Requirements Engineering Scorecard and the Next-Generation Space Suit

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The objective for a NASA contractor, the performing organization in this case study, is to provide engineering services to develop and deliver the next generation space suit to NASA, the customer in this case study. A case study with qualitative and quantitative analyses regarding a new process and approach to requirements engineering is described, with the intent that if utilized, these tools may have contributed to improvements across the project in terms of meeting cost, scope, budget and quality while appropriately accounting for risk management. The procedure entails a research method in which the current state of the project, current state of the art, and the identified systems engineering challenges are evaluated. Iterative models are tempered through development by continual improvements by engineering evaluation of engineers on the project. The current results have produced a prototype of a requirements engineering scorecard with implementations of FMEA and quantitative analysis to (i) identify root cause of underdeveloped requirements and (ii) project management impacts with regards to project risk. Forward work includes customer, performing organization, acceptance against applicable INCOSE community accepted practices.

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Nomenclature

ADD	=	Architecture and Design Document
Con-Ops	=	Concept of Operations
DCU	=	Display and Control Unit
EMU	=	Extravehicular Mobility Unit
INCOSE	=	International Council of Systems Engineers
ISS	=	International Space Station
FMEA	=	Failure Modes and Effects Analysis
GtNR	=	Guide to Needs and Requirements
lumens	=	luminous flux, amount of light emitted/second
NRM	=	Needs and Requirements Manual
OIG	=	Office of the Inspector General
PTRS	=	Project Technical Requirements Specifications
RPN	=	Risk Priority Number
SME	=	Subject Matter Expert
V&V	=	Verifications & Validations
xEMU	=	Exploration Extravehicular Mobility Unit

I. Introduction

The Exploration Extravehicular Mobility Unit (xEMU) has been in development as of 2007 and serves an extension of the current space suit, the Extravehicular Mobility Unit (EMU). The xEMU is designed to for operations in cis-lunar orbit, low-earth orbit, the lunar surface and eventually provide data to inform deep space missions. As a result of presidential administration's expectation to return to the moon by 2024[1], there was a radical shift in the system context of the current development of International Space Station (ISS) space suit to the development of a lunar suit. One of the areas heavily impacted were the Project Technical Requirements Specifications (PTRS) In 2021, the Office of the Inspector General (OIG) released an audit indicating that flight-ready suits remain years away from completion and that NASA officials would expect to spend in excess of $1 billion dollars on design, testing, qualification and development efforts before the new suits would be ready for use. In addition to cost and schedule concerns, the OIG indicated that there was concern regarding the development of technical requirements. The OIG recommended that NASA would direct efforts to utilize contractor-developed suits instead of providing flight suits in-house[2]. As a result of project closure and handoff to the new contractors, a case study was performed across all facets of the xEMU project within the context of systems engineering challenges. Initial and intermediary data collection from across the project and a dissection of current state-of-the-art tools yielded a case study into requirements engineering with two sub-case studies regarding the lunar dust requirements and the auxiliary lighting requirements of the suit. This yielded a novel approach to requirements engineering: a risk mitigation tool to quantify requirement robustness in order to inform project or engineering on the risk posture and possible mitigation efforts to increase robustness within a requirement or requirement set. This approach while currently tested in an aerospace context, has the ability to be repurposed and used across various fields of engineering. Intended forward work to retrofit this tool for other industries include vetting and testing with guidance from INCOSE officials and performing tests against this tool with inputs from various, differing fields of expertise.

II. Background & Research Approach

To establish a baseline for change, data collection began by eliciting stakeholder feedback from engineers and management across the xEMU project. Initial and intermediate efforts with regards to focus groups, interviews and brainstorming sessions surfaced multiple challenges across the project within the context of systems engineering. Further efforts to refine which challenges would qualify as acceptable case studies were determined by a selection criteria by which a candidate case study must qualify:

i. The candidate case study presents a challenge on the project and is under the systems engineering field of study.
ii. The candidate case study has qualifiable data that can be assessed to determine potential root causes.
iii. The candidate case study has quantifiable data that can be assessed to determine potential root causes.
iv. The candidate case study has qualifiable data that can be assessed against a hypothesis.

v. The candidate case study has quantifiable data that can be assessed against a hypothesis.
vi. The candidate case study has qualifiable data that can be utilized to be tempered in an iterative model to satisfy an approach to solving a challenge on the project.
vii. The candidate case study has quantifiable data that can be utilized to be tempered in an iterative model to satisfy an approach to solving a challenge on the project.
viii. The candidate case study, within itself and juxtaposed to lateral candidate case studies, has a scope that can be illustrated, investigated and results analyzed within a dissertation boundary.

