In Situ Requirements Analysis: A Deeper Examination of the Relationship between Requirements Determination and Project Selection

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Abstract

There has been sparse study of how requirements analysis is performed in situ*, i.e. by organizations building large, complex systems. We assert that a better understanding of* in situ *requirements practice is necessary to improve and ground current theories of requirements analysis. We performed an empirical field study to examine in detail the issues faced by practitioners in forming and stabilizing requirements and the procedures they created to overcome them. We found that the process of requirements determination was intimately related to project selection. We further observed that these two processes were based on the interplay of 1) applied technical, project, and organizational authority with 2) design, sensemaking, and negotiation activity. The ethnography produced an idealized, grounded authority-activity model of requirements analysis and project selection. The model is a generalized form of requirements analysis-project selection for large, complex, risk adverse (highly sensitive to failure) projects. It represents a method to balance the differentiated authority of the stakeholder groups with the activities necessary to form and stabilize technology-project candidates and their related requirements. We argue that the core issues addressed in this field study are generalizable across organizations that build large, complex systems and hence, the results of this study form a basis for a general theory of requirements analysis practice.*

1. Introduction

How requirement analysis is performed *in situ* is not well understood. Although there is a great deal of work on eliciting, formalizing, and transforming requirements into specifications [1-3], there is less work on how and why requirements are elicited and utilized in "live" software and system engineering projects. To better understand this, it is necessary to consider when and under what conditions requirements analysis is usually performed, i.e. the start of project design.

Most organizations do not develop systems from scratch. Instead, to deal with economic constraints, organization demands, and customer needs, they often: a) identify possible problems that represent customer demand [4, 5], b) consider which possible technologies are useful to address these problems, e.g. commercial off-the-shelf software (COTS) [6] or open source software [7], c) select which problems to address, and d) implement a project to solve these problems. The initial choices for problem selection, in turn, involve a process of balancing and negotiating requirements from multiple sources [8-11].

In some views, the hardest part of project design is identifying the problem to be addressed [5, 12]. As March (1994) [4] describes, there is rarely only one clear problem to choose to address. Indeed, problems, and their respective technology choices, co-exist in competition with one another. A problem-technology choice can be viewed as a prospective project for possible funding by an organization's principals. Principals are those who have the power and resources to authorize and fund a project [13]. Each problem-technology set represents a different (yet sometimes overlapping) group of stakeholders. Each stakeholder group has its own set of requirements that underlie their problem-technology choice. This set may overlap with other stakeholder groups' sets, but usually not with all of them.

Each project represents one or more choices of technologies. Based on the requirements of all of the stakeholders, there are hundreds of different project possibilities. How does an organization choose which project to do? In addressing this question, a more detailed question appears: what is the relationship between requirements analysis and project selection? More specifically: empirically, how does an organization address its correlated issues of requirements analysis and project selection for large, complex systems?

1.1. Project Selection and Requirements Analysis

Bergman and Mark (2002) [14] claim project selection and requirements analysis are interrelated. Requirements informed project selection and selection instigated and focused requirements analysis. This paper examines this relationship in more detail.

We conducted an empirical field study to examine in detail the issues faced by practitioners in forming and stabilizing requirements during project selection and the procedures they created to overcome them. We observed that these procedures were an interplay of 1) applied technical, project, and organizational authority with 2) design, sensemaking, and negotiation activity. Based on these observations, we constructed a grounded model of the project selection-requirements analysis process. This led us to the general finding that requirements analysis is practiced differently at the different authority levels and how an organization combines these different levels is key in understanding how *in situ* requirements are formed and stabilized for large, complex projects.

2. Research Methods

The field site we observed was the Jet Propulsion Laboratory (JPL), which is a NASA (National Aeronautics and Space Administration) research laboratory located in southern California. The group we studied was the New Millennium Program (NMP). Field site data collection consisted of: 1) participant observation of the NMP space flight validation process in action, 2) semi-structured interviews with NMP members and many of those they interacted with, 3) informal and semi-formal (lunchroom) discussions with small groups of NMP program and other Lab members, 4) attending detailed technical presentations, and 5) a collection of documents and presentations that were either used in, or informed the NMP process. All interviews and many of the small group discussions were audio recorded digitally. This was augmented with extensive fieldnotes. The fieldwork was conducted over a period of 18 months. It examined the process enacted across four space technology (ST) projects (ST5-8), parts of which overlapped during observation.

Interviewees were either identified by key informants or by participation in on-site meetings and presentations. Altogether, there were 59 one-on-one (including a few one-on-two) person semi-structured interviews, and 41 lunch meeting interviews. The average interview length was one hour, but some lasted much longer (3+ hours) or shorter (15 minutes). There were 11 main NMP members that were observed and interviewed repeatedly. Three of the NMP members were key informants. Also, across the various lunch meetings, there were 24 other Lab members (project leaders, technologists, research scientists) who participated in detailed discussions about ongoing NMP related work as well as unrelated Lab work. There were 13 technology providers, five internal and eight external to the Lab, which gave detailed technical (functional capabilities and constraints) and economic (cost, time, risk) presentations about their technologies. We were allowed to participate in six of these meetings. The presentations were followed up by short (15-30 minute) semi-structured interviews. Only one NASA administrator was interviewed. Yet, there was a great deal of discussion by the NMP members about the roles of the NMP program director and the theme mission directors in the NMP selection process. This discussion was obtained from internal documents. There were hundreds of related documents, slide sets and papers, of which there were key internal documents [15, 16] and an insightful conference paper authored by the NMP group [17].

