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Technology Choice as a First Step in Design: The Interplay of Procedural and Sensemaking Processes

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ABSTRACT
Project design involves an initial selection of technologies, which has strong consequences for later stages of design. In this paper we describe an ethnographic-based field work study of a complex organization, and how it addressed the issue of front-end project and technology selection. Formal procedures were designed for the organization to perform repeatable, definable, and measurable actions. Yet, formal procedures obscure a great deal of what processes were actually being applied in performing technology and project section. In actuality, the formal procedures were interwoven with sensemaking activities so that technologies could be understood, compared, and a decision consensus could be reached. We expect that the insights from this study can benefit design teams in complex organizations facing similar selection and requirements issues.

Keywords
Design, organizations, sensemaking, technology choice, project choice, requirements analysis

INTRODUCTION
In some views, the hardest part of design is identifying the problem [9, 11]. One aspect of a design problem is identifying appropriate technology as a basis for development, to satisfy user requirements. We assert that the "front-end" activities of a system project lifecycle are, in themselves, an important component of design. Indeed, they are often the first steps in doing design.

Consider the following scenario. You are a decision-maker in an organization that wants to design and implement an information system to better facilitate sales, customer retention and customer service. There are millions of dollars to be budgeted for developing this project. You recognize that you have many different groups of customers that have somewhat-to-very different needs and constraints. Not only do the customers have diverse requirements, but so does management, IT support, the developers, and so on. Your organization is faced with multiple sets of requirements that are competing. All your potential or actual customers cannot be satisfied by a chosen solution. At the start of a project, there exists sets of available technological capabilities that could be used in addressing some of the customer demands. In this scenario, the technological capabilities that fit the spectrum of customer demand are mobile, hand-held, web, database and middleware systems. These technological capabilities are represented by individual or combinations of existing technologies, all significantly different from the others. Each combination, plus any additional work necessary, represents a possible project choice. Therefore, a project choice also represents one or more choices of technologies. There are hundreds of different project possibilities. How do you choose which project to do?

This study examined how one organization faced with a similar scenario made this choice. In this paper, we focus on the initial actions of problem and "upfront" technology selection. Still, any initial problem or technology choice only constrains and informs design, but often does not replace further design. Until now, to the best of our knowledge, the initial choices that influence subsequent design have not received much attention among researchers. We argue that they are indeed a crucial part of design, as they have strong consequences on the later stages of design, especially system architecture and detailed design.

Most organizations do not develop systems from scratch. Instead, to deal with economic constraints, they often: 1) identify possible problems that represent customer demand [29], 2) consider which possible technologies are useful to address these problems, e.g. commercial off-the-shelf software (COTS) [7] or open source software [16], 3) choose which problems to address, and 4) implement a project to solve the problem. The initial choices for problem selection, in turn, involve a process of balancing/negotiating, etc. requirements from multiple sources [25, 27, 32].

As March (1994) [29] so aptly 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. Each problem-technology set represents a different (and sometimes overlapping) group of stakeholders, but usually not all of them. Each stakeholder group has its own set of requirements that underlie their problem-technology choice. Altogether, the front-end of system design can be seen as a project selection process that involves multiple parallel heterogeneous requirements.

This paper presents a field study which illustrates how a complex large organization managed the initial problem/technology choice. We will discuss how the process owners and participants wanted to create and follow a *formal, procedurally-based* process model, similar to those espoused by business and software process modellers [12, 35, 41] and the CMM (Capability Maturity Model) [22, 39]. Although this was the proscribed method, it was perhaps not surprising that the actual choice process did not, and could not, fit a procedural process model.

The research questions that motivated the fieldwork study were: how does an organization perform problem-technology selection in a domain of conflicting customer demands? To what extent are formal procedures followed, and when not, what other activities are used in the selection process? How do formal and interpretive processes inter-relate in performing problem-technology selection?