The current process for requirements engineering development involves the integration of (4) project artifacts. While there is not a specific, sequential order of operations while developing the project requirements, the project artifacts integrate as needed to help establish a methodology, baseline and organization of project requirements. The Architecture Description Document (ADD) provides a description of the functionality and purpose of the xEMU hardware in addition to detailing the various configurations. The Concept of Operations (Con-Ops) provides both a tabular method in conjunction with natural language to define an operation or activity relating to xEMU hardware. The PTRS defines the highest level of requirements (i.e., project level) requirements which inform the system, subsystem and component level requirements. While not existing at the highest echelon of requirements with respect to NASA stakeholder agencies and programs, the PTRS exists as the authoritative, highest echelon with respect to the xEMU project. Cradle® operates as the project's requirements management tool where engineers may upload, design, organize and create specification documents. Likert scaling indicated that while overall project success was found as a function of the ADD, PTRS, Con-Ops and Cradle®, two distinct requirements packages found struggles during their development with respect but not limited to the (4) project artifacts for requirements engineering.

		Overall Project		Lunar Dust		Auxiliary Lighting	
#	Requirements Engineering General Questions	Mean	Count	Mean	Count	Mean	Count
1	Systems engineering in terms of team hierarchy is appropriately organized on the project	4.5	22	-	-	-	-
2	Systems engineers are appropriately able to influence processes on the project	4.1	21	-	-	-	-
3	There is a need for systems engineer to influence processes on the project	4.45	22	-	-	-	-
4	Systems engineers are appropriately familiar with the xEMU system	3.95	21	3	2	5	1
5	In place architectures have been built appropriately to properly satisfy requirements building	3.82	17	-	-	4	1
6	I prefer to work with an MBSE for requirements management over standard DBSE tools	3.94	18	-	-	-	-
7	In place MBSE tools (i.e., Cradle) have been used appropriately as it pertains to requirements building	3.5	18	-	-	-	-
8	Configuration management is appropriately followed in terms of Cradle requirements management	3.86	14	-	-	-	-
9	The Architecture Design Document has been effective in requirements building	3.83	18	4	2	3	1
10	The Concept of Operations have been effective in requirements building	3.61	18	2.5	2	3	1
11	The Systems Engineering Management Plan was appropriate for the project	3.8	15	2.5	2	3	1
12	A specification tree across the entire system (including subsystems, units) was appropriately developed	3.86	14	2	1	4	1
13	Requirements building in terms of stakeholder elicitation has been appropriate on the project	3.85	20	2	2	1	1
14	Requirements building in terms of project management was appropriately managed on the project	4.06	17	2.5	2	3	1
15	Decomposition of requirements via top level customer needs was appropriately used to derive requirements	3.78	18	1.5	2	2	1
16	Decomposition via goals was appropriately used to derive requirements	3.62	13	2	2	1	1
17	Decomposition via sub-goals was appropriately used to derive requirements	3.75	12	1	1	1	1
18	System requirements are indicative of the stakeholder needs	4.47	19	3.5	2	1	1
19	Subsystem requirements are decomposed accurately from their system requirements	4.29	17	3	2	1	1
20	End item requirements are decomposed accurately from their subsystem requirements	4.11	18	1.5	2	5	1
21	Use cases were appropriately used to derive requirements	3.5	18	3	2	2	1
22	Scenarios were illustrated when developing requirements	3.31	16	2.5	2	1	1
23	Requirements were appropriately decomposed	4	17	3	2	2	1
24	Verifications were appropriately written	3.63	19	1.5	2	2	1
25	Validations were appropriately written	3.38	16	1	2	1	1
26	Unit tests appropriately represent the verifications and validations they are written against	4.18	17	1	1	3	1
27	Subsystem tests appropriately represent the verifications and validations they are written against	4.53	15	1	1	2	1
28	System tests appropriately represent the verifications and validations they are written against	4.27	15	1	1	1	1
29	There is a clear distinction of difference between verifications vs. validations	3.5	20	1.5	2	2	1
30	Successful unit tests correlate to robustly written and developed verifications and validations	4.18	11	1	1	3	1
31	Successful subsystem tests correlate to robustly written and developed verifications and validations	4.08	12	1	1	2	1
32	Successful systems tests correlate to robustly written and developed verifications and validations	4.2	10	1	1	0	0
33	The Engineering Vee model implementation is not critical to the project's success	2.21	19	2	1	3	1
34	The Engineering Vee model was appropriately utilized by the project	3.82	17	4	1	3	1
35	I understand when a requirements package completely meets the customer's needs	4	19	3.5	2	5	1
36	There was a tool to illustrate when a requirements package completely met the customer's needs on the project	2.69	16	1.5	2	1	1
37	There was an appropriate rubric to build requirements on the project (scoring, grading, etc.)	2.5	14	1	2	1	1
38	Having a score card would be beneficial when developing requirements	3.81	16	4.5	2	5	1
39	I am appropriately versed in INCOSE requirements standards	3.37	19	2.5	2	4	1
40	We used INCOSE requirements standards on the project	3.85	13	3	1	1	1
41	Having a requirements matrix decomposition tool starting from high level customer needs all the way through to end items specifications would	4.4	20	4	2	5	1
42	We used a requirements matrix decomposition tool to organize high level customer needs all the way through to end items specifications	3.36	14	1	1	1	1
43	I prefer having a glossary for terms during requirements building	4.35	20	4	2	5	1
44	We had a glossary for terms during requirements building	3.91	11	2	1	4	1
45	Requirements are appropriately given owners during their development	3.88	17	3.5	2	5	1
46	Rationales were documented for the requirements appropriately	4.45	20	4	2	4	1
47	Requirement characteristics were appropriately captured	3.89	18	2.5	2	2	1
48	Requirement attributes were appropriately captured	3.73	15	2.5	2	1	1
49	Requirements are appropriately traceable to parents	4.7	20	4	2	2	1
50	Requirements are appropriately traceable to children	4.37	19	4	2	5	1
51	The xEMU system context was appropriately represented	4.2	15	1.5	2	3	1
52	Current state to desired state requirements transformation in terms of a lunar suit was appropriately captured	3.6	15	1	1	1	1

