Presented at the 2010 ISPA/SCEA Joint Annual Conference and Training Workshop - www.iceaaonline.com

Risk Identification and Visualization in a Concurrent Engineering Team Environment

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Abstract

Incorporating risk assessment into the dynamic environment of a concurrent engineering team requires rapid response and adaptation. Generating consistent risk lists with inputs from all the relevant subsystems and presenting the results clearly to the stakeholders in a concurrent engineering environment is difficult because of the speed with which decisions are made. In this paper we describe the various approaches and techniques that have been explored for the point designs of JPL's Team X and the Trade Space Studies of the Rapid Mission Architecture Team. The paper will also focus on the issues of the misuse of categorical and ordinal data that keep arising within current engineering risk approaches and also in the applied risk literature.

Section 1: Background -Concurrent Engineering Teams at JPL

The Jet Propulsion Laboratory (JPL) is NASA's prime center for deep space missions. In response to the need to reduce the cost and time to complete early concept studies and proposals, JPL created the first concurrent engineering team in the aerospace industry: Team X. Started in 1995, Team X has carried out close to 1000 studies, dramatically reducing the time and cost involved compared to prior conceptual studies, and has been the model for other concurrent engineering teams both within NASA and throughout the larger aerospace community. The success of Team X has also spawned new related JPL teams such as the Rapid Mission Architecture (RMA) Team for trade studies.

At JPL, the Team X and RMA concurrent engineering teams work in the early parts of the lifecycle as shown in Figure 1. As a large proportion of project resources are committed in early in the project lifecycle, one of the primary challenges in engineering system design is making decisions in the concept exploration phase that will result in designs that are viable throughout the operational lifetime of the system. A concurrent engineering team consists of diverse specialists working simultaneously, in the same place, with shared data, to yield an integrated design or designs.

In a typical Team X study, a team of up to 20 subsystem chairs generates one or two point designs over three sessions, with additional supporting work often done outside of the sessions. Team X has a standard set of tools, and all key study data is passed through an integrated database. Not all chairs are required for every study. In a typical Team X design study there are 15 chairs, with a minimum of 8 for small partial studies. Examples of Team subsystems include Structures, Flight Software, Mission Design, and Instruments. The Risk chair is an optional chair in Team X and only participates in approximately one-third of the studies, in response to a request from the customer. In Team X, the subsystem chairs work in a room arrangement similar to an operations center setting, to enable ease of communication between chairs during the study. For a more detailed discussion of Team X and its tools, see [i] and [ii].

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[1] The research described in this presentation was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not constitute or imply its endorsement by the United States Government

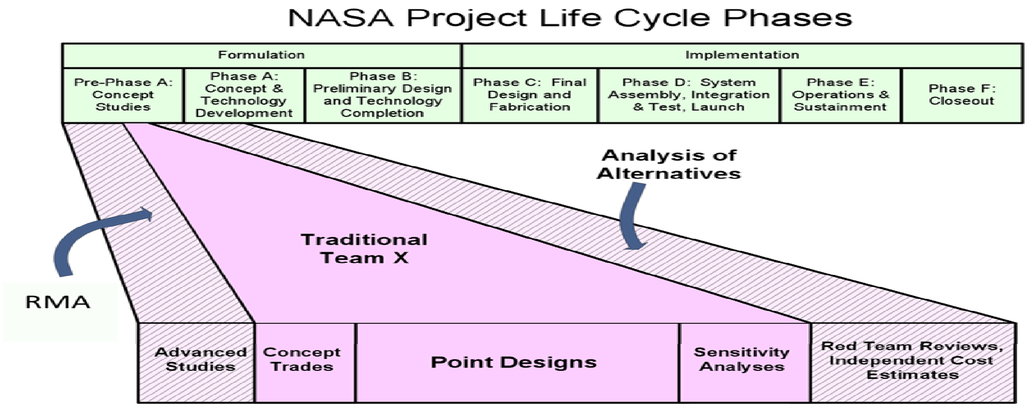


Figure 1: Concurrent Engineering Teams and the NASA Lifecycle

While there are similarities with Team X, RMA is a very different type of concurrent engineering team. In contrast to Team X, which produces one or two fairly detailed point designs, an RMA study will generate 10 to 20 mission architectures that vary widely from flybys with only a few instruments, to very large multi-element missions costing billions of dollars. A typical RMA study takes approximately 9 sessions over 3 or more weeks, with a large portion of the study analysis being done outside the sessions. The focus of an RMA study is on understanding the feasibility of a mission and its potential to extend the scientific knowledge of our solar system, and then comparing on a relative basis the science value, cost and risks of a variety of potential architectures for the mission. RMA has approximately 10 engineering team members, mostly in system engineering roles, but also includes a science panel as part of the study team.