RESEARCH METHODOLOGY

Lately, most research in project decision-making is done using quantitative methods, often employing econometric and other similarstatistical techniques. Examples of quantitative work that apply to project selection include Felli, et al's, project selection model at the Monterey Bay Aquarium [18]. Butler, et al [10] applied multiple attribute approach to ranking sets of technology configurations against one another for project fit. Cook and Green used data envelop analysis to perform project prioritization [13]. Jiang and Klein studied project selection based on organizational strategy criteria [23]. Parnell, et al, use a more general approach to multivariable decision analysis in evaluating the need for technology for air and space forces [38]. Indeed, the Parnell article is one of the exceptionally few articles that even addresses the issue of front-end technology selection.

Although many researchers have employed econometric and statistical techniques for analyzing decision-making in projects [10, 18, 38] we feel that they do not provide insight on process details for how project and technology selection actually are performed. For example, the "invisible work" that is a part of selecting candidates and making choices is not included in such models [33, 42-44].

Methods

Ethnographic-based field work was conducted to understand how a complex organization addressed the issue of front-end project and technology selection. This approach has been used in similar research to understand how complex organizations deal with designing, maintaining or repairing technology [14] [34]. Also, field work methods have been used extensively to understand design [5, 20, 21, 31, 37].

The field site, "the Lab," was a NASA (National Aeronautics and Space Administration) research laboratory located in southern California. The group we studied was the VAL[1] program. Field site data collection consisted of: 1) participant observation of the VAL space flight validation process in action, 2) semi-structured interviews with VAL members and many of those they interacted with, 3) informal and semi-formal (lunchroom) discussions with small groups of VAL program and other Lab members and 4) a collection of documents and presentations that were either used in, or informed the VAL process. All interviews and many of the small group discussions were digitally audio recorded. This was augmented with extensive fieldnotes. The field work was conducted over a period of five months.

Interviewees were either identified by key informants or by participation in on-site meetings and presentations. Altogether, there were 46 one-on-one (including a few one-on-two) person semi-structured interviews, and 34 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 VAL members that were observed and interviewed repeatedly. Three of the VAL 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 VAL related work as well as unrelated Lab work. There were 13 technology providers, five internal and eight external to the Lab, that gave presentations about their technologies. 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 VAL members about the roles of the VAL program director and the theme mission directors in the VAL selection process. This discussion was obtained from internal documents. There were hundreds of related documents, slide sets and papers, of which there were two key internal documents, four sets of slides and a conference paper authored by the VAL group.

The data was analyzed using open and axial coding [43]. The open coding was used to identify the important components in the VAL 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." [42].

Using an "autopiloting" method of data review [4], the "correctness" of the captured process was validated by the VAL members themselves. The autopiloting method started approximately halfway into the field research. The comments from the self-reflective reviews were also used to gain further insights into the details of the VAL process. It should be noted that the VAL members, in general, were highly insistent on making sure the details were correctly identified and learned by the researchers.

[1] VAL is a pseudonym for the actual program's name.

This method of data collection, data analysis and review enabled early insights as to how well the VAL process compared to theoretical process modelling, requirements analysis, and decision sciences. If a notable difference between what was seen and what was procedurally stated was discovered, then follow-up semi-structured interviews were conducted to examine the difference. The findings in this paper focus on these differences.

THE FIELD SITE

The Lab 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, the Lab'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.

Space Systems are Interactive Systems

Technologies being developed at the Lab are generally called systems or subsystems. A system usually represents a full spacecraft or an essential aspect of its design, for instance navigation, propulsion, communication and mission control. Subsystems are technologies that "go along for the ride," but are not usually essential for the spacecraft to function, for instance sensors and probes for experiments. As seen from the examples, the types of technologies used in space systems are very diverse. Any new space system under design can contain multiple different systems or subsystems. Hence, each spaceship contains a wide array of heterogeneous technologies. Space system technology diversity is due to the need to satisfy multiple user, customer and NASA institutional requirements.

Each spacecraft is an interactive system, once deployed. Altogether, a space system can be viewed from one point-of-view as a combination of a moving vehicle, advanced cell phone, many different sets of delicate sensors and instruments, and a fault tolerant personal computer. It is a system that usually no one ever touches in operation, but many people use and manipulate remotely.