Table 1 – Likert Scale Polling Results

Results indicated that one overall case study with respect to requirements engineering would benefit from an analyses into methods for optimization, comprised of two distinct case studies: (i) in the development of lunar dust requirements and (ii) in the development of auxiliary lighting. Once a case study was identified, an analysis of both the current-state-of-the-art with respect to requirements engineering and the current state of the project commenced in parallel. This effort was performed to establish which practices the project may benefit from with regards to challenges (i.e., PROBLEM on Figure 1) and also help inform the academic and systems engineer communities on current knowledge gaps in an attempt to help advance the current state-of-the-art. Likert scale responses indicate that (i) questions 16-18 suggest inclusion of a use case tool, (ii) questions 21-32 suggest inclusion of a requirements matrix decomposition tool, use case tool and requirements scorecard, (iii) questions 36-38 suggest inclusion of a requirements matrix decomposition tool, (iv) questions 40-44 suggest inclusion of a requirements matrix decomposition tool, use case tool, glossary tool and requirements scorecard and 47-48 and 51-52 suggest the inclusion of requirements matrix decomposition tool. While the ultimate deliverable focuses on a process to include all of the aforementioned tools, a considerable novel approach determines a method by which INCOSE standards may be utilized to create a scoring and quantification method for robusticity of a requirement. While this approach has precedent in academia and the professional field of systems engineering, elicitation from INCOSE experts and performing a literature review indicate that there exists a knowledge gap in this area of systems engineering. A graphical representation to characterize the academic and current state-of-the-art and project is illustrated.