The analysis initially focused on examining the process as professed, usually via documents and slide presentations. This was utilized to help guide the capture of the process as enacted, i.e. “invisible work” [18]. The observed process was rectified with the NMP documented process to produce a deep, rich description of the NMP process. The NMP members themselves validated the “correctness” of the captured process by utilizing an “autopiloting” (self-reflective) method of data review [19]. The comments from the self-reflective reviews were also used to gain further insights into the details of the NMP process. It should be noted that the NMP members, in general, were highly insistent on making sure the details were correctly identified and learned by the researchers.

The data was analyzed using open and axial coding [20]. The open coding was used to identify the important components in the NMP process. Axial coding was then performed to organize and relate the components to faithfully reproduce and represent what was observed. Autopiloting was applied to verify these representations. During coding, groupings of authority and activity were observed. These groupings are based on repeated application and outcomes of the “invisible work” that went into forming technology proposals and mission project plans. Process codes were developed based on these groupings. The process codes were applied and a final grounded analysis of the NMP process was performed to determine the details of how requirements analysis and project selection were performed *in situ*.

3. Field Site

The New Millennium Program (NMP) was started in 1994. The main mission of the NMP is to perform space flight validation of new technologies [15]. It is located at the Jet Propulsion Laboratory, yet it represents all of NASA. It was created to address a problem with the lack of utilizing new technologies in space science missions. The primary reason science missions need new technologies is to reduce mission cost, allow a measurement, or enable a new function or capability. But, new technology is considered to risky for space use, and hence off-limits to science missions.

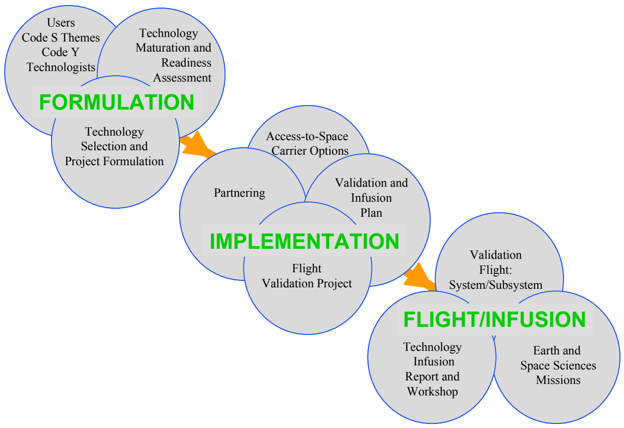

Figure 1. NMP Process Triad

A main issue that the NMP program faces is how to select the technologies for validation in space. There are thousands of possible technologies that need space flight validation, hundreds of which are considered important by NASA directors and science mission technologists at any one time. The technologies tend to cluster into sets of related functionality, such as propulsion, communications, sensors and control systems. Each new technology was viewed by the NMP as a possible project choice. The process NMP follows to perform *project selection* is called "formulation," as shown in Figure 1. An examination of the relationships between formulation and implementation (i.e. detailed design and building of a system) and flight/infusion (i.e. sending the flight system into space, executing the validation mission, and infusing the validated technology to the NASA customers) is beyond the scope of this discussion.

3.1. Field Site Participants

After one year of observation, clear role groupings of those involved in the NMP selection process became evident. NMP Participants include: NASA Headquarters (Principals), NMP Managers (Managers), NMP technologists (NMP), Mission Theme Technologists (TT's), Technology Providers (Providers), Peer Reviewers (Reviews), Peer Review Panel (PRP) members, System Review Committee (SRC) members, and Independent Review Board (IRB) members. Each group had its own goals and requirements in the NMP selection process.

The requirements of the NASA administrators, NMP managers, customers, and suppliers must all be reasonably met to create a project selection agreement. The providers, reviewers, and panels determined and applied (technology, system, and mission level) requirements to provide expert feedback to inform the selection process. The NASA administrators (e.g. NMP process principals) want to satisfy as many of NASA's general objectives as possible with the introduction of new technology. They empowered the NMP to conduct an "open and fair" competition to determine which technologies would be selected for flight validation. The principals support and provided budgets for starting up at least one new space flight validation cycle per year. This way, those technologies not chosen in a previous cycle would have another chance to be selected in an upcoming cycle. This insures an ongoing pipeline of new technologies being validated and made available by the NMP.

The main job of the NMP technologists, who shepherd the selection process during formulation, is to create and foster an environment in which technology selection can be made by achieving a generally acceptable consensus by the NASA principals and themes. From examining the general requirements needs of the various participants, it is evident that creating such an environment was nontrivial and fraught with political, economic, and technical risks. The NMP technologists and management have created and evolved a process over the past nine years to deal with this situation.

4. NMP Process Coding

The observation of the NMP selection cycles produced a great deal of process participant and activity information. These process steps were examined across four space technology (ST) projects (5-8) and then (open and axial) coded. This resulted in identifying a set of common authority and activity groupings. This section defines and describes the process codification scheme.

Process codes were developed based on these groupings. These codes are not derived from a NASA or JPL specific standard. Instead, they are a product of the ethnographic data analysis. The codes are used to better identify and understand the key steps applied in performing a process. In addition, they are utilized in determining the relationships between these steps, and thus, the codes explain why the steps were defined and implemented as they were. The process codes are applied to the NMP formulation process in the next section, where they are used to guide the detailed analysis.

