

Exploring the Relationship between Project Selection and Requirements Analysis: An Empirical Study of the New Millennium Program

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Abstract

The relationship between project selection and requirements analysis is important, yet has not received much attention. The decisions made during project selection directly affect and frame a project's requirements analysis. In current practice, it is expected that requirements analysis begins after project selection has occurred. Yet, we know little empirically about the procedural relationship between project selection and requirements analysis. We performed a field study to examine in detail how project selection is performed and what procedural relationship, if any, exists between project selection and requirements analysis. We found, contrary to the common view of requirements engineering practice, that requirements analysis occurred in multiple parallel streams. We observed that requirements analysis helped define the initial project choices. In addition, as the project selection process progressed, each candidate project's requirements were further refined. We call this process multiple parallel competitive requirements analysis (MPCRA). We argue that MPCRA should be considered as a viable alternative to current requirements engineering practices, especially for determining and designing large-scale complex projects.

1. Introduction

The relationship between project selection and requirements analysis is important, but is not well understood. It is important because the decisions made when selecting a project frame the project's requirements analysis. These early decisions arguably impact the ultimate success or failure of the project. And, as commonly asserted, requirements errors are the most costly to fix [1, 2].

Yet, there have been few studies which examine the relationship between project selection and requirements. Project selection studies tend to be modelled from a

quantitative economic perspective, i.e. determining the most important decision factors and using them in a model to inform the decision, e.g. [3-5]. Although the needs and the shareholders are somewhat addressed in these models, the details of their requirements are often lost in aggregation. In addition, the specific issues of technology design are usually not a factor in the decision model construction.

Requirements analysis is commonly viewed as a first step in transforming a given problem into a new solution [6, 7]. The details of the stakeholders' requirements are fundamental to the process of creating a requirements specification and are used to help define system design. During requirements analysis, economic factors are often used as nonfunctional requirements to inform design, rather than solely used to decide which design to implement.

Hence, there has been little crossover between the study of project selection and of requirements engineering (RE). Also, another difficulty in studying this relationship is that those who are responsible for performing project selection are in a sensitive economic and political situation. As the project choice increases in economic impact, i.e. costing in the millions of dollars, the scrutiny of the selection process and its influences become very high in an organization. Sites we contacted to study were uniformly reluctant to be observed because of the fear of 1) sensitive business information being "leaked" to those who should not have access it and 2) the fear of bias being introduced into the process by having a third party watch. Altogether, these "barriers to entry" reduce the number of detailed studies of the relationship between project selection and requirements analysis.

We found a group, the National Air and Space Administration's (NASA) New Millennium Program (NMP), who allowed us to observe their project selection and requirements analysis processes. Two important factors allowed this to occur. First. The NMP's selection process is mandated by NASA, by a United States

congressional policy, to be an “open and fair” process. Since their process was “open,” it was generally observable (at least the parts that were not highly sensitive) and well documented. Details about this process are discussed later in this paper. Second, they repeat their selection process at least once a year. This allowed the NMP and the investigators to plan for and conduct the investigation, and to observe a few selection cycles. The repeated processes enabled us to compare current results with the program’s past selections. This paper reports results of the empirical investigation.

1.1. Background

There is a small, but growing, body of research that deals directly with the issue of conflict and negotiation during RE. This includes the application of formal techniques to resolve stakeholders’ goal conflicts [8], analyzing how modeling of goals can help deal with goal inconsistency [9], a cost-value framework for carrying out requirements analysis negotiation [10], the use of a goal-oriented model view of requirements to reveal stakeholders’ interests and concerns [11], and the “WinWin” framework [12]. Although these are good approaches to revealing conflicting requirements, they do not deal with the details in the process of selecting projects that underlies and generates requirements and goal conflicts.

We assert that a careful empirical examination of the process of selecting projects may reveal some of the procedural intricacies that relate the determination of projects to requirements analysis. Hence, in this field study, we explored the following questions: does the order of first determining project choices, making project selection and then performing requirements analysis have an empirical basis? Are these processes really conducted this way in practice? If not, what are possible relationships between project choice construction, project selection and requirements analysis? How are they similar or different to current RE views?

2. Research Methodology

Although econometric and statistical techniques have been employed widely for analyzing decision-making in projects, we feel that they do not provide insight on process details for how project selection actually is performed in the field and what is, if any, the application of requirements analysis to this process. In addition, although there has been work on applying ethnography to the requirements process, especially requirements elicitation [13, 14], there has been little empirical work on observing the requirements process itself.