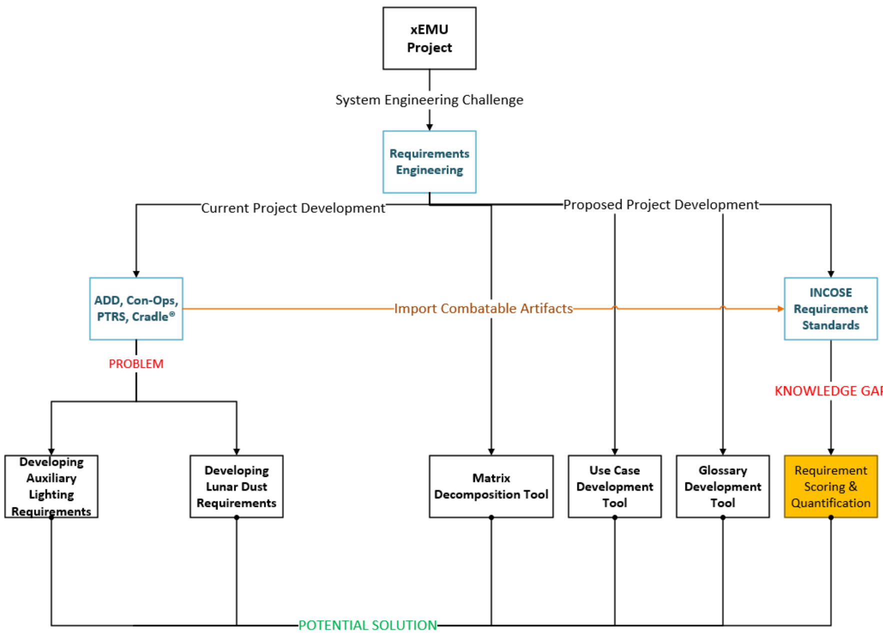

Figure 1 – xEMU Requirements Engineering Challenge Overview

The first hypothesis regarding the formulation of the proposed requirements engineering development states, “if the lunar dust requirements including verifications and validations were decomposed via an INCOSE-influenced scorecard process, the project would have better approximated the anticipated product against the customer’s expectations when compared against the current process.” The second hypothesis regarding the formulation of the proposed requirements engineering development states, “if the auxiliary lighting requirements including verifications and validations were decomposed via an INCOSE-influenced scorecard process, the project would have better approximated the anticipated product against the customer’s expectations when compared against the current process.” Analysis to test the hypothesis includes iterative and incremental requirement engineering scorecard tempering where focus groups of subject matter experts evaluate the additions of the tools represented in Figure 1 until the tempered model across three iterations is satisfactorily accepted by panel approval. Likert scale, panel scoring and Failure Modes and Effects Analyses (FMEA) were the quantitative measures used as success criteria measurements as resources were not available to effectively run a full requirements decomposition in its entirety as a function of the hypothesized approach for vetting against the project’s current requirements engineering model. Results from the research currently indicate that if the scorecard approach is implemented as opposed to implementation of no new process, requirements may better approximate the customer’s expectation while preserving project management concerns of cost, schedule and scope. It must be noted that while multiple tempered model tests across multiple subject matter experts has approximated a solution that is specific for the lunar dust and auxiliary lighting team needs, by no means is this a definitive or fully optimized model. With regards to the requirement teams’ specific needs and within the context of the work performed, tempered model testing helped disqualify certain approaches or facets of approaches while preserving those that testing deemed satisfactory for implementation. The initial hypotheses were verbatim with the exception that verification and validation activities were not present. This change was a result of the data from both the lunar dust and auxiliary lighting analyses which illustrated the need for these activities to be robust in order to compliment a robust requirement set.

III. Testing Outline & Data Collection

The requirements engineering scorecard is an implementation of a modified FMEA to examine risks with selected requirements with the intent of requirement grooming and increased robusticity. Robustness in the RES is defined as a requirement having the appropriate quality and condition of being fit for procession of product development in the following areas, which INCOSE has defined as the following: requirement characteristics, requirement set characteristics, accuracy, concision, non-ambiguity, singularity, completeness, realism, conditions, uniqueness, abstraction, quantifiers, tolerance, quantification, uniformity of language, modularity, intent and definition, verification and validation, and organization maintenance. The requirements scorecard has built upon these to include the following areas: ability to be challenged, project knowledge availability, operational settings comprehension, additional requirement organization, project management, concerns with current verifications and validations. The overall product structured but tailorable process to grade, help support modification or challenge existing requirements to increase robusticity. The sub-products specific to the scorecard are best practices INCOSE-inspired checklist with scoring, additional practices checklist with scoring and FMEA-modified scoring to include best practices and additional practices with the intent of creating a streamlined method for requirement robusticity challenge and augmentation. The requirements scorecard usage is most effective under the following conditions: (i) when requirements have been established but upon initial inspection are plausibly challengeable, (ii)when requirements are built around new or novel technologies where robustness is a challenge, (iii) when requirements have been added to reasonably large requirement packages, (iv) when requirement system context has changed dramatically, (v) when requirement packages have had significant changes to top level customer needs or requirements that may impact decomposed requirements, (vi) when a feature has been promoted to fulfill a requirement, (vii) when a new project is undertaken and this tool is used at the onset, (viii) when a postmortem or lessons learned on a project involving requirements engineering.

For context, the lunar dust mitigation requirement, a top level (i.e., project, Level 1) requirement on the xEMU project and an auxiliary lighting requirement at mid-level (i.e., subsystem Level 3), will be given to provide context to the user. For simplicity and expedition of the analysis, not all properties of the requirement are given (i.e., attributes, characteristics, etc.). For the user, the holistic usage of the scorecard is exclusively at the disposal to the individual or performing organization. Requirements may be analyzed for robusticity holistically against all best and additional practices included, any unidentified or niche additional practices the user may identify for their needs and incorporated into the scorecards or itemized areas of interest may be evaluated.

Requirement ID & Level	Project Level Requirement	EVA Requirement Shall Statement
R.SS-3033 Project Level	Lunar Surface Dust Mitigation	The xEVA System shall limit the amount of regolith liberated in the cabin environment to less than 100 grams for each two-crew lunar surface EVA.
R.DCU-685.XXX Subsystem Level	Auxiliary Source Lighting Location	The DCU emergency lighting shall provide 350 lumens of white light emitted across 4 source locations separated across the anterior surface of the DCU.

Table 2 – Sample Lunar Dust & Auxiliary Lighting Requirements

After the requirement, requirement set or itemized areas of interested are investigated, the item(s) were graded against the following rubric. While the scoring rubric is tailorable to smooth coarseness of ranking, the xEMU case studies did not reconcile a specific ranking associated with one trait carrying more weight or a smoother ranking system. For the case studies utilized in the scorecard, either a meets, does not meet, might meet or is not applicable to meeting a level of robusticity.