4.1. NMP Process Authority

Authority levels are the alignments between organizational power levels and corresponding engineering expertise levels. The observed NMP process roles represent different levels of engineering expertise and organizational power. At the JPL, those at various organizational position powers also had corresponding levels of engineering expertise, as shown in Table 1. For example, technologists are those people who had positional authority over the design of a technology under development. They also had the engineering expertise to develop the technology. The process analysis produced three authority levels – Technical, Project, and Organizational.

Table 1. Authority Levels

Authority Levels	Position Power	Engineering Expertise
Technical (T)	Technologist	Specific Technology
Project (P)	Project Leader, Manager	System
Organizational (O)	Administrator, Director	Across Systems

Technical – Technical authority is defined as a combination of engineering expertise across a related set of technologies along with the organizational position power to be able to create these technologies. People at this level are usually called technologists, i.e. NMP technologist or theme technologist. In general, the technologists at JPL, including the NMP, were research engineers working on new, cutting edge technologies for (usually non-NMP) flight missions.

Initially, technical authority is based on how well a person knows a specific engineering discipline (i.e. propulsion, electrical, mechanical, etc.) and its related technologies. Additionally, it includes knowledge of cost, risk, and other related technical development issues. It is not unusual for technologists to create cost models of complex technologies they are working on. Technologists also have organizational authority (i.e. power) over the design and development of the technology they are assigned to. This authority is limited and governed by the project leaders or managers, as well as the NASA principals.

Project – Project authority is defined as the combination of system level engineering expertise along with system level management authority. At the JPL, these people are project leaders or managers. Sometimes, they are program managers, yet that includes other organizational responsibilities that are beyond the scope of any one project, such as planning and budgeting.

People with project authority can (within organizational rules) promote, name, change or fire those with technical authority. This also includes the ability to start, change, and end technical design activities. Yet, technical design itself is generally left to those with technical authority, although those with project authority may sometimes assist.

Organizational – Organizational authority is defined as the combination of multiple systems engineering expertise along with organizational (across multiple projects) management authority. People in this role have the power to start a new project (i.e. mission) and bring resources to fund the activity. They can also change and end projects. In general, they care for the general welfare of the organization as a whole. This guides their perspective when creating objectives and goals, as well as implementing projects.

People as this level, i.e. NASA directors and administrators, have worked on a wide variety of projects, usually over several decades. They have developed a very broad level of system engineering expertise. In addition, they have organizational authority power over whole divisions, and possibly the overall organization.

Summary – Each process step had a *key authority*. Key authority is the authority level of the group that was at the center of the primary activity of the process. The application of authority levels to the process roles (Table 1) is presented in Table 2. Each process step had a process role that was clearly identifiable as it key authority.

Table 2. Process Role Authority Levels

Process Roles	Authority Level
NASA Principals	Organizational (O)
NMP Managers	Project (P), Technical (T)
IRB	Project (P)
Customers (TTs)	Technical (T), Organizational (O)
Suppliers (Providers), SRC	Technical (T), Project (P)
Reviewers, PRP	Technical (T)
NMP Technologists	Technical (T)

4.2. Process Activities – Design, Sensemaking, and Negotiation

There were many different process activities observed in the NMP process. After careful review, they were classified into three categories – Design, Sensemaking, and Negotiation [21].

Design – Simon views design as the devising of artifacts to obtain goals [22]. It is an art that is concerned not with the way things are, but how things ought to be. Design work is all of the activities that are applied in devising and implementing technologies that satisfy the goals as set by those with the power to create and resources to implement these goals [13]. Examples of design work in the NMP process include the initial gathering of technologies, determination of theme technologists' requirements, reflective examination of the technology's rankings by the TT's, NMP managements' ratings, and NASA principals' down selection.

Sensemaking – Sensemaking is the art of creating understanding (e.g. sense) in uncertain or ambiguous circumstances, in an attempt to reduce or eliminate these uncertainties or ambiguities [23]. In general, the NMP is faced with uncertainty in determining which technologies to space flight validate. Hence, the overall selection process is an intricate act of sensemaking [24]. Still, sensemaking does not stop at the general level of technology selection. As observed, sensemaking was applied whenever understanding, judgment, and learning were entailed. Each process step was an example of isolating and performing separate, yet interrelated, sensemaking activities.

Negotiation – Negotiation is the act of resolving the differences between two or more interested parties towards the creation of an agreement or contract [25]. The NMP selection process had many instances of negotiation. In general, conflicts over how to rank and down select technologies and projects were resolved using negotiation. More specifically, observed deal construction that occurred during technology proposal reviews and rankings sessions was indicative of technical and authority (e.g. power) conflicts that needed to be resolved. Indeed, coming to consensus can be seen as a successful outcome of negotiation.

In this case, negotiation relied upon design to define the context and substance of the selection conflict and sensemaking to understand the technical, economic, and political aspects of the conflict. It was observed that the NMP process fostered negotiation between interested parties (TT's to TT's, principals to principals) as a way to resolve sensitive conflicts, instead of imposing their own views. They let those who had the authority and the interest work out their issues, while supporting these negotiations by supplying the needed engineering, risk, timeline, and cost information.

Summary – Design, sensemaking, and negotiation do overlap in application. For instance, sensemaking is used during design to understand one's options. Negotiation can be applied in sensemaking to choose the best sense of an uncertain situation. To clarify this confusion in process coding, we utilize a process's *primary activity*, i.e. the main focus of activity for a repeatedly observed process step, to determine its activity code. For example, if the primary activity of a process were to create a requirements specification, then this would be coded as design (D). A panel debating and coming to a consensus rating for a technology would be coded as negotiation (N). And, the process of one or more technologists learning about newly developed technologies would be coded as sensemaking (S).