We decided to use ethnographic field work methods [15] to capture a detailed understanding of a complex

process used for project selection, and to observe the relationship between project selection and requirements analysis. This approach has been used in similar research to understand how complex organizations deal with designing, maintaining or repairing technology [16] and to understand new system design [17].

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 over five months of the NMP space flight validation process in action, 2) 46 semi-structured interviews with NMP members (one NASA administrator) and 34 group meetings, 3) informal and semi-formal discussions with small groups of NMP program, and other JPL, members, 4) attending five detailed technical presentations and 5) studying hundreds of related documents, slide sets and papers that described the NMP process.

All interviews and many of the small group discussions were digitally audio recorded and transcribed. The data was analyzed using open and axial coding [15]. The open coding was used to identify the important components in the NMP process. The axial coding was used to organize and relate the components in a way to faithfully reproduce and represent what was observed. The analysis focused on comparing the process as professed, usually via documents and slide presentations, and the process as enacted, i.e. “invisible work.” [18]. Using an autodiving method of data review [19], the “correctness” of the observed process was validated by the NMP members themselves. It should be noted that the NMP members, in general, were highly insistent on being sure the details were correctly identified and learned by the researchers, as they repeatedly quizzed and corrected the researchers on the process details during many onsite visits.

The findings in this paper focus on the differences between the theoretical view of project selection and requirements analysis and the process as observed. When a notable difference was discovered, follow-up semi-structured interviews were conducted to examine and better understand the difference in detail.

3. The Field Site

The JPL has been in existence for over 40 years. It had been involved in the design and development of technologies used in nearly all of the NASA space (and Earth) based missions during that time, including landing on the moon and the Mars rover. In general, JPL’s main mission is to research, invent and develop new technologies to promote and enable (mainly) space based scientific research. The members of the lab participate in

all aspects of spacecraft design from research on new technologies to architecting, building, and assisting in flying the craft. In addition, work at this site tended to be of the highest standard, arguably, exemplary for those practicing system design and construction.

3.1. The NMP Program

The New Millennium Program (NMP) was started in 1994. The main mission of the NMP is to perform space flight validation of new technologies. It was created to address a problem with utilizing new technologies in space science missions. The primary reason science missions want to use new technologies is to reduce mission cost or to conduct, and even enable, experiments. Yet, new technology is not considered reliable for space use, and hence off-limits to science missions.

The NMP space flight validation selection process is a *project selection process*. Space flight validation means the technology is tested in the environment where it is expected to be used. This is done in order for the technology's functional performance characteristics to be captured, understood and precisely modelled as well as discovering the technology's limitations and problems. Most of the time, the validation environment is outer space. But sometimes, it can be another planet (such as Mars) or the sun.

A main issue the NMP program faces is how to select which new technologies to validate in space flight. 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 systems or subsystems of functionality, such as propulsion, communications, sensors and control systems. Each new technological system or subsystem was viewed by the NMP as a possible project choice.

The overall process the NMP followed was mandated by NASA to be technically rigorous in detail. As part of the JPL and NASA, each step performed by NMP members had to be well understood, documented, repeatable, and justified to those who funded and who participated in the process. At JPL, attention to detail is considered fundamental to success. Working to insure success is critical to JPL, since a spacecraft, once launched, is hard, if not impossible, to fix in flight. Also, any high profile NASA related failure, such as the recent Mars probe, is usually headline news around the world. It is arguable that JPL's exposure to ongoing high risk makes them more likely to take the processes of project selection and project requirements analysis more seriously than those who are exposed to less risk. Altogether, the mission, history, openness, complexity and importance of

the New Millennium Program made it an excellent match for the type of field site needed to do this study.

3.2. Field Site Participants

The JPL members include natural and space scientists, research engineers, project managers, NASA managers and general support staff. Many lab members have a great deal of experience in doing aerospace work, many (hundreds) having been in the field more than twenty years. The expected competence level of the people at the JPL is very high. It was not unusual to observe during meetings and side conversations *very* technical and/or scientifically detailed discussions. Each person needed to "hold their own" and be able to competently ask and answer questions as well as exchange detailed, precise information. As researchers, we found this atmosphere somewhat intimidating, yet reassuring. It was reassuring in that the lab members were highly experienced, deeply focused on the tasks at hand and performed them well. In addition, lab members were rather upfront with their statements and opinions. The high level of articulation of the JPL members made it easier to observe and capture the essential details of their activities and processes.