Scoring Rubric		
Ranking	**Response**	**Criteria**
0	N/A	Not Applicable or Not Graded
1	No/False	Needs Corrective Action
2	Maybe	Consideration Given for Possible Corrective Action but Acceptable
3	Yes/True	Acceptable

Table 3 – Best Practices Scoring Rubric

The Additional Practices rubric below allows for grading of the requirement against any of the itemized categories. These categories and associated identification numbers were derived from INCOSE Guide to Needs and Requirements (GtNR) v1[3], Guide to Verifications and Validations (V&V) v1[4], Requirement Working Group Guide to Writing Requirements (GtWR) v.3.1[5] and the Needs and Requirements Manual (NRM) R1.1[6] but tailored to suit the specific requirement inquires of the lunar dust and auxiliary lighting team's needs. The user may utilize the template such that: (i) the user may give an overall grade on specifically graded practices to derive a score with the average against only the items in question graded, (ii) the user may find areas that are given a Ranking of 1 or 2 and execute corrective action regardless of overall score, (iii) at the conclusion of grading, if the requirement or set of requirements does not meet the success criteria, FMEA grading will follow. It is recommended that the scorecard FMEA be followed to be used to take corrective action if any one of the of the following categories item is at a ranking of below a score of "3."

Category	#	Additional Practices	Score (1-3)
Challenge Requirement	CR1	The requirement is not based around an existing features.	
	CR2	The new requirement does not need to change existing designs?	
	CR3	Customer need cannot be met by simpler means?	
	CR4	There is not an alternative method available?	
	CR5	Requirement should not be challenged.	
	CR6	Requirement not implicit of a design solution.	
	CR7	Does the requirement limit the design potential?	
	CR8	Is the requirement constrained based on existing hardware?	
	CR9	Requirement does not require existing hardware to significantly change?	
	CR10	No alternative requirement possible to satisfy the need?	
Knowledge Availability	KA1	Requirements have a value that has an adequate basis?	
	KA2	Environment is understood in a way that is measurable for requirement feasibility?	
	KA3	Is project knowledge on the topic adequate to support this requirement?	
	KA4	Do vendor supplied parts meet the intent of the requirement?	
Operatio nal Settings	OS1	Temporal setting don't affect the requirement?	
	OS2	Requirement does not initiate any emergent behavior in the system?	

	OS3	Environmental factors impact the requirement validation success?	
	OS4	An environment change during usage will not invalidate requirement?	
	OS5	Does the requirement consider cycling of usage?	
	OS6	Does the auxiliary lighting indicate a for use design?	
	OS7	Is the failure mode conditions fully comprehensible?	
Requirement Organization	RO1	Does the added requirement conflict with existing requirements?	
	RO2	Has the new change been approved by all stakeholders formally?	
	RO3	Are all glossary terms comprehensible to adequately build the requirement?	
	RO4	Requirement does not require a change in system context?	
	RO5	Requirement does not require a change in concept of operations?	
	RO6	Requirement does not require a change in the architecture design document?	
	RO7	Is upstream parent need or requirement not driving the downstream requirement?	
	RO8	This requirement does not need to be added in other subsystems?	
	RO9	This requirement does not have a TBX?	
Project Management	PM1	Changes to existing designs will not affect cost?	
	PM2	Changes to existing design will not affect schedule?	
	PM3	Changes to existing design will not impact quality standards?	
	PM4	Changes to existing design will not impact safety concerns?	
	PM5	The requirement does not hinge on more than one business need?	
	PM6	The requirement does not hinge on more than one customer?	
Verifications & Validations Concerns	VV1	Is the requirement range achievable?	
	VV2	During operation at the user level, can the requirement be validated?	
	VV3	Can the requirement environment be simulated?	
	VV4	Verifications do not need to be developed before writing the requirement?	
	VV5	Validations do not need to be developed before writing the requirement?	
	VV6	Can the cleanliness be verified before cleaning?	
	VV7	Can the cleanliness be validated after cleaning?	
	VV8	Can a simulant be used?	
	VV9	Can a simulant be made?	
	VV10	Additional testing does not need to be performed before the requirement is written?	
	VV11	Has any testing been performed prior to the requirement being written?	
	VV12	Has a testing method (feasible or not feasible) been defined?	

Table 4 – Additional Practices Scorecard

For an example, the lunar dust and auxiliary lighting case study requirements will be evaluated against the additional practices only for implementation in the Risk and FMEA Tool. It is important to note while these categories were selected for further risk management and scoring, they are not an exhaustive list and are strictly given for notional context for user. These scores should be collected while performing a focus group or brainstorming session with identified, relevant stakeholders.