4.3. Process Codes

Table 3. Process Codes: Authority-Activity Levels

Authority	Activity		
	Design (D)	Sensemaking (S)	Negotiation (N)
Technical (T)	TD	TS	TN
Project (P)	PD	PS	PN
Organizational (O)	OD	OS	ON

Each process step had a *key authority* and *primary activity*. Together, the identified authorities and activities form a set of codes that covered all of the observed NMP process steps. These codes are presented in Table 3.

TD – Technical Design focuses on the creation of requirements specifications, cost and risk models, and proposed technology architectures by those with technical authority.

PD – Project Design refers to all activity utilized to create and manage a fully viable and operationalizable system by those with project level authority. In the NMP, it focuses on the flight system as a whole, i.e. system plan (technology + satellite carrier + launch vehicle), budget plan, validation plan, mission plan, and so forth.

OD – Organizational Design stands for all activity performed to manage multiple projects to develop different systems by those with organizational authority.

TS – Technical Sensemaking includes all actions applied in making sense of a technical situation (ambiguity, uncertainty, unexpected or new event) by those with technical authority. This includes understanding new technical designs and technologies (capabilities, constraints and drawbacks, cost, risk, timeliness), stakeholders' requirements (wants, needs, and constraints), and other technologists' as well as managerial (project, organizational) views' regarding technology issues.

PS – Project Sensemaking refers to all steps taken to make sense of a project situation by those with project authority. Examples of this include understanding project plans and their components, proposed system designs, project level requirements (system, resource cost, risk, timelines) and objectives, and the views of other project leaders or managers as well as technologists and organizational principals.

OS – Organizational Sensemaking stands for all activity performed to make sense of an organizational situation by those with organizational authority. This includes understanding various different project proposals and details of ongoing projects, views and objectives of those with process authority.

TN – Technical Negotiation occurs when there are two or more competing technologies, sets of requirements, design approaches, etc.

PN – Project Negotiation occurs when there are two or more competing project proposals of a system or other project level planning and implementation issues. Those with project level authority performed the negotiations themselves without a mediator, but with informational support from those with technological authority.

ON – Organizational Negotiation occurs when there are competing projects of different systems (at various stages of development), and other organizational level planning and objectives issues. As observed, this included NMP cycle budget plans and objectives, balancing organizational needs versus specific project demands (selecting, continuing to support, or killing projects), keeping the organization viable and productive now and into the future. The outcome of ON can affect the overall strategy and success of the organization.

5. Process Analysis

The process codes were applied to identify and understand the steps applied in performing the NMP formulation process (Figure 1). They facilitated the determination of the relationships between the process steps; allowing us to examine why the steps were defined and implemented as observed. The process analysis resulted in the production of a grounded model of the NMP project selection process and its relationship with requirements analysis.

Table 5, in the Appendix, contains the coded version of the NMP formulation process. Although the process is quite complex, further analysis reveals some consistent patterns. One of these patterns is how the organizational structure was used to form, manage, stabilize, and ultimately select requirements.

5.1. Requirements Analysis as an Organizational Process

It was observed that the NMP used the organizational authority structure of the JPL, NASA, and technology providers to form and stabilize requirements and project candidates. These were organizational, as opposed to individual based processes, i.e. the processes were executed within and across the different authority levels without a single individual or small group leading or mediating the activities and outcomes. Figure 2 reveals that the requirements activities are broken up and focused at the three key authority levels. The initial process starts with a handoff from organizational to technical authority levels. The NASA principals, with organizational authority, start the process by setting the initial budget and high-level NASA requirements. The process is taken over by the NMP technologists who focus on forming and stabilizing requirements of customers, i.e. theme technologists' (TTs), in the form of technology concept areas (TCAs). Each TCA represents a proposed project candidate, i.e. sets of technical and economic requirements. The TTs rank the TCAs. They keep their highest ranked TCAs and drop the rest.

At this point, the requirements move up through the organizational hierarchy, with a stop at each authority level. The TCAs are fed forward to inform the NMP managers. The managers determine and add project level requirements to each TCA. They also rank and reduce the TCAs. The NMP managers send the remaining TCAs (technical and project requirements) back to the NASA principals. The principals do a final ranking and selection of the TCAs.

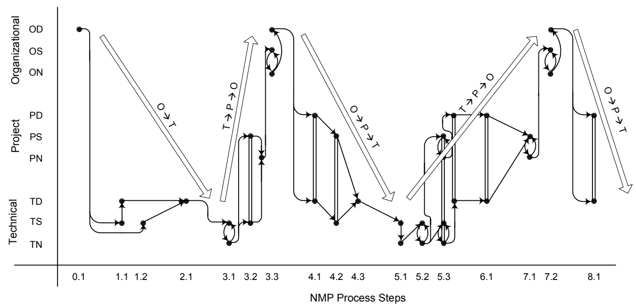

Figure 2 NMP Key Authority Process Chart

The walk through the authority levels starts again with the "open and fair" competition portion of the NMP formulation process. The NASA principals send their selections back to the NMP. The NMP technologists and managers use the TCAs to create a call for technologies. This call goes out to United States based suppliers, e.g. providers of technology. A provider's technologists create technology proposals and send them in to the NMP for review and selection. This completes the walk from O back to T authority in Figure 2.