After five months of observation, clear role groupings of those involved in the NMP selection process became evident. These role groupings are described in Table 1. NMP selection process contained many participants of each role type.

The requirements of the various NMP groups created conflicts in the initial selection objectives. The NMP selection process was set up to resolve these. Each group involved in the NMP process has their own, rather well defined requirements. But, there were too many possible selection process participants, especially providers and customers, for these groups' needs to be satisfied in any single space flight validation project.

The NMP administrators wanted to satisfy as many of NASA's general objectives as possible with the introduction of a new technology. So, they empowered the NMP group to conduct an "open and fair" competition to determine which technologies would be selected for flight validation. The administrators also supported a program of starting up at least one new space flight validation cycle per year. This way, those who "lost" in a cycle's competition would have another chance to "win" in an upcoming cycle, to support a pipeline of new technologies. It could be argued that the main job of the NMP technologists, who shepherded and managed their selection process, was to create and foster an environment in which a technology, and hence project selection, can be made and achieve enough consensus by the NASA administrators and the mission themes to be acceptable.

Table 1. Field Site Participants and Their General Requirements.

| Organizational Role | Process Role | Description | General Requirements Profile |
|--------------------------------------|----------------------------|---|---|
| NASA Administrators (Administrators) | Process Owners, Principals | NASA upper management: Decision makers with the authority to assign organizational resources to implement their decision. They are also the most vulnerable to impacts of mission failure. | <ul style="list-style-type: none"> ○ Want new technologies to be flight test validated so that they can be applied to as broad an array of science mission themes as possible, i.e. to meet as many NASA mission themes' needs as possible. ○ Want to maximize NASA-wide scientific return on investment. ○ Requirements tend to be general, somewhat vague, and usually conflicting. ○ Constrained by budgetary and policy guidelines from the US Congress. |
| Mission Themes (Themes) | Customers | Science mission technologists, scientists, and managers: Planners, designers, builders, and managers of science mission space systems. They are the main consumers of new aerospace technology. | <ul style="list-style-type: none"> ○ Look for new technology that would lower their future science mission system costs or enable experiments. ○ Want to maximize their specific scientific mission return while minimizing cost and time. ○ Due to the difficulty of doing space based research, theme science mission requirements are technically explicit and precise in their needs and constraints. ○ Constrained by tight budgets and project deadlines. |
| Technology Providers (Providers) | Suppliers | Technology makers: Builders of new aerospace related technologies. Providers are usually represented by a team of engineers that produced a system or subsystem under consideration. | <ul style="list-style-type: none"> ○ Want their technologies space flight validated, so they can then be purchased and used in future scientific space missions, likely creating a long term revenue stream. ○ Want to maximize revenue return on investment. ○ Have very precise constraints and usage guidelines. ○ Have specific, semi-customizable technical functionality available. |
| NMP Technologists | Process Actors, Agents | NASA Technologists: Those who assisted and promoted the technology and project selection process. Each technologist represented a different field, such as sensors, software control systems, bio-chemistry, and space systems engineering. | <ul style="list-style-type: none"> ○ Want to balance and satisfy the needs of the administrators and themes, while validating as many providers' technologies as possible under allotted budgets and given deadlines. ○ Want new technologies to space flight validate. ○ Need to insure that new technologies are qualified for space flight validation. |

From examining the 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 eight years to deal with this situation.

3.3. NMP Project Choice Construction: The Creation of Concepts

The overall NMP process contains 3 major steps: selection, implementation, and flight/infusion. The selection process determines which new technologies become space flight validation projects, and thus become implemented and flown/infused. Each year, NMP starts a new process *cycle*. The first step in a cycle is the allocation of a budget by the NASA administrators. The budget, usually \$25 million to \$50 million for all costs associated with a flight, limits what systems and subsystems can be space flight validated during this cycle.

Once a new cycle has been approved by the NASA administrators, NMP technologists visit the various NASA centers (Goddard, Langley, etc.) and find out the technical wants, needs and constraints from the various themes. These are usually very explicit and precisely defined. NMP technologists use their knowledge and expertise in their fields as well as space flight systems to improve the gathering of tacit technical and scientific details. They desire to have multiple NMP and there technologists per interview, but logistics may limit them to one-on-one interviews. It was claimed by the NMP technologists that having multiple people with a variety of highly specialized backgrounds helps discover some requirements that may have been overlooked by using a single analyst.