Unlike the current process in Team X, a Risk engineer is a required member of the team for all RMA studies. In addition, a Science Value Matrix (SVM) is an integral part of the comparative assessment of architectures in RMA. In the SVM, the architectures under consideration are assigned relative science merit by the RMA science team for each science objective. The lead of the science panel has primary responsibility for the SVM but incorporates inputs from the other members of the science panel, the mission architect and the RMA science/payload chair. There are currently no standardized integrated tools for RMA, though there are several independently developed stand-alone tools that have been utilized for analysis.

As described above, these two teams are different in various ways. RMA does not have standard tools or configuration, as does Team X. RMA is organized brainstorming that aims to find multiple options for what may potentially be done for a particular science mission, while Team X involves taking a specific mission architecture and determining whether it can be realistically carried out. RMA is primarily a systems engineering team while Team X utilizes engineers across all the mission disciplines. Given the differences in the teams and the types of studies they perform it is not surprising that risk identification and analysis is performed in each team also differs.

Section 2: Risk Identification and Analysis in JPL Concurrent Engineering Teams

Section 2.1: Team X Risk Methodology

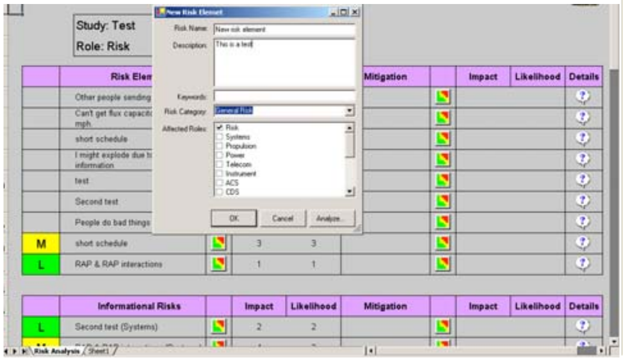
Risk is a relatively new capability on Team X, introduced in 2001. The chair was created because concurrent engineering teams often face tremendous pressure from the principle investigators and proposal managers to be optimistic with the cost estimate and with timing of emerging technologies, and the concerns of the engineering team in relation to mission, schedule or cost risks needed to be captured in a systematic way. Prior to the addition of the Risk Chair to Team X, the subsystem chairs would identify their issues and concerns at the end or buried in the sub-context of their section of the study reports. Unfortunately this made it easy for the customer and proposal teams to sweep risks under the proverbial rug. Until as recently as two years ago, the risk report was still delivered as a separate product and not included in the official study report so that only the customer saw the results. In most cases the main objective when identifying risks is to provide input to the proposal team regarding areas they need to address carefully in the proposal, or to the concept design team identifying areas for further study as the project moves forward.

The risk focus in Team X is not on risk management but rather on risk identification and initial assessment. There is no analysis using fault/event trees or other formal methods. There is little quantitative data that is accessible during a study to provide a basis for risk estimates. Generating consistent risk lists with inputs from all the relevant subsystems and presenting the results clearly to the stakeholders is difficult because of the speed with which decisions are made and the semi-organized chaotic environment of Team X. Often things are moving so fast that it is not possible to formally review the risks for each option as the study progresses, but only at the very end of the study. If a serious risk is identified during a session it is brought up to the customer in a side bar in case they wish to make any changes to the design requirements. In addition, mitigations are recorded for risks, especially those risks that appear significant.

The current risk tool used in Team X is the Risk & Rationale Assessment Program (RAP). The design and original use of the RAP tool is described in detail in [ii]. The use of the RAP tool has changed over time but the core process for its use has been stable since its inception.