The proposals are peer reviewed. Then, three different panels consider the proposals. The first panel, PRP, compares the reviews of each technology to their experience with similar technologies and rates each proposal. They make note of any important issues that they feel would positively or negatively impact the viability of a technology. At this stage, they identify "negative requirements" – unwanted capabilities, constraints, costs, or risks) – to separate the proposals. These requirements are used in determining proposal ratings. The next panel, SRC, considers the peer reviews and the PRP ratings. They consider and select which technologies are the best candidates to continue on to the project planning stage.

The remaining providers create project proposals as well as a demonstration of their technologies. This step adds, modifies, and clarifies project level requirements for each candidate proposal. After 6 months, the project proposals are presented to the final panel, IRB (Independent Review Board). They consider the project proposals from a flight mission, i.e. project perspective. They also separate the proposals by negative requirements. Yet, this time these are project level requirements, such as flight viability, safety, and logistics of validation. The IRB makes final rankings and recommendations based on all of the data gathered and presented by each project. They send their recommendations to the NASA principals, who make the final selection. This completes the second and last progression up the organizational levels.

Altogether, the NMP uses the organizational structure to break up and focus the requirements and project selection process. This allows authority "equals" at each level to form, negotiate, and stabilize their own level of requirements, while being informed by the other authority levels. This is necessary since each level brings a significantly different perspective and expertise to the problem of requirements determination and project selection. Altogether, the NMP process utilized an organizational process to foster requirements stabilization and project selection consensus.

5.2. The Activity Triangle

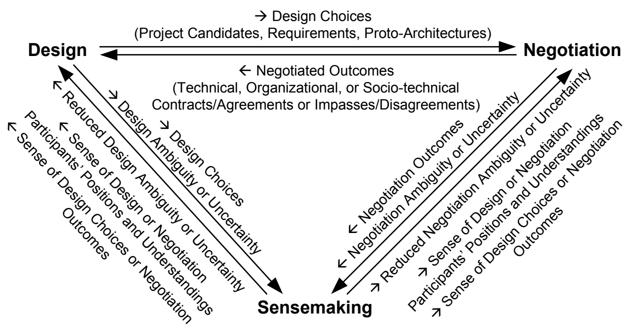

Figure 3 DSN Activity Triangle

The authority levels were also used to focus the process activities. Each level utilized design, sensemaking, and negotiation, albeit in different combinations. Design was utilized to *form* requirements and technology/project proposals. Negotiation was used to clarify and *stabilize* design outcomes. Sensemaking was used to *understand* and *link* the outcomes of design and negotiation. Design, sensemaking, and negotiation form a process triangle, as displayed in Figure 3.

Table 4 Process Boundary Objects

	Boundary Objects
Design	Specifications (Requirements, Project) Proto-architectures (Concepts – TCAs)
Sensemaking	Individual or Collective: ▪ Sense of Design ▪ Sense of Agreement/Disagreement ▪ Sense of Process Participants' Positions or Understandings
Negotiation	Functional (Technical, Socio-technical) Agreement/Contract Political (Organizational Power, Resource Allocation) Agreement/Contract

In general, the outcomes of design, negotiation, and sensemaking are routed to other authority-activities. Any artifacts, data, sense, or related objects that cross between authority levels or primary activities are called a boundary object [26]. The primary boundary objects observed in the NMP process are listed in Table 4. They are passed across the activity connections shown in Figure 3. Altogether, boundary objects 1) represent and contain the useful outcomes of each activity, and ultimately, the selection process, 2) propel the project candidate design and selection process, and 3) build and reinforce legitimation of the overall process.

5.3. Authority-Activity Process Chart

Figure 4 shows the combined authority-activity codes against the NMP selection process. There are a few interesting features of this chart. One salient feature is the U-shaped (downward, bottom, then upward) movement through the process. Downward movement indicates that design-centric activities are occurring though a top-down authority structure. Design-centric activities mainly focus on the production of requirements and project specifications, and proto-architectures (i.e. Technology Concept Area as a prototype architecture). By design-centric, we mean that the primary activity is design, which is being supported by sensemaking and negotiation activities. Design and related sense boundary objects are formed and refined through this downward process. More generally, this is a process of design formation.

The movement along the bottom is initially done to determine the technical details of design, while applying the design insights and criteria from the organizational and project levels. The results of these initial designs produce multiple design choices and technical candidates. It was observed that design choices were internally negotiated within an authority level by a key authority group to further form or refine technical candidates, mainly in the form of proto-architectures, with supporting high-level specifications.

Design deliverable sense and artifacts are passed to other key authorities across authority-activity boundaries to determine which candidates should continue to be considered. The upward process movement in Figure 4 is a negotiation-centric activity in which the products of design are being rated, ranked, refined, and ultimately selected or rejected. Negotiation-centric indicates that the main activity performed is negotiation, which is being supported by sensemaking and design. More generally, the upward movement results in project candidate and requirements stabilization (i.e. reduction of design variance).

