subsystems and components, high degree of customization, complex system architecture, multiple design paths, feedback loops from later to earlier stages, a variety of distinct knowledge bases and skill of engineering inputs, intensity of user involvement, uncertainty in user requirements, or intensity of other supplier involvement [12][17][33]. There is a high probability of generalizing the results of this research to projects that have characteristics similar to this case study project [39].

Most projects, however, are not as extreme the project studied here. Therefore, a fundamental question for future research is "how well do the results presented here apply to other types of projects?" Do projects at the other extreme (low risk) address risk in a similar way as this team? Similarly, do the results apply to projects at later stages of development?

6. Conclusion

Our ability to understand and manage risk is critical as we face a future with significantly greater social, technical, financial, and environmental challenges. This study investigated how a team, operating under conditions of high risk and uncertainty, *thought* about risk, with the hope that improved understanding of a real-world conceptualization of risk would lead to insights on how to improve our abilities to address risk. Results indicated a rich and varied structural model of risk that goes significantly beyond classical representations to include the ability to influence outcomes and probabilities, networks of goals, interaction effects, and qualitative judgments about the acceptability of risk, all affected by associated uncertainties.

7. Acknowledgements

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8. References

[1] Barley, B., Gilbert, P. and Newhouse, M. "Improving the Life Cycle Cost Management of Planetary Missions: Results from the Life Cycle Cost Growth Study performed by the Discovery and New Frontiers Program Office at NASA Marshall Space Flight Center." 2010. On line at http://discovery.larc.nasa.gov/PDF_FILES/33LifeCycleCostStudyReport-Final.pdf Accessed 15 June 2005.

[2] Bernstein, P. L. *Against the Gods: The Remarkable Story of Risk.* New York: John Wiley & Sons, 1996.

[3] Bloom, M. & Milkovich, G. T. "Relationships among risk, incentive pay, and organizational performance" *Academy of Management Journal, 41*(3), 1998, 283-297.

[4] Bromily, P. & Curley, S. P. "Individual differences in risk taking." In J. F. Yates (Editor), *Risk- Taking Behavior*. NY: John Wiley & Sons, 1992, 87-132.

[5] CAIB, "Columbia Accident Investigation Board Report," Volume 1, August 2003. http://caib.nasa.gov/news/report/volume1/default.html Accessed 15 June 2010.

[6] Cardinal, L. B. & Lei, D. "Structuring research and development teams in the technological conversion process." In M. M. Beyerlein, D. A. Johnson & S. T. Beyerlein (Editors), *Team Performance Management (Vol. 6)*, Stamford, CT: JAI Press, 2000, pp. 31-62.

[7] Carley, K.M. "Extracting team mental models through textual analysis." *Journal of Organizational Behavior, 18,* 1997, 533-559.

[8] Chapman, C. B. & Ward, S. *Project Risk Management: Processes, Techniques, and Insights.* Chichester, NY: Wiley, 1997.

[9] Clemen, R. T. *Making Hard Decisions: An Introduction to Decision Analysis, 2nd Edition*. New York: Duxbury Press, 1996.

[10] Cohen, S. G. & Bailey, D. E. "What makes teams work: Group effectiveness research from the shop floor to the executive suite." *Journal of Management, 23*(3), 1997, 239-290.

[11] Cooper, L.P., (2008). *How project teams conceive of and manage pre-quantitative risk.* Dissertation. http://digitallibrary.usc.edu/search/controller/view/usctheses-m1448.html. Accessed 14 Sept 2010.

[12] Dvir, D., Lipovetsky, S., Shenhar, A. & Tishler, A. "In search of project classification: A non-universal approach to project success factors." *Research Policy, 27,* 1998, 915-935.

[13] Flyvbvjerg, B. "Five misunderstandings about case-study research." *Qualitative Inquiry, 12(*2), 2006, 219-245.

[14] GAO. "NASA: Assessments of Selected Large-Scale Projects. US Government Accountability Office Report to Congressional Committees." 2010. On line at http://www.gao.gov/products/GAO-10-227SP Accessed 15 June 2010.

[15] Glaser, B. G. & Strauss, A.L. *The Discovery of Grounded Theory: Strategies for Qualitative Research*. NY: Aldine de Gruyer, 1967.

[16] Hecht, M.H. & Saunders, R.S. "CryoScout: A descent through the Mars polar cap." Presented at the 3rd International conference on Mars Polar Science and Exploration, Alberta, Canada, October 13-17, 2003.