The key features of the tool are

- All chairs can enter and score a risk (see Figure 2a)
- All risks are scored using the NASA 5x5 Matrix (see Figure 2b)
- All chairs notify all other chairs that may be affected by the risk so that they can also score the risk
- All affected chairs are notified if any change is made
- The Risk Chair determines the final wording and scoring of all mission level risks and presents the results to the customer and the team, usually near the end of the last session
- All final scores and descriptions at the mission and subsystem levels are archived in a database

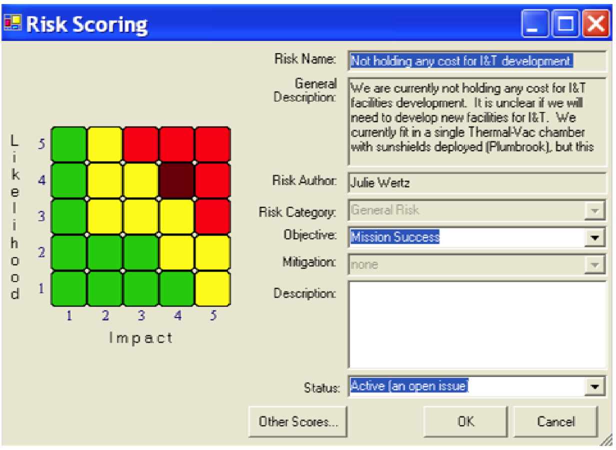

Study: Test
Role: Risk

New Risk Element
Risk Name: New risk element
Description: This is a test
Keywords:
Risk Category: General Risk
Affected Roles: ☑ Risk ☐ Systems ☐ Propulsion ☐ Power ☐ Telecom ☐ Instrument ☐ ACS ☐ CDS

	Risk Elem				Mitigation		Impact	Likelihood	Details
	Other people sending								
	Can't get flux capacit mph								
	short schedule								
	I might explode due t information								
	test								
	Second test								
	People do bad things								
M	short schedule		3	3					
L	RAP & RAP interactions		1	1					

	Informational Risks		Impact	Likelihood	Mitigation		Impact	Likelihood	Details
L	Second test (Systems)		2	2					

Figure 2a: RAP Risk Input Form



Risk Name: Not holding any cost for I&T development

General Description: We are currently not holding any cost for I&T facilities development. It is unclear if we will need to develop new facilities for I&T. We currently fit in a single Thermal-Vac chamber with sunshields deployed (Plumbrook), but this

Risk Author: Julie Wertz

Risk Category: General Risk

Objective: Mission Success

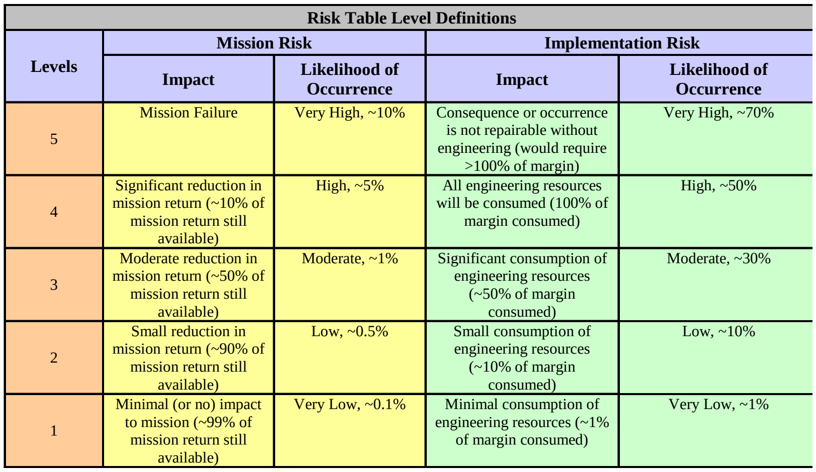
Mitigation: none

Description:

Status: Active (an open issue)

Figure 2b: RAP Risk Scoring Form

The guidance that was used in scoring risks until recently is shown Table 1. The boundary values appear to have been originally recommended by Futron based on an analysis they did for NASA, in the context of manned missions [iii].