In the NMP, it was observed that each selection cycle traversed two of these U-shaped authority-activity processes. The initial U was used to determine and begin to address the requirements at all five participant levels (theme technologists-customers/technical, internal NASA providers-suppliers, administration-organization, NMP managers-project, and NMP technologists-technical). The gathered requirements were applied in creating initially viable project candidates' proto-architectures. The second U used these requirements and proto-architectures to perform a call-for-technologies from industry, academia, and government labs or departments. This U represents the

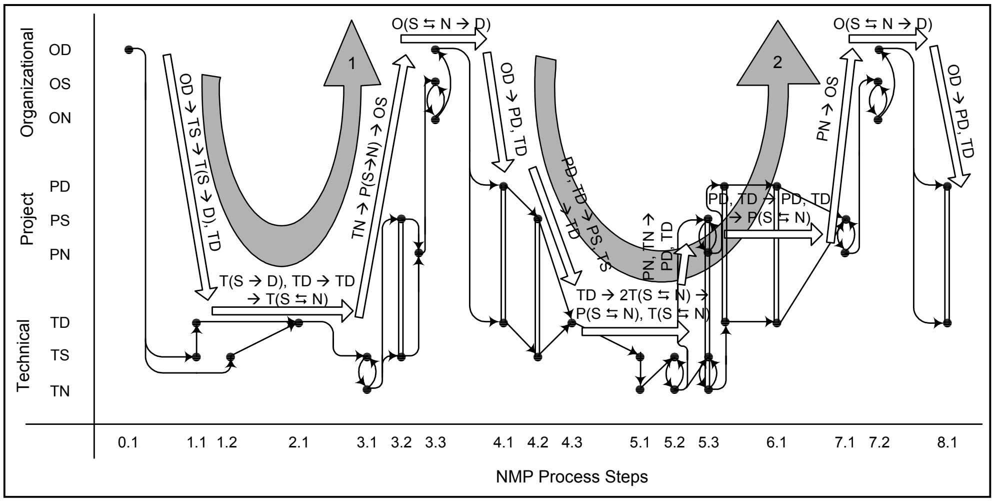

Figure 4 NMP Authority-Activity Process Chart

"open and fair" competition held to determine the final project selections.

5.4. Empirically Grounded Authority-Activity Model

The authority levels combine with the primary activities to form an idealized, empirically grounded model of the project selection and requirements analysis process. The process model, as shown in Figure 5, is a combination of activity triangles connected across the hierarchy of authority levels via sensemaking processes. Each triangle represents the potential activity within an authority level. In addition, there can be internal loops between the activity steps, i.e. within as well as between activity triangles.

As observed in the NMP, process movement starts at OD (organizational design). Ideally, the process would progress down through the project and then technical design-centric activities. This would result in the formation of alternative requirements, project plans, or proto-architectures. These design candidates are then passed via a design sense explaining exercise (with supporting documentation and artifacts) into a series of negotiation-centric stabilization and selection activities. The outcome of a negation from one authority level is then passed on to the next authority body that performs its level of project and requirements analysis on the design candidates. What emerges from the last ON activity is the final selection for that U-cycle. As observed in the NMP, there were 2 consecutive U-cycles.

Still, when we apply the model to the NMP (Figure 6), there are a few significant differences. Although the main part of the U-cycle is intact, there are a few skips in and some unexpected connections. Most notably, there was no observed sensemaking step from OD (organizational design) to PS (project sensemaking). The NMP technologists took the requirements from the NASA administrators and started to investigate new technologies, elicit customer requirements and then develop proto-architectures, without considering higher-level project considerations. But, it was observed over many selection cycles that this process path has been an ongoing and current source of problems. It has been difficult for the NMP technologists to form sets of proto-architectures that well meet mission, i.e. project, level NMP and customer demands. Indeed, they are now considering how to construct proto-architectures that are in more alignment with the NMP and customer project requirements. Altogether, this indicates that the ideal form of the process pointed out a likely weakness in the NMP process – the skipping of the OD-PS and subsequent process steps.

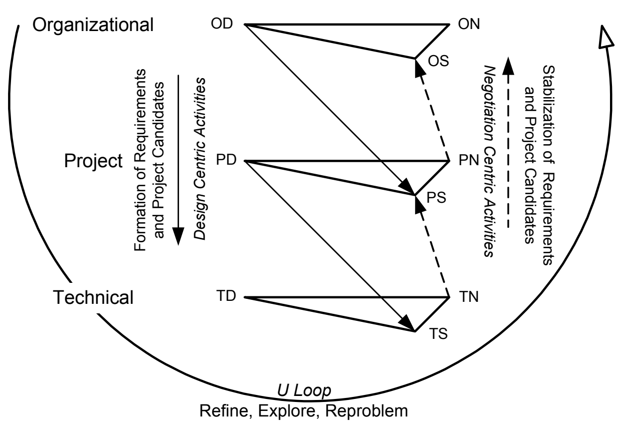

Figure 5 Idealized, Empirically Grounded Authority-Activity Model of Project Selection and Requirements Analysis

It was also observed that there was one connection from TD (technical design) to PS (project sensemaking). This was late in the process when the project teams presented their live demonstrations of their technologies. Indeed, the NMP could have chosen to compare the technologies with a technology-centric panel, like the PRP and SRC. Instead, the presentations were made to the project panel for direct project level sensemaking, which was then used in the negotiation over which projects to recommend.

This is a reasonable departure from the ideal process so long as the members of the project panel have enough technical expertise to perform the equivalent technical negotiations in parallel with the project negotiations. In the case of the NMP, this held true. Still, for other organizations, this may incur an increased risk of misunderstanding and poor technical selection.