After interviewing the theme technologists, and other related people, the NMP technologists tabulate the information per theme, examining the requirements that were gathered. At this point, the theme requirements sets are allowed to coexist, i.e. they are not condensed into a

singular set of requirements. Based on these sets of requirements, the NMP technologists consider and discuss, over a period of about a week, the existing new technologies that may be a good fit for one or more theme's requirements set.

Part of an NMP technologist's job is to be current on the new technologies that are available, at least internally to NASA, for space flight validation. This comes from 1) knowing which new technologies (and their relative costs) were not selected from previous NMP cycles and are still available and 2) actively seeking out new technologies. Technology seeking was usually done by attending conferences and tapping one's own professional social-technical networks. The details of the methods used by NMP technologists to seek out new space flight validation candidate technologies are discussed in Bergman and Mark [20] and are beyond the scope of this paper.

Each technologist constructs a set of existing and new technologies (that can potentially be validated), which together would likely address some or all of one or more sets of theme requirements. Multiple constructions per requirements sets were made and documented in a "one-pager" format. These constructions are then collected and analyzed. The NMP technologists individually and in many informal meetings discuss and extract the general technical functional requirements and constraints needed to address one or more of the sets of theme requirements.

The outcome of this analysis is a set of *concepts*. Each concept represents an aggregate set of one or more theme's technical requirements for future space-based science missions. A concept is equivalent to a requirements set for a product family [21], i.e. requirements that fit a group of related technologies (c.f. economies of scope). It was desired by the NASA administrators, and thus the NMP technologists, that a concept cover the widest amount of themes' requirements as possible. The more themes' requirements are addressed by a concept, the more important that concept becomes to the NMP.

3.4. NMP Selection Process

The creation of concepts initiates a project and technology selection competition. Each concept represents a candidate project. Each project could have its initial requirements address by one of many proposed technologies. The NMP selection process is used to "run" this competition until enough information and insight about the candidates is known to make a final selection.

Once a set of concepts has been constructed, they are sent to the NASA administrators, specifically the ones in charge of the NMP, and the directors of the various themes, for a first cut. We were not allowed to observe this process. Yet, second hand interviews told us that most of the discussion revolved around negotiating and

balancing the future, especially near term, needs of the themes with current budget constraints and likely technical space flight validation mission risks. Sometimes, the administrators would ask the NMP technologists to gather more details (usually technological capability and cost related) to help them make their first choices.

As part of the first cut, the administrators allot an amount of funding per concept for providers to use to 1) improve their proposals about their technologies and 2) if selected in later rounds, prepare a space validation mission project plan. The selected concepts and funding allocations are published in a *Technical Announcement* (TA). Each TA identifies the current NMP cycle and specifies, legally, the requirements and the award allocations for each announced concept. It also contains the overall budget for this cycle as well as the expected cost of validating a system or subsystem per concept. For concepts that require large systems, like a constellation of spacecraft (Space Technology 5 – ST5), there is likely only enough money to validate one technical system in the cycle. For concepts that can be satisfied with a subsystem, as many subsystems that are approved and aggregately paid for by the budget can be space flight validated in that cycle, for example Space Technology 6 (ST6) had three subsystems funded. The selection outcome could thus result in multiple "winners."

Table 2. Steps of the NMP Selection Process.

| | |
|----|---|
| 1) | Proposals are reviewed by individual expert reviewers (similar to the journal peer review process). |
| 2) | A peer review board takes the reviews and rates each proposal (fund, fund if there are still funds available, do not fund). |
| 3) | Another board takes the proposal, ratings, and reviews and selects which proposals get funded for further investigation and which are to be dropped. At this point, all of the concepts in a TA are still in competition. Technology sets are paired down until there is only one project proposal per concept. A project proposal may include multiple technologies to satisfy all of a concepts requirements. |
| 4) | Each proposal creates a project plan and does a demonstration of its new technologies. |
| 5) | The results of the demonstration and the project plans are reviewed by a third board. This board recommends which project, and hence concept and technology, to be selected. |
| 6) | The final selection is done by the NASA administrators. |

A TA is an open call to any United States based provider to submit technology that meets the stated requirements of a concept. Providers can and do submit multiple proposals, each of which covers a different concept. The main submitters are aerospace industry companies, universities and U.S. government departments

and laboratories, like JPL. The rest of the NMP selection follows the steps in Table 2.