Risk Table Level Definitions

Levels	Mission Risk		Implementation Risk	
	Impact	Likelihood of Occurrence	Impact	Likelihood of Occurrence
5	Mission Failure	Very High, ~10%	Consequence or occurrence is not repairable without engineering (would require >100% of margin)	Very High, ~70%
4	Significant reduction in mission return (~10% of mission return still available)	High, ~5%	All engineering resources will be consumed (100% of margin consumed)	High, ~50%
3	Moderate reduction in mission return (~50% of mission return still available)	Moderate, ~1%	Significant consumption of engineering resources (~50% of margin consumed)	Moderate, ~30%
2	Small reduction in mission return (~90% of mission return still available)	Low, ~0.5%	Small consumption of engineering resources (~10% of margin consumed)	Low, ~10%
1	Minimal (or no) impact to mission (~99% of mission return still available)	Very Low, ~0.1%	Minimal consumption of engineering resources (~1% of margin consumed)	Very Low, ~1%

Table 1: Impact and Likelihood Thresholds Used in Risk Scoring

Section 2.2: RMA Risk Methodology

Along with cost and performance, risk is an important basis for comparison between architectures in conceptual design tradespace exploration. Systematic risk identification and assessment is thus a key aspect of the RMA process in which several architectures are assessed and compared. The identification of the driving or high risks in RMA also allows the design team to make early architectural decisions to mitigate those risks.

The risk identification and assessment method employed in Team X, as described in Section 2.1, was used as the initial basis for development of the risk methodology originally used in RMA. The risk definitions used in the initial risk approach were the same as those used in Team X, and are shown in Table 1. However, due to the lack of specific subsystem chairs and limited in-session work, the RAP tool was not used in the identification and initial scoring of risks. Risks are identified by the Systems Engineering Risk Lead as well as the RMA and science team members. However, the Risk Lead is the primary scorer of all risks with assistance from the mission architect. These risks are defined as either mission risks – risks that involve negative events that occur during operations, resulting in loss of mission data – or implementation risks – risks that involve negative events that occur before operations, resulting in expenditure of mission margin in the form of either budget or schedule. In Team X, a single point design is assessed at a time, while in RMA, there are usually several (as many as 10-20) architectures selected for concurrent assessment. Thus an important aspect of the risk capture was to assign the identified risks to the appropriate architectures. Scoring of the impact and likelihood of occurrence of these risks also varied by architecture. Scoring of mission and implementation risks were done using team inputs on risk 5x5 fever charts, and risks were often found to have varying impacts and likelihoods for different architectures.

For ease of comparison between architectures, it was necessary to have a risk metric that would produce a single risk value for mission risks and implementation risks for each architecture. The need to aggregate risks was a new requirement that did not arise in Team X, which only considered one mission at a time. The initial approach used in RMA assumed that the numerical values in the 5x5 matrix could be treated as real numbers. Then making the simplifying assumption that all of the identified mission risks were independent, the expected value of the science loss if a mission risk occurred could be calculated for each architecture. Implementation risks were again assumed independent, and impact was scored in terms of percentage of resource contingency consumed. The likelihood scores for the implementation risks were then used to calculate the probability of exceeding the resource contingency. The percentage science loss and the probability of exceeding resources were then used to rank order the different architecture options in the tradespace according to risk. The numerous issues associated with this initial approach are discussed in Section 3.

Section 3: Risk Identification and Assessment Process Issues and Resolution

Over the many risk assessments done in Team X and several RMA studies, a number of key process issues have been identified that influence the identification, scoring and aggregation of risks.

Section 3.1: Risk Identification Issues

Risks in both Team X and RMA can be identified by all members of the study team and clarified through discussions among the team members. This is a useful method when the team members are highly experienced designers who have sufficient time during the design sessions to devote to thinking about risk. Unfortunately, this is not always the case, contributing to an inability to maintain consistency and completeness in the risk assessments for different studies. Though the design team is capable of generating many risks based on their expertise and prior experience, there is a currently a lack of ability to systematically leverage risk information from previous missions. This disparity between studies became apparent when a number of Team X and RMA study results had the potential of being compared against each other, and corrective measures had to be taken to maintain consistency in risk assessment between the studies.