Finally, it was noted that some activities either occurred in parallel or had direct implication across levels. These are indicated with the parallel, vertical dotted lines in Figure 6. It was observed that the outcome of organizational negotiation was a design decision. It was seen at the end of the first and second U-cycles that the organizational design decision was also a project and technical design decision as well. Also, as project plans were being designed, technology demonstrations were being designed in parallel. It was also observed, as previously discussed, that there were panels (SRC, IRB) that performed PS-TS or PN-TN in parallel. This was only performed in panels where the members had sufficient technical and project level authority. It was noted that they were able to compare and contrast technical design candidates and then utilize this information in project issues determination, negotiation and eventual selection or recommendation.

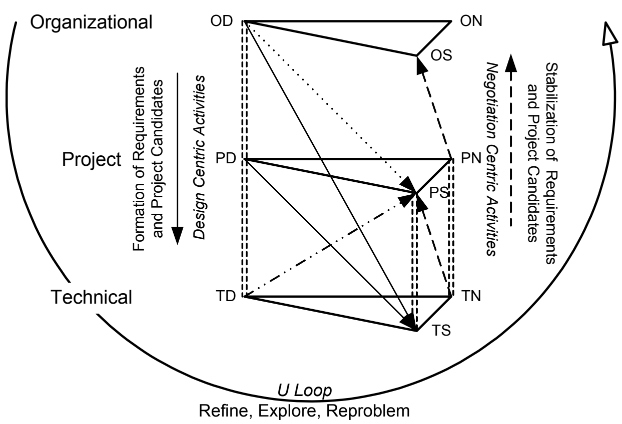

Figure 6 NMP Version of the Authority-Activity Model

Altogether, this analysis indicates that the ideal form of the authority-activity model is a good foundation to work from, while allowing organizations to adapt it to their specific needs, utilizing their authority level strengths. Also, this model is extensible in that different activity triangles can be added or removed as per an organization's needs, including increased or decreased organizational hierarchy levels and "external" third party authority-activity triangles. Hence, the empirically grounded, ideal authority-activity model is presented as a candidate for a general project selection-requirements analysis process model.

6. Conclusions

We conducted an empirical field study to examine in detail the issues faced by practitioners in forming and stabilizing requirements during project selection and the procedures they created to overcome them. We observed that these procedures were an interplay of 1) applied technical, project, and organizational authority with 2) design, sensemaking, and negotiation activity.

The ethnography produced an idealized, grounded authority-activity model of requirements analysis and project selection (Figure 5). The model is a generalized form of requirements analysis-project selection for large, complex, risk adverse (highly sensitive to failure) projects. It represents a method to balance the differentiated authority of the stakeholder groups with the activities necessary to form and stabilize technology-project candidates and their related requirements. The model is built from authority-based combinations of DSN triangles. Each triangle's authority-activity codes are from Table 3.

The authority-activity model indicated that the NMP applied their organizational structure (as well as NASA's) to implement the requirements analysis and project selection processes. No single or small group of analysts ran or mediated these processes. Instead, the NMP technologists shepherded participants and related boundary objects through the process, letting the different authority-activity levels of the organization perform the work. This is a new perspective from which to organize and enact requirements analysis and project selection for large, complex, risk adverse projects.

The idealized authority-activity model is useful to uncover issues with current processes, such as skipped or missing steps, isolating problems with design and negotiation, or uncovering malformed or misinformed sense. It was observed that malformed sense leads to poor design or negotiation outcomes. This was usually correctable by including more sensemaking feedback from other process members after design and negotiation steps. Indeed, a viable technology-project selection candidate requires a "balanced" sense of design and negotiated agreements within and between all of the stakeholder groups. The model indicates that the process should loop (U-Loop) across and within authority-activity triangles to refine selection choices, explore other candidates, or reconsider what problems (i.e. reproblem) are being addressed by the candidates until this balance-of-sense is achieved. The NMP selection process is one example of a process that applies this strategy. In addition, the authority-activity model is extensible in that different activity triangles can be added or removed as per an organization's needs; for example, including or dropping other organizational hierarchy levels as well as adding "external" third-party triangles.

We argue that the core issues addressed in the field study are generalizable across organizations that build large, complex systems and hence, the results of this study form a basis for a general theory of requirements analysis practice. Still, this is only a first step to theory. There should be further study to determine the generalizability and applicability of these findings.