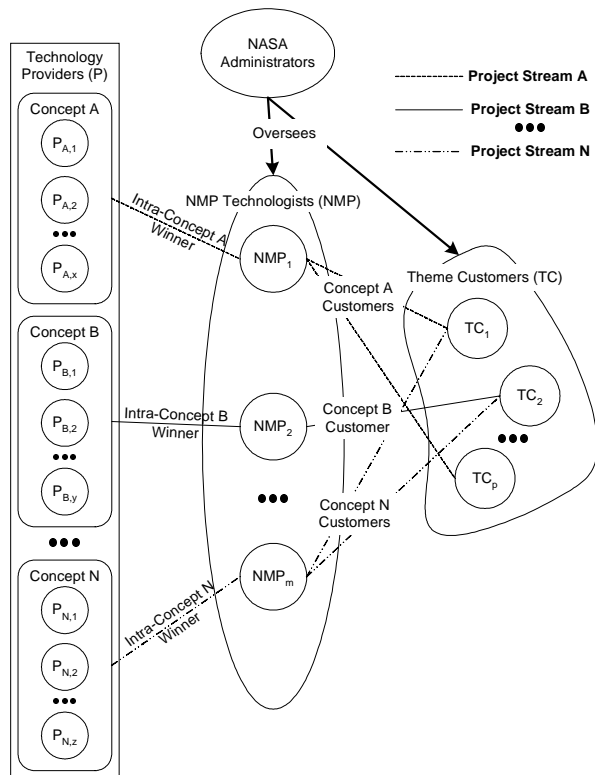


Figure 1. NMP Participants and Intra-, Inter-concept Competition. Project Streams A...N represent the inter-concept competition.

Each technology proposal can be seen as an individual set of requirements, even though these requirements overlap in part with other proposals. As proposals are pared to become potential projects, new requirements are added. Mission project requirements need to cover all issues for the design, implementation, flight, and validation of the proposed system or subsystem and its attendant spacecraft and space launch system. Each of these requirements sets exist in parallel and are in competition with one another. During the six months usually allocated for project plan development, project requirements are examined, refined and conflicts are dealt with.

All proposals compete against one-another intra-concept (steps 1-3, in Table 2), and then inter-concept (steps 4-6, in Table 2), as shown in Figure 1. In steps 1-3, all proposed technologies are reviewed against the published requirements as well as the NMP space flight validation requirements, a.k.a. “fltval” filters [22]. The main purpose of the filters is to determine which technologies must be validated in space, i.e. cannot be

validated on the Earth, and which technologies are likely to be more important to NASA as a whole than others.

Concept requirements and “fltval” filters together, per concept, represent the requirements of the NASA administrators, NMP technologists and the themes (customers). The providers supply initial functionality that could address these requirements (but not usually all of them), but also add their own requirements as well. These requirements are mostly operating constraints, yet can also include other required functionality to work. For example, a sensor system would need a matching communication system to get its data back to Earth. All proposed technologies also came with “negative requirements,” i.e. unwanted capabilities, constraints, costs, or risks. It was observed that selection of technologies, and later, projects, often depended on which candidates had the least negative requirements.

The purpose of the final review panel (step 5, in Table 2) is to resolve the competition between the multiple project streams. As shown in Figure 1, each project stream represents a participant network comprised of provider(s) of intra-concept system or subsystem winner (there can be multiple technology providers for a system), an NMP technologist and one or more theme customers. It is the people in this network who create a project plan for their stream. They also create and present a demonstration of the technology that they want to validate. The final panel considers the demonstration and examines the proposed project plans in detail. They balance what is presented with their own tacit set of (usually) space system risk requirements gathered from decades of experience with space systems. They view each project as a space system and discuss the likely risks associated with flying each proposed validation mission, i.e. mission requirements. This board, like the other boards, are comprised of experts in different fields, that together, help cover the “holes” in the other panelists’ expertise. Their knowledge of the realities of space flight operations is used as an “*experience*” requirements set (e.g. “*experience* filters”). These experience filters are applied to the project proposals in much the same way as NMP fltval filters are applied to technology proposals.