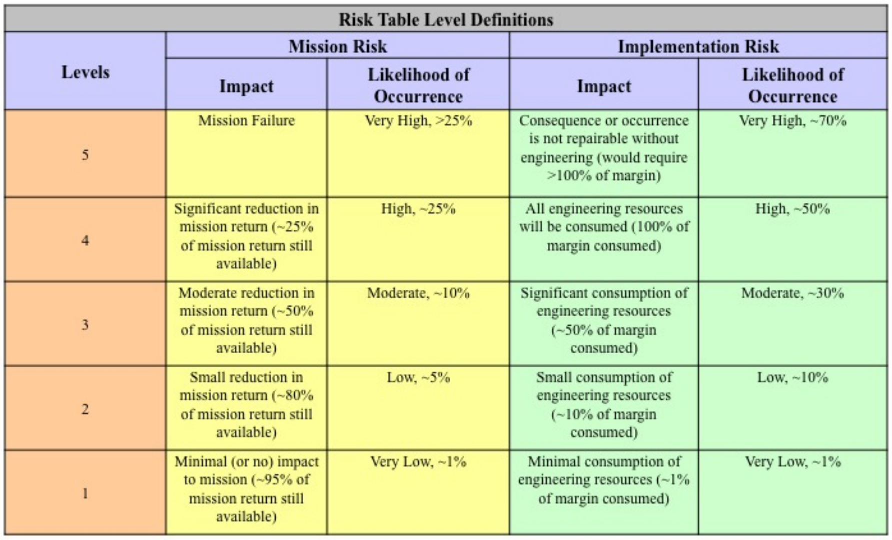
Identification and scoring of risks is observed to be a subjective process. Identification of risks by subsystem chairs is very dependent upon their immediate experiences. For example, if they have recently worked on a project where a particularly challenging risk was faced, they are likely to over-specify or score the same risk higher than usual, or if they have been recently involved in studies that push the boundaries and are high risk, they tend to identify fewer risks on subsequent studies that appear comparatively less risky. In addition, an individual’s risk outlook – whether risk averse or risk seeking – has an effect on the risks that she records in the Team X environment.

To enable the more complete identification and assessment of risks for each study as well as consistency across studies in Team X, lists of common risks for each subsystem were compiled based on previous studies and discussion with Team X subsystem representatives. These risk lists have been utilized in two ways in studies – they were distributed to the subsystem chairs to enable faster and more comprehensive risk identification at the subsystem level, and they have also been used by the Risk chair to identify the basic set of risks for a study which are then revised by the Team X design team. These risk lists were also leveraged in RMA in order to generate the initial list of potential risks for a study, and this initial list was used as the starting point for identification of risks in RMA. In order to have a better understanding of the types of risks that are associated with particular missions, the Team X RAP tool database is also being mined to find correlations between risks and missions. Previous risks and the associated scores can then be extracted and used to improve the consistency of risk identification and scoring in Team X. In addition, there is an ongoing research task to capture the risk mental models of the Team X chairs so that the checklists and the database information can be presented in a way that is useful to the chairs and enables the extraction of more consistent risk information.

Section 3.2: Risk Scoring Issues

The risk 5x5 definitions for impact and likelihood values are provided as guidance for scoring. However, the earlier definitions used in Team X, as shown in Table 1, are more suited for manned missions where the risk posture is extremely conservative, than for robotic science missions where a relatively higher level of risk is routinely accepted. At the early stages of mission development, such as in an RMA study, it is very difficult to determine the potential for science loss with enough precision to distinguish between the medium (>1%), low (>0.5%) and very low (>0.1%) likelihood levels. Using these bins for probability, even the Delphi oracle would have had a hard time selecting an accurate probability bin without a formal Probabilistic Risk Assessment (PRA). In addition, many risks may have likelihood higher than 10%, the top of the likelihood scale. There was a need to revise the mission risk scale to provide more realistic guidance to engineers for risk scoring.

To improve some of the risk scoring difficulties faced in Team X and RMA, the mission risk likelihoods were changed to more appropriately capture the likelihoods that can be estimated in the early phase of conceptual design when only incomplete information is available. The new definitions are shown in Table 2**Error! Reference source not found.**.