[17] Hobday, M. "Product complexity, innovation and industrial organisation." *Research Policy, 26(*6), 1998, 689-710.

[18] Jasanoff, S. "The political science of risk perception." *Reliability Engineering and System Safety, 59*, 1998, 91-99.

[19] Jorgensen, D. L. *Participant Observation: A Methodology for Human Studies*. Newbury Park, CA: Sage; 1989. (Applied Social Research Methods Series; 15).

[20] Kozlowski, S.W.J. and Klein, K.J. "A multilevel approach to theory and research in organizations: Contextual, temporal, and emergent processes." In K.J. Klein & S.W.J. Kozlowski (Eds.), *Multilevel theory, research, and methods in organizations: Foundations, extensions and new directions.* San Franscisco: Jossey-Bass, 2000, 3-90.

[21] Lee, D. Y. "The impact of poor performance on risk-taking attitudes: A longitudinal study with a PLS causal modeling approach." *Decision Sciences, 28*(1), 1997, 59-80.

[22] Marks, M.A., Mathieu, J.E., and Zaccaro, S.J. "A conceptual framework and taxonomy of team processes." *Academy of Management Review, 26*, 2001, 356-376.

[23] Maxwell, J. A. *Qualitative Research Design: An Interactive Approach*. Thousand Oaks, CA: Sage; 1996. (Applied Social Research Methods Series; 41).

[24] McDaniels, T. L. "Ten propositions for untangling descriptive and prescriptive lessons in risk perception findings." *Reliability Engineering and System Safety, 59*, 1998, 129-134.

[25] Mohammed, S., Ferzandi, L., and Hamilton, K. "Metaphor no more: A 15-year review of the team mental model construct." *Journal of Management, 36*, 2010, 876-910.

[26] NASA. "NASA Procedural Requirements: Risk Management Procedures and Guidelines," NPR 8000.4. National Aeronautics and Space Agency, Office of Safety and Mission Assurance, 2002.

[27] NRC: National Research Council. *Improving Risk Communication*. Washington, DC: National Academy Press, 1989.

[28] Pritchard, J. McDonald's pulls 12 million cadmium-tainted Shrek glasses. USA Today Online. 2010, http://www.usatoday.com/money/industries/food/2010-06-04-mcdonalds-recall-shrek_N.htm Accessed 15 June 2010.

[29] Roberts, K. H. & Rousseau, D. M. "Research in nearly failure-free, high-reliability organizations: Having the bubble." *IEEE Transactions on Engineering Management*, *36*(2), 1989, 132-139.

[30] Rogers, W.P. "Report of the Presidential Commission on the Space Shuttle Challenger Accident" (commonly called the Rogers Commission Report). 1986. Accessed 15 June 2010. http://history.nasa.gov/rogersrep/51lcover.htm

[31] Rouse, W.B., Cannon-Bowers, J.A., and Salas, E. "The role of mental models in team performance in complex systems." *IEEE Transactions on Systems, Man & Cybernetics, 22*, 1992, 1296-1308.

[32] Shapira, Z. B. & Berndt, D. J. "Managing grand scale construction projects: A risk-taking perspective." In L. L. Cummings & B. M. Staw (Editors), *Research in Organizational Behavior, Vol. 19.* Stamford, CT: JAI Press, 1997, pp. 303-360.

[33] Shenhar, A. J. "From Theory to Practice: Toward a Typology of Project- Management Styles*." IEEE Transactions on Engineering Management, 45*(1), 1998, 33-48.

[34] Sundstrom E., DeMeuse K.P., & Futrell D. "Work teams: Applications and effectiveness." *American Psychologist, 45*, 1990, 120-133.

[35] Waller, M.J., Gupta, N. and Giambatista, R.C. "Effects of adaptive behaviors and shared mental modls on control crew performance." *Management Science, 50*, 2004, 1534-1544.

[36] Wärneryd, K.-E. "Risk attitudes and risky behavior." *Journal of Economic Psychology, 17*, 1996, 749-770.

[37] Weise, E. and Schmit, J. (2007). Pet food may have killed scores more. USA Today online. 2007. http://www.usatoday.com/news/health/2007-03-25-pet-food-scare_N.htm?csp=34 Accessed 15 June 2010.

[38] Yates, J. F., & Stone, E. R. "The risk construct." In J. F. Yates (Editor), *Risk-Taking Behavior*. NY: John Wiley & Sons, 1992, pp. 1-25.

[39] Yin, R. K. *Case Study Research: Design and Methods*. 2nd ed. Newbury Park: Sage, 1994.