All of the information gathered from the construction and application of the requirements through the extended competitive review process is then presented to the NASA administrators for final selection and funding. So far, the administrators have agreed with the recommendations of the final review panel. In over 10 NMP cycles there have been no challenges to the final project selection(s).

4. Discussion and Implications

The NMP selection process included determining: which concept, and thus project, to design and implement, which starting technologies were to be used in the new

project, and the technical and economic requirements for the project and related technologies. All of these issues affect the design of any system [7, 23, 24]. Yet, the importance of the front-end design decisions affect the rest of design. The NMP selection process posits one view of this front-end: a competitive, feedback relationship between project selection and requirements analysis.

4.1. Selection and Requirements

As seen in the study, technology and project analysis and selection complemented requirements analysis and vice versa. The selection process supported performing many different requirements analysis for the concepts and projects in parallel, i.e. multiple parallel competitive requirements analysis (MPCRA). As observed, MPCRA consisted of 1) gathering the theme's requirements, 2) determining the requirements of the concepts, 3) using the requirements as guidelines for soliciting and obtaining technology candidates, 4) using the concept requirements and the NMP flight validation requirements to filter and reduce the technology candidates, while using the information from the technology candidates to further define a concept's technical requirements, 5) using the resulting concept and technical requirements as a base to create multiple competing projects, and 6) selecting which project to design, implement and fly. As previously mentioned, it is possible for multiple projects to be selected at step 5 (in Table 2).

Each process step from the beginning through to final project selection supports multiple parallel paths of requirements analysis. This includes uncovering both desired (positive) and negative requirements for the candidate technologies and projects. As the selection process progresses, the requirements of each path (especially the negative) are used to assist in making the technology and project selection choices, which, in turn, further refine the requirements per path. By the end of the process, the insights gained by doing MPCRA are essential to making the final project selection.

In addition, the selection process incorporates an initial matching of technology and system design to customer requirements. This exposed and documented project requirements issues very early in the system design lifecycle. Even if a technology is not selected, the technology's provider would have learned a great deal about the strengths and weakness of their technology from a customer's perspective. This information was often used by providers to improve their technology for submission to a later NMP selection cycle.

4.2. Comparing MPCRA to RE

Although much of the requirements analysis per concept and project were gathered using techniques

espoused by RE, especially participatory design, these analyses were carried out in parallel, and mostly, independent of one another, and not in a "single file" process. To illustrate, consider Pohl's requirements analysis "walk" in a three dimensional search space of specification, representation and agreement [24]. Instead only one process trace path, there could be multiple parallel process trace paths. As observed in this study, these paths may reduce to a few coexisting paths or resolve into a single path. This opens up the possibility that the requirements analysis can start with many paths and could produce one or more distinct, though perhaps related, requirements specifications.

Although the drive to produce a single requirements specification has its roots in economic rationality (maximizing return on investment, minimizing cost and time) and design clarity, it may not be an appropriate response to customers' design needs, as demonstrated in this study. The parallel process promoted and supported the prolonged sensemaking (learning, judging, reviewing and selection) [25], which was needed by the project participants so that each technology and project choice could be understood well enough to make informed selection decisions. Also, it was observed that the competition fostered the creation of more detailed and complete (both positive and negative) requirements as well as the application of tacit experience requirements.

5. Conclusions

The study showed that one way to address the project selection competition was to use requirements analysis to better inform each project choice. In so doing, as each surviving choice progressed through the process, its requirements specification would become more detailed and refined. Altogether, the selection process mirrored a high-stakes market, where requirements were used to define, manage and ultimately resolve this market. Although the proposal and project requirements were used later in system design, they were also applied to better understand technically, economically, and organizationally each available project choice. In this sense, MPCRA not only created requirements specification(s), it *used* them to further the project selection process. In so doing, the connections between organizational objectives, requirements, and design were strengthened throughout the NMP process. At the end of the process, the requirements, at least in part, had been verified and validated by the process participants and tested in competition and review. Although the resulting set(s) of requirements are not perfect (none ever are), they are arguably of a higher quality and utility than those requirements gathered in a single path, non-competitive process.

All of this indicates that requirements analysis likely has a larger role in project identification and selection than has been previously identified. We contend that MPCRA is a first step in bridging the organizational problem of project selection and the technological problem of requirements generation. As observed in this study, the two problems not only appear related, but may require one another to be adequately addressed.

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