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1	Minimal (or no) impact to mission (~95% of mission return still available)	Very Low, ~1%	Minimal consumption of engineering resources (~1% of margin consumed)	Very Low, ~1%

Table 2: Revised Impact and Likelihood Thresholds for Risk Scoring

When initially scoring risks, many engineers rely on a three-level mental qualitative categorization of risks based on the colors in the 5x5 matrix. Issues that are of concern, but unlikely to be mission ending are usually thought of as green; issues that may cause total mission loss are red risks; risks that are significant, and may potentially be worse than currently understood are yellow risks. In general, engineers appear to find quantitatively scoring impacts relatively easier than quantitatively scoring likelihood. Engineers are able to describe the consequences of a mission risk on a science measurement to be taken, when sufficiently detailed information is available about the science being done in the mission. Experienced subsystem chairs are usually able to score consequences relative to their own subsystem rather than from a mission perspective, especially in the case of implementation risks where the consequences are more readily quantifiable in terms of cost. Most engineers have difficulty estimating likelihood quantitatively, in particular when there is limited statistical information on the basis of which they can assess the probability. Even given the new probability definitions, it is challenging to make meaningful selections for probability of mission risks. There are several techniques that may be applied in the future to aid the risk likelihood estimation in a concurrent engineering environment. These techniques include expressing likelihoods in terms of betting odds (such as 100:1, 20:1, or 4:1), or using a probability wheel [iv].

Unlike in Team X, in RMA, detailed information about the science being done in the mission is readily available to the design team through the Science Value Matrix that is developed by the RMA Science lead and the science customer team. By utilizing the SVM, mission risks, i.e., risks that result in loss of mission science return can be scored by assessing risk impact based on the science objective values in the SVM. In the science value matrix, the architectures under assessment are assigned relative science merit by the RMA science team for each science objective. In determining the impact on the science return if a mission risk occurs, the effect on the appropriate objectives is estimated. The percentage loss of the science value due to the occurrence of a risk is translated into a risk score based on the impact score definitions listed in Table 2. The likelihood of occurrence of mission risks must still be estimated on the basis of previous experience or the limited available information. Implementation risks are scored on the basis of the estimated expenditure of margin and the likelihood of the risk.

Scoring is also often inconsistent between risks, especially when considering risks that might arise far in the future. Mitigations which are not necessarily included in the design but are assumed will be available in the future are often included in the scoring assessment, leading engineers to score risks with implied mitigations much lower than might be expected. To maintain consistent scoring, an effort is being made in both teams to score risks as unmitigated. This enables more consistent scoring of risks, and the explicit capture of mitigations and associated cost. In case of implementation risks it is especially important to score risks as unmitigated unless they are specifically addressed in the design through particular design choices.

Section 3.3: Risk Aggregation

In Team X, risks are identified and scored, and these are provided as a list of risks ordered by red, yellow and green in a report to the customer. The scoring of risks is also subject to the ‘politics’ of risk. As most engineers appear to think about risks qualitatively in terms of colors, at least initially, reporting a red risk can often set off alarm bells and lead to considerable discussion. A red risk cannot go out in a study report unless one has a very strong case, preferably with some form of supporting quantitative data. The way reddest risks get reduced is by specifying a mitigation. While the mitigation is almost always reasonable there is little analysis of the mitigation to understand its feasibility and whether it introduces any new risks.