Requirement	Additional Practice Violation Categories Identified (Below Score of 3)
The xEVA System shall limit the amount of regolith liberated in the cabin environment to less than 100 grams for each two-crew lunar surface EVA.	RO3, VV1, VV2, VV3, VV4, VV5, VV6, VV7, VV8, VV9, VV10, VV11, VV12, PM1, PM2, PM4, PM6
The DCU emergency lighting shall provide 350 lumens of white light emitted across 4 source locations separated across the anterior surface of the DCU.	CR6, CR7, KA1, KA3, RO3

Table 5 – Selected Case Study Additional Practice Categories

Once the scoring rubrics for both or either the best or additional practices have been reviewed, those selected requirements and categories were populated to the FMEA tool. The potential requirement issue, undesirable effect, next level effects and end effects are meant to illustrate either or both a cascading failure representation and failures that may occur disjointed as a result of the current requirement state. After population of the preliminary information was completed, an assessment the following categories allowed for a risk posture to be established. An additional feature of this FMEA is the Reach category, which was optional but allows for an additional facet in understanding the criticality associated with the requirement's current robusticity position.

- Consequence: How severe is the impact should the risk manifest?
- Likelihood: What is the probability of this risk manifesting?
- Reach: What is the breadth and depth of this requirement impacting peripheral requirements?

Templates for each of the consequence, likelihood and reach categories were given . For this case study, the categories were presented with a general, non-numerical value so that the user or FMEA team may modify them to suit their needs.

	Consequence Ranking for Additional Practices				
Category	**1**	**2**	**3**	**4**	**5**
Project Management: Quality	Remote loss of quality	Minimal loss of quality	1 standard deviation away from quality standard	2 standard deviations away from quality standard	3 standard deviations away from quality standard
Project Management: Safety	Remote risk of injury	Minimal risk of injury	Minor injury	Severe injury	Loss of life
Project Management: Cost	< $50K impact	$50k to $100K impact	$100K to $250K impact	$250K to $500k impact	> $500K impact
Project Management: Scope	Remote impact to scope objectives	Minimal impact to scope objectives	Considerable impact to scope objectives	Major impact to scope objectives	Severe impact to scope objectives
Project Management: Schedule	Minor or no schedule impact	1 to 2 month impact	3 to 4 month impact	5 to 6 month impact	> 7 month impact to schedule

Requirement Organization	Minor or no risk of disorganization	Minimal risk of disorganization	Some risk of disorganization	Major risk of disorganization	Severe risk of disorganization
Verifications & Validations	Minor or no risk of ambiguation	Minimal or possible inability to verify or validate requirement	Some inability to verify or validate requirement	Major inability to verify or validate requirement	Unable to verify or validate requirement in any capacity
Operational Setting	Operational setting full understood	Operational setting possibly or minimally misunderstood	Operational setting somewhat understood	Operationally setting majorly misunderstood	Operational setting severely misunderstood
Knowledge Availability	Minor or no lack of project knowledge to substantiate	Minimal lack of project knowledge to substantiate	Considerable lack of project knowledge to substantiate	Major lack of project knowledge to substantiate	Severe lack of project knowledge to substantiate
Challenge Requirement	No need to challenge requirement	Requirement could be challenged but not strongly recommended	Requirement could be challenged	Requirement should most likely be challenged	Requirement should without doubt be challenged

Table 6 - Consequence Ranking, Additional Practices

Likelihood Ranking		
Score	**Description**	**Probability Range**
1	Very Unlikely	< 10 %
2	Unlikely	10% to 30%
3	Possible	> 30% to 60%
4	Likely	> 60% to 90%
5	Very Likely	> 90 %

Table 7 – Likelihood Ranking

Reach Ranking		
Score	**Description**	**Requirement Range**
1	Negligent Reach	Impacts no other requirements
2	Minor Reach	Impacts 1 requirement
3	Considerable Reach	Impacts 2-4 requirements
4	Major Reach	Impacts 5-10 requirements
5	Extensive Reach	Impacts 10+ requirements

Table 8 – Reach Ranking

At the conclusion of the consequence, likelihood and reach assignment will be the population of the Risk Priority Number (RPN) wherein the systems engineer will take the product of the three (consequence by likelihood by reach, refer to Figure 2). This RPN is given twice: once before analysis of alternatives and recommendations and once after analysis of alternatives or recommendations. The range is a number between 1 and 125. The template will automatically populate a risk color associated with the degree of risk and requirement posture if left unmitigated. The RPN is a product of the three risk categories:

Risk Priority Number = Consequence x Likelihood x Reach

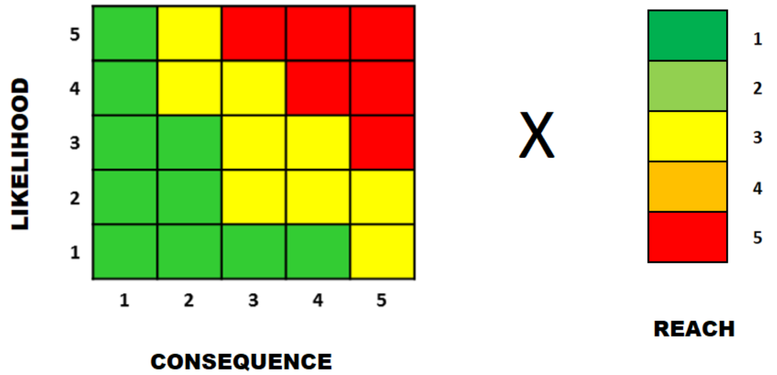

Figure 2 - RPN Matrices

For simplicity to illustrate the FMEA, only one violation from one requirement set will be presented with regards to the auxiliary lighting team.