7. Appendix

Table 5 NMP Formulation Process

Process	Code	Key Authority	Primary Activities
0 Start 0.1 NASA Principals Start a New NMP Cycle	OD	(O) NASA Principals	(D) Create and submit new NMP cycle budget (D) Form NASA (O level) requirements for the new NMP cycle
1 Gathering 1.1 Theme Technologists contacted: 1.1.a. NMP requests a list of technologies needed by the Themes	TS, TD	(T) Theme Technologists	(S) NMP technologists make sense of NASA administrators' requirements (S) NMP technologists make sense of current theme technologists' projects (D) NMP technologists generate lists of customer (theme technologists) requirements and requested technologies
1.2 NASA Centers Visits 1.2.a. Centers informed about NMP process and Theme needs 1.2.b. Centers supply a list of technologies/ presentations	TS	(T) Providers (NASA Centers)	(S) NMP asks Centers to produce Center Quads for each technology. A Center Quad, e.g. quad chart, shows a picture of the technology, its main (formal) technical capabilities and usage constraints, cost, and current development timeline. NMP technologists make sense of the new technologies developed by the NASA Centers.
2 Forming 2.1 NMP combines Center Quads into initial TCAs (Technology Concept Areas)	TD	(T) NMP Technologists	(D) NMP technologists design technically viable combinations of the new NASA technologies (e.g. Technical Concept Areas – TCAs), each of which cover a portion of the customers' requirements.
3 TCA Ranking and Reduction 3.1 Theme Technologists Prioritization: 3.1.a. Reduce the initial TCAs into TT recommended TCAs 3.1.b. Criteria: Ranking and Relevance to Themes	TS-TN Loop	(T) Theme Technologists	(S) Theme technologists (TTs) make sense of the initial TCAs (S) NMP Technologists set up the initial rating and ranking criteria (S) TTs perform initial rankings by themselves (N) TTs negotiate rankings and ratings with one-another (S, N) Based on one-another's feedback, the TTs form a collective sense of the TCAs. They adjust the rankings and ratings criteria and redo the negotiation process until they reach consensus. (N) TTs reach consensus to form their final a set of TCA rankings and ratings. Only the highest ranked TCAs are retained.
3.2 NMP management rank the TT recommended TCAs	TS= PS, PN	(T, P) NMP Management	(S) NMP Managers make sense of the received TCA rankings and ratings from the TTs (S) They judge the technologies from a project (P level) perspective to rate each TCAs' Technology Readiness Level (TRL), Cost, and Access to Space (S, N) They rate each TCA with their collective sense of these three criteria. These ratings are added to the existing TCA rankings and ratings.
3.3 NASA Principals select TCAs for publication in a Call for Technologies	OS, ON, OD	(O) NASA Principals	(S) The NASA principals (O level) make sense of the TCAs and their respective rankings (S, N) They discuss the TCAs and negotiate as to which ones best cover their objectives and requirements. This is used to form a collective sense of the proposed TCAs. (N, D) They reach consensus to decide which TCAs go forward into a general call for technologies. The rest of the TCAs are dropped from this NMP cycle.
4 Call for Technologies 4.1 Publish the NRA or TA	TD= PD	(T, P) NMP technologists, NMP managers	(D) NMP technologists and managers create the call for technologies (NRA or TA). The technology announcement contains each of the TCAs technical requirements, NMP general technical and project level requirements (e.g. filters), and the budget for each TCA.
4.2 Hold a Phase A Kick-off Meeting with Providers	TS= PS	(T, P) Providers	(S) Providers make sense of the TCAs technical and project requirements. NMP technologists and managers hold a meeting with interested providers to discuss the TCAs as well as answer questions about the NMP technology proposal selection process.
4.3 Collect Technology Candidate Proposals from Providers	TD	(T) Providers	(D) Providers are given two weeks to create and submit technology proposals. Each proposal is a technology design specification aimed towards addressing a specific TCA. Providers, individually, can submit many different technology proposals.

5 Technology Proposal Reviewing and Rating 5.1 Peer Reviews	TS	(T) Reviewers	(S) Technical experts receive technology proposals. They read each proposal to understand and make sense the proposed technology. (S) Based on their sense of the proposal and their technical expertise in the field of the technology, they form a review of the proposal. This is performed in much the same manner as research conference and journal reviews.
5.2 PRP (Peer Review Panel) Recommendations	TS, TN	(T) PRP Panelists	(S) Technical experts on the panel make sense of the peer reviews (N) Panel members discuss and negotiate technology recommendations with one another. They compare the reviews of each technology to their experience with similar technologies. They make note of any important issues that feel would positively or negatively impact the viability of a technology. At this stage, negative requirements (unwanted capabilities, constraints, costs, or risks) tend to separate the proposals. (N, S) Panel members reach consensus form a final collective sense of each technology. This is expressed as each technology's consensus recommendation
5.3 SRC (System Review Committee) Ratings and Rewards	TS= PS, TN= PN, TD= PD	(T, P) SRC Panelists	(S) Another panel of senior technologists make sense of the PRP recommendations and the peer reviews (S, N) Panel members discuss and negotiate technology ratings with one another. Panel members form collective sense of each technology. (N) Based on the comparison of technologies within TCAs, the panel comes to consensus proposal ratings. (D) Based on the outcome of the ratings, a set of proposals per TCA is selected to continue on to the project-planning phase. (D) The rest of the proposals are rejected
6 Project Proposal Planning 6.1 Produce Candidate Project Proposals	PD= TD	(P, T) Providers	(D) Each accepted technology provider works with NMP technologists to form project proposal teams (D) Each team writes a project proposal, including system implementation plans, mission plans, validation plans, budget, timeline, and so forth (D) Each team also prepares a demonstration of their proposed technology for the IRB Panel
7 Final Review and Selection 7.1 IRB (Independent Review Board) Reviews and Recommendations	PS, PN	(P) IRB Panelists	(S) A panel of senior project (mission) specialists receive and make sense of the project proposals (N, S) Panel members discuss and negotiate each project with one another. They also observe each team's demonstrations. (S) Panel members form collective sense of each project proposal and the technology it represents. They compare this to their experience in executing projects. They make note of any important issues that feel would positively or negatively impact the viability of a project. (N) They compare all of the proposals and to consensus proposal recommendations – accept for implementation or reject
7.2 NASA Administrators' Final Selection	OS, OD	(O, [P, D]) NASA Principals	(S) The NASA administrators make sense of the IRB reviews are recommendations, along with the proposed project plans, and all other supporting documentation (D) They select which projects will be funded for implementation. The rest of the projects are rejected. They (so far) have followed the IRB recommendations.
8 Start of Implementation	TD= PD	(T, D) Providers	(D) Systems Engineering Design and Development

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