The VAL Program

The main mission of the VAL program, begun in 1994, 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 main reason science missions want to use new technology is to reduce cost or to conduct experiments. Yet, new technology is not considered reliable, and hence off-limits to science missions.

The VAL program's mission is to take new technologies that are deemed important to future science missions and perform validation on them. Validation means the technology is tested in the environment where it is expected to be used, in order for the technology's functional performance characteristics to be captured and precisely modelled. Most of the time, the environment is space. But sometimes, the environment is on another planet or very near the sun.

A main issue the VAL program faced was 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 tended to cluster into sets of functionalities, such as propulsion, communications, sensors and control systems. Any final technology and project selection has to satisfy the NASA directors and competing science mission technologists. Altogether, the VAL space flight validation program concerns heterogeneous technology choice. The choice of technology therefore defines which space flight validation project to fund and fly.

The process the VAL program followed was mandated by NASA to be technically rigorous in detail as well as open and fair to the involved competing participants. As part of the Lab and NASA, each step performed by VAL members had to be well understood, documented, repeatable, and justified to those who funded and who participated in the process. At the Lab, attention to detail is considered fundamental to success[2]. The focus, experience and openness of this VAL program made it an excellent match for the type of field site needed to do this study.

Field Site Participants

The Lab 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. Everyone we met was highly technically proficient, even the support staff, though to a lesser degree.

The expected competence level of the people at the Lab is very high. It was not unusual to observe during meetings and side conversations *very* technically 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 focused on the tasks at hand and doing them well, as well as being rather upfront with their statements and opinions. From the researchers' point-of-view, it was a reassurance that was fostered by ongoing experiences with a highly competent group of people, who were committed to dealing with incredibly difficult problems while aspiring to serve others.

[2] Any Lab related failure is usually headline news, such as the recent Mars probe failures. Hence, the need for the Lab to succeed in doing space projects is highly reinforced externally and internally.

After five months of observation, clear role groupings of Lab members became evident, via observation and open coding of the field notes. Each selection process contained many participants of each role type. These role groupings were:

NASA Administrators, i.e. NASA upper management were principals (i.e. process owners) who wanted new technologies to be flight test validated so that they can be applied to as broad an array of science mission themes as possible. They were process principles, i.e. decision makers with the authority to assign organizational resources to implement their decision. In NASA, they tended to be very senior system engineers, with usually 20+ years of experience in either engineering or managing space flight system projects.

Mission Themes, also known as *themes*, were customers who had upcoming science missions and were looking for new technology that would lower their mission system costs and/or enable functional capability or performance in some specific way(s). Themes tend to be represented by theme technologists, but can be represented by theme managers as well. Due to the difficulty of doing aerospace research, theme science mission experiments were very precisely defined. Hence, theme technologists were technically explicit and precise in their needs and constraints.

VAL Technologists are agents (i.e. process actors) who assisted and promoted the technology and project selection process. These people were very senior NASA technologists, each having 15+ years of experience at NASA and 40+ years in their specializations. Each one represented a different field, such as sensors, software control systems, bio-chemistry, and space systems engineering. They all have experience in many previous space design and flight projects.

Technology providers (i.e. suppliers) had technologies they wanted to have space flight validated. Once a technology is space flight validated, it can then be purchased and used in future scientific space missions. Providers were represented by a team of engineers that produced a system or subsystem under consideration. They were, in general, highly technical and experienced. In fact, to work with (or at) NASA, one must show a high level of technical competency, quality of product and economic efficiency (in budget and on time). Due to this, there was a great deal of use of quantitative models to describe a technical system or subsystem functionally (capability, tolerances, constraints), physically (size, mass and alike) and economically (costs per specific configuration).

PROCEDURE IS NORMAL FOR ORGANIZATIONS

Starting with the birth of management science, usually attributed to Frederick W. Taylor [45], and proceeding to modern day with business process reengineering, business objects and workflow automation systems [8, 15, 19, 24, 26, 41], organizations have wanted to become more procedurally oriented. The term "procedural" is used to be consistent with Osterweil's use of the term in process programming [12, 35, 36]. There has been a clear trend in modern organizations to define and automate repeatable, formal procedures to be used in performing the organization's tasks.