Challenge Description	ID No.	Best Practice or Additional Practice Description	Potential Requirement Issue	Potential Undesirable Effect	Potential Next Level Effects	Potential End Effects					Action Recommended	Responsible Party	Actions Taken				
What is the challenge or summary of challenges associated with the requirement?	What is the INCOSE Best Practice or RE Prototype Additional Best Practice ID No.?	What is the INCOSE Best Practice or RE Prototype Additional Best Practice description?	What is the potential issue associated with moving forward with this requirement if unchanged?	What are the immediate effects after decomposition if the requirement is not changed?	What are the next level effects if the requirement is not changed?	What is the potential end effect if the requirement is not changed?	CONSEQUENCE (1-5)	LIKELIHOOD (1 - 5)	REACH (1 - 5)	RPN (1 - 125) (BEFORE ANALYSIS)	What are the possible actions to remedy the requirement?	Who is responsible for making sure the actions are completed?	Will the Action Recommended be taken with respect to RPN?	CONSEQUENCE (1-5)	LIKELIHOOD (1 - 5)	REACH (1 - 5)	RPN (1 - 125) (AFTER ANALYSIS)
4 locations is over prescriptive.	CR7	The requirement does not limit a potential design.	The 4 source locations and anterior surface designation could hamper design process, number of lamps is overly prescriptive.	Potential lower level requirements will levy location restrictions and further constrain unit level components.	Design process could become more expensive and produce a product of lesser quality or modularity.	Design process could become more expensive and produce a product of lesser quality or modularity.	4	5	3	60	The DCU ~~emergency~~ auxiliary lighting shall provide average minimum illumination of ~~350 lumens of white light~~ 150 lux [TBD] at the angles and distances defined by the suited crewmember's visible two-handed work envelope for microgravity translation ~~emitted from at least 4 source locations separated across the anterior surface of the DCU~~. Crew two-handed work envelope is shown in Figure X.	SE&I Auxiliary Lighting Team	Change the requirement	1	1	3	3

Figure 3 – FMEA Entry Example: Auxiliary Lighting

IV. Test Results

A total of 30 unique requirements for lunar dust were processed through the FMEA with a total of 169 violations. The majority of these violations converge if the requirement(s) (i) can be verified/validated, (ii) if ranges are well defined, (iii) if terms are well defined, (iv) if the requirement is a parent to a significant portion of child requirements. High level root causes suggest that the range of lunar dust is strict, challenging to verify/validate and rationale of 100 gram regolith liberation target questionable. Regolith is a very broad terms and most of our lunar dust and simulants are not indicative of actual lunar dust. Current testing capabilities are extremely limited, and any testing so far has not yielded results that support a requirement that can be written for this domain. Violations and their pre risk posture score are given before FMEA and post FMEA to illustrate how corrective actions may inform project to mitigate the risk to lower the RPN.

Violation Description	Violation #	# of Occurrences
Is the requirement complete?	C4	1
Is the requirement conforming?	C9	3
Requirements have a value that has an adequate basis?	KA1	14
Changes to existing designs will not affect cost?	PM1	1
Changes to existing design will not affect schedule?	PM2	1
Changes to existing design will not impact safety concerns?	PM4	1
The requirement does not hinge on more than one customer?	PM6	1
Is the sentence structured correctly?	R1	10
Are "or" and "and" logical expressions used correctly?	R15	2
Are ranges appropriately defined?	R33B	16

Are measurable performance targets available and appropriate?	R34	8
Are specific terms defined?	R4	17
Are escape clauses avoided?	R8	1
Are all glossary terms comprehensible to adequately build the requirement?	RO3	21
Is upstream parent need or requirement not driving the downstream requirement?	RO7	9
This requirement does not have a TBX?	RO9	1
Is the requirement range achievable?	VV1	1
Additional testing does not need to be performed before the requirement is written?	VV10	12
Has any testing been performed prior to the requirement being written?	VV11	1
Has a testing method (feasible or not feasible) been defined?	VV12	12
During operation at the user level, can the requirement be validated?	VV2	1
Can the requirement environment be simulated?	VV3	1
Verifications do not need to be developed before writing the requirement?	VV4	1
Validations do not need to be developed before writing the requirement?	VV5	1
Can the cleanliness be verified before cleaning?	VV6	6
Can the cleanliness be validated after cleaning?	VV7	6
Can a simulant be used?	VV8	10
Can a simulant be made?	VV9	10