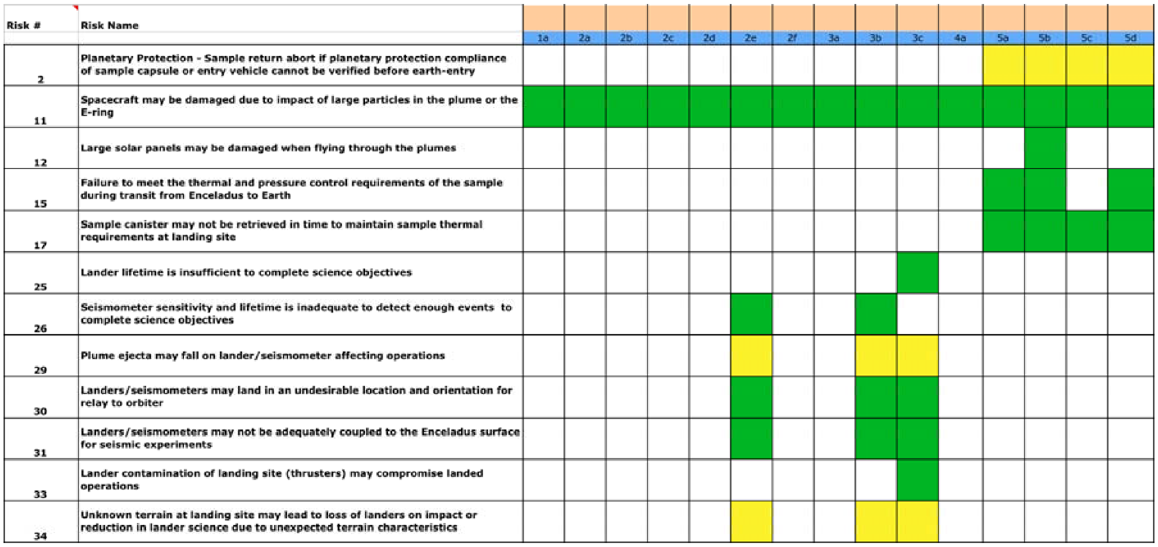
In RMA studies, it was seen that the aversion to reporting red risks often resulted in situations where, if a red risk was brought up, design changes were made to mitigate the risk during the design session. In RMA, it is part of the procedure to record these risks as ‘retired’. In Team X, the same process of risk identification and subsequent modification of the design in response to red risks happens in the background and is rarely recorded. However, this has been identified as an area for process improvement, as particular risks that are identified as being design drivers constitute an important piece of information for the study customer.

In RMA, the impact and likelihood scores were used to calculate expected values in RMA as described in Section 2.2. With each risk assigned a red, yellow, or green code depending on the 5x5 combination of consequence and likelihood, measuring the overall risk of an architecture was necessary to distinguish the different architectures. However, the red, yellow, green scheme could just as easily be one, two, three, or 17, 45, 192—that is, it is an ordinal scale, not a cardinal scale or an absolute scale. The only definitive conclusion that can be drawn from the risk score data is that red is more risky than yellow, which in turn is more risky than green. One cannot say, for example, that a red risk is twice a risky as a yellow risk, or that one red risk is riskier than another based on the given information. With ordinal scaling, the analyst is very limited in the types of computational analyses and manipulations that can legitimately be performed. In particular, rank ordering and grouping are the only valid operations on a set of ordinal data.

In calculating expected values as was done in the initial RMA risk methodology, operations that are invalid for ordinal numbers, such as multiplication and addition, were applied to the ordinal set of risk scoring data.

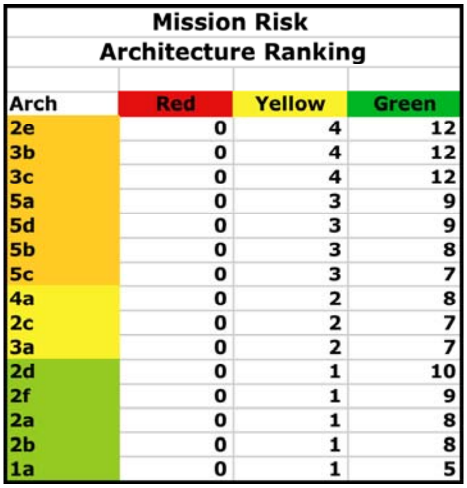
In the new RMA risk methodology, the ordinal scoring data is used to group and rank order risks for architectures. Based on the impact and likelihood score of each individual risk, it is binned into red, yellow or green areas of the 5x5. Risks are assigned to the architectures that they affect. Architectures are then ranked lexicographically, i.e., on the basis of the number of red risks, then subsequently the number of yellow, and then the number of green risks. The simple rank ordering according to number of risks of each color is a valid operation for ordinal data, and thus is an acceptable method to apply to the risk data and is also reflective of the mental models of many engineers in utilizing the three risk color levels.

While Team X has the RAP tool, which provides a basic interface, to capture and score risks, RMA initially had no equivalent tool to enable capturing, scoring and aggregation of risks. Due to the constantly evolving architectures and quick turnaround decisions made during an RMA study, it was necessary to have an appropriate tool to aid the efficient capture and scoring of risks. An Excel tool was developed which allows the Risk lead to capture risks and approximate scores, and assign them to the corresponding architectures quickly. Risks are assigned a status of active, cross-cutting or retired based on the changing information available during the study. Based on the risk information entered into the tool, the tool automatically generates summary charts of risks associated with architectures, as shown in Figure 3. These summary charts are very effective in communicating the risks to the team during discussions of risk. Once the final set of risks is determined, the tool produces the lexicographic ranking of architectures by risk as shown in Figure 4 below.