The Official VAL Procedure

The Lab, and in turn, the VAL program, embraced procedural processes to define their work. According to NASA policy [1], all programs and projects in the Lab must have well defined procedural processes, similar to the CMM's (Capability Maturity Model) business process definitions and structure. According to the CMM and related work process literature, procedural design processes are usually formally repeatable, definable, measurable, and, eventually, optimizable [22, 39]. A procedural process should be repeatably executable with reasonably predictable results. Each use of the process should have well-defined inputs, expected outputs, known roles for the process actors (i.e. people who perform the process) and a clearly defined set of activities to follow. Once a procedural process is performed a few times, it is easier and faster to perform it again in the future.

The VAL program also had their own situated reasons to create procedural processes. As per the group's Program Plan, they had to have a fair and open process when soliciting new technology. More generally, a well-defined procedural process made it easier to account for, and defend, final technology and project selection decisions. Each provider would know what the process is, how it is conducted, what they need to do, and how the selection outcome was determined. The published procedural view of the VAL program's selection process had the following steps.

1) A Technology Announcement (TA) is created and announced using the concepts approved by the NASA administrators and defined by the theme and VAL technologists.
2) Technology proposals that fit the concepts are submitted for consideration and review.
3) Proposals are reviewed by individual expert reviewers (similar to the journal review process).
4) A review board takes the reviews and rates each proposal (using the previously mentioned ratings).
5) 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. Technologies 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.
6) Each proposal creates a project plan and does a demonstration for each of its component technologies.
7) 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.

The final selection is done by the NASA administrators.

A TA contained many different sets of precise functional requirements and constraints. Each requirements set represents a *concept*. A concept is equivalent to a product family [2], i.e. requirements that fits a group of related technologies (c.f. economies of scope). Each concept represented an aggregate set of one or more theme's technical needs for future space-based science missions. The more themes represented by a concept, the more important the concept was to the NASA administrators. The most important concepts, which are also considered reasonably affordable (again, by the NASA administrators), appear in a TA. A proposed technology must meet one of the concept's set of requirements for it to be considered for space flight validation selection. Still, more concepts were announced in a TA than can be funded in a single space flight validation cycle. Hence, the VAL selection process chose concepts, in the form of projects, and the technologies to best represented a concept.

The need for a well defined, repeatable and fair procedural process led to the Lab's use of review boards as repeatable processes. The Lab utilized three different selection review boards. The first board reviewed and rated submitted technology proposals from providers. The second review board then used the results from the first board and decided which of the proposals to fund and which to drop. A funded proposal became a candidate project. Each candidate project was represented by a provider and Lab member based project team. Each of the project teams were assigned to 1) produce a project plan that showed how the proposed technology would be put into space and then validated once in space, and 2) demonstrate a working version of their technology. The funding for the candidate project teams ranged from tens to hundreds of thousands of dollars. After a six month period, the project proposals and demonstrations were due. The third review board observed the demonstration, reviewed and debated the project proposals and then made final project selection recommendations. The final selection was done by the NASA administrators. So far, they have followed the recommendations of the third review board.

A new space flight validation process cycle (e.g. cycle) started once a year. These review boards usually contained different people for each cycle of the selection process. Hence, there was little or no carryover history from one board to another. Due to this, the board process procedures were well-defined and repeatable with: defined requirements for who can and cannot be a board member, a description of what each board member was to do, the general procedure of how the review process was to be performed, a well defined rating system (as appropriate), a standard format for all (input) documents to be reviewed, and a standard way to publish the results of the process. There were defined procedures to deal with known process exceptions, such as replacing a board member, dealing with lost reviews or proposals, technology demonstration problems and improperly filled-out proposal or project documents. Altogether, creating a procedural process framework for the review boards made it possible to "plug in" new people to boards from cycle to cycle, move data through the selection process, produce "paper trails" to document and defend the selection results, and determine and publish a final selection within a specified time and budget.