Table 9 – Lunar Dust Requirement Suite Violations

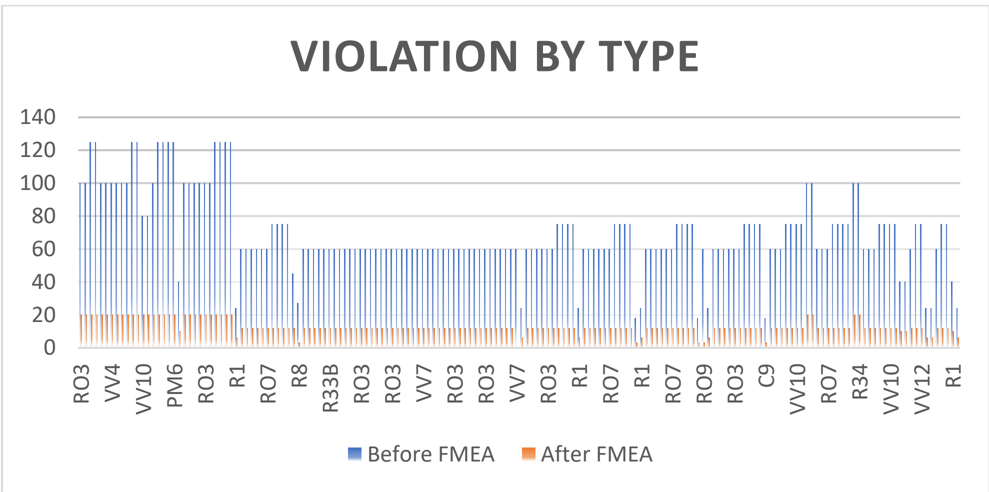

Figure 4 – Lunar Dust Requirement Violations

A total of 5 unique requirements for lunar dust were processed through the FMEA with a total of 22 violations. The majority of these violations converge if the requirement(s) (i) has a parent, (ii) if ranges are well defined (iii) if terms are well defined, (iv) is not implicit of a design solution. High level root causes suggest that no parent requirement or customer need was formally stated before the subsystem team altered existing designs to facilitate for auxiliary lighting while in reflection, a portable light source may have been sufficient.

Violation Description	Violation #	# of Occurrences
Are all glossary terms comprehensible to adequately build the requirement?	RO3	2
Does the requirement trace to a parent?	A4	3
Requirements have a value that has an adequate basis?	KA1	3
Environment understood in a way that is measurable for requirement feasibility?	KA2	4
Requirement not implicit of a design solution.	CR6	4
Does the requirement limit the design potential?	CR7	5

Table 10 – Auxiliary Lighting Requirement Suite Violations

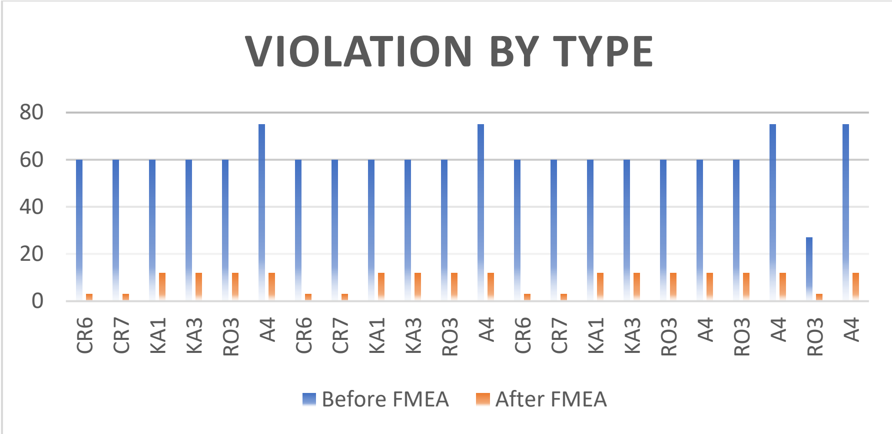

Figure 5 – Auxiliary Lighting Requirement Violations

V. Conclusion

The results from testing the FMEA tool with the panel of SMEs was deemed adequate by the panels in terms of a risk management tool and a thorough approach of testing robustness against INCOS E standards. Any potentially relevant benefits to the project would only be derived if the process was executed within the context of an actual project and therefore results only indicate a plausible approach for improving requirements engineering. While the working groups for lunar dust and auxiliary lighting served as case studies for this requirements engineering FMEA, future work considerations include modification of the FMEA and scoring tools to further vet the model against alternatives. Forward testing with additional projects, both within the NASA scope and outside to other industries in a manner in which the requirements engineering scorecard will process requirements to both aid in requirements engineering, project management and further approximation of a hypothesized, optimal requirements scorecard solution.

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