Risk #	Risk Name	1a	2a	2b	2c	2d	2e	2f	3a	3b	3c	4a	5a	5b	5c	5d
2	Planetary Protection - Sample return abort if planetary protection compliance of sample capsule or entry vehicle cannot be verified before earth-entry												🟨	🟨	🟨	🟨
11	Spacecraft may be damaged due to impact of large particles in the plume or the E-ring	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
12	Large solar panels may be damaged when flying through the plumes													🟩		
15	Failure to meet the thermal and pressure control requirements of the sample during transit from Enceladus to Earth												🟩	🟩		🟩
17	Sample canister may not be retrieved in time to maintain sample thermal requirements at landing site												🟩	🟩	🟩	🟩
25	Lander lifetime is insufficient to complete science objectives										🟩					
26	Seismometer sensitivity and lifetime is inadequate to detect enough events to complete science objectives						🟩			🟩						
29	Plume ejecta may fall on lander/seismometer affecting operations						🟨			🟨	🟨					
30	Landers/seismometers may land in an undesirable location and orientation for relay to orbiter						🟩			🟩	🟩					
31	Landers/seismometers may not be adequately coupled to the Enceladus surface for seismic experiments						🟩			🟩	🟩					
33	Lander contamination of landing site (thrusters) may compromise landed operations										🟩					
34	Unknown terrain at landing site may lead to loss of landers on impact or reduction in lander science due to unexpected terrain characteristics						🟨			🟨	🟨					

Figure 3: Summary of Risks by Architecture (blue cells list architecture identifiers, the colored cells in each column represent the risks that apply, and the severity for each architecture)



Mission Risk
Architecture Ranking

Arch	Red	Yellow	Green
2e	0	4	12
3b	0	4	12
3c	0	4	12
5a	0	3	9
5d	0	3	9
5b	0	3	8
5c	0	3	7
4a	0	2	8
2c	0	2	7
3a	0	2	7
2d	0	1	10
2f	0	1	9
2a	0	1	8
2b	0	1	8
1a	0	1	5

Figure 4: Architecture Ranking by Risk

Section 4: Summary and Conclusion

The Risk methodology used in the concurrent engineering teams at JPL is evolving in order to generate more complete risk assessments that will aid engineers in later stages of the proposal or project. The expert subsystem engineers in the team provide valuable risk information drawing upon their prior experience and knowledge, but there is also a need to leverage knowledge from previous missions as well as provide a system-level risk perspective. In order to achieve this, the new Risk methodology being used in Team X and RMA combines team member input with information from previous studies and utilizes new tools that enable easier recording and assessment of risks during study sessions. Emphasis is also placed on effectively communicating the risk through reports (e.g., through colored summary charts and architecture ranking) such that the risk information gathered can be used to inform subsequent design choices after the study.

While progress has been made on more consistently scoring the risk impacts on the basis of science value assessments, risk likelihood scores are still educated guesses drawn from engineers' prior experience. Likelihoods are often difficult to estimate in areas where there is limited information available, such as during an RMA study. The method commonly used by engineers is analogy with prior missions. Further study of better ways of estimating likelihood will enable consistent and accurate scoring of risks, providing a basis for comparison between missions.

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[i] Warfield, K. and Hihn J., “Spreadsheets in Team X: Preserving Order in an Inherently Chaotic Environment”, Proceedings of the 42nd Hawaiian International Conference on System Sciences (HICSS 42), Waikoloa, HI, January 5-8, 2009

[ii] L.Meshkat, R.E. Oberto, “ Towards a Systems Approach for Risk Considerations during Concurrent Design”, United Nations Space Conference, Beijing, China, 2004.

[iii] Malone, M. and Moses, K.. Development of Risk Assessment Matrix for NASA Engineering and Safety Center (NESC), Project Management Challenge 2005.

[iv] Morgan, M.G. and Henrion, M., “Uncertainty : A Guide to Dealing with Uncertainty in Quantitative Risk and Policy Analysis”, Cambridge University Press, 1990.