VAL Selection Process Execution

The VAL technologists manage the technology and concept selection process. Managing includes defining and abiding by the TA, creating and monitoring the review boards and shepherding the process to completion. Shepherding means assisting participants in understanding the selection process and producing documents that conform to the selection process standards without giving any specific technical advice nor any information about a competitor's technology. It was observed that this did help keep the process moving in a timely manner, since small problems in the proposals or project plans could be caught and dealt with swiftly.

Interestingly, shepherding led to some consternation amongst the VAL technologists. They repeatedly expressed frustration over not being able to help out with technical problems they observed with a technology and not being able to "leak competitor information" that would allow for combining proposals to make a better proposal. Still, to be seen as fair, the technologists must be seen as unbiased, and thus not allowed to "interfere" in the selection process. The VAL technologists expressed that this restriction limits the ability for the selection competition to conform to the "best" principle. But, they consider it a necessary social "fairness" requirement, which allows the process to work at all.

This "unbiased" view of the Lab has yet to be achieved, as per the VAL technologists and some of the providers. Since all of the technologists are in one location, i.e. at the Lab, there is a perception that the Lab favors its own internal providers. In addition, the Lab's internal providers have stated that too much attention is given to "non-Lab" providers. This indicates that even with clear, published procedural processes, it is not possible to remove the view of bias in a competition.

Still, the Lab endeavors each cycle to improve its "fairness" based on feedback from providers. This has led to the desire to quantify every selection rating and review. The NASA administrators wanted the front end of the selection process (technology reviewing and rating) to determine the quantitative data. Then, they wanted to use the quantitative data in an algorithm to make the project selection. Since all of the technologists were experts in quantitative metrics and methodologies, it was expected that quantifying the ratings and creating a selection algorithm should have been reasonably doable. Oddly to the VAL members, it was not.

A MIX OF SENSEMAKING AND PROCEDURE

After a couple months of observation and participation in the selection process, the observer mentioned during a lunch meeting, which included most of the selection process VAL technologists: "*It looks like you are doing a lot of sensemaking.*" The response was a drawn out silence. After a few seconds, a flood of questions were asked by the VAL technologists: "*Sensemaking, what is that? I have never heard of it.*" "*Why do you think this?*" "*Why is that important?*"

Not a single person at the table had heard of the term or knew what it meant. Indeed, mentioning the term to others in the Lab elicited a similar response.

The questioning stretched into months. It was clear that the technologists were very curious, open to this "new" idea and eagerly wanted to see if it would assist them in their work.

What is a Sensemaking Process?

Sensemaking processes are quite different than procedural processes. Sensemaking processes are performed when 1) the process goals are ambiguous and need to be defined or 2) the process goals are clear but there is no known procedural (prescriptive) process that can be performed to satisfy the goals [46]. Sensemaking processes are usually imprecise in description and indefinite in duration, although a specific time limit can be specified.

Sensemaking tends to be an individual (or small group) artesian activity or it occurs during complex interactions amongst likewise interested process actors (even if each actor has different objectives) [3]. In general, sensemaking processes occur when there needs to be some required *learning* or *judgment* to be able to satisfactorily perform the process [46] and the process can be performed within a set of given (by the process owners) economic and political constraints.

Sensemaking and the VAL Selection Process

Though technology selection was considered procedural by the selection process participants, it ended up being a multiple-stage sensemaking process. Although the overall process and some of the steps were clearly procedural, many of the steps, as performed, were not. When examined more closely, many selection subprocesses had *neither* known process activity steps, known inputs, expected outcomes, nor precise metrics of success.

The VAL selection process was a blending of procedural and sensemaking processes. The VAL program used sensemaking processes, but not in the general way Weick describes. Instead, they used their procedural processes as a framework to focus, separate, and manage specific sensemaking subprocesses. The 8 main steps contained necessary structure to make technology and project selections. The procedural processes utilized interprocess exchange requirements, like standard ratings and project specification formats, to smooth the transition between process steps. But, each procedural process contained one or more sensemaking subprocesses dedicated to dealing with the issues and achieving the objectives of its procedural process. In addition, each procedural process had specific time limits and localized budgets. These constrained their sensemaking processes so they would focus solely on what was needed to complete the specific procedural process, while minimizing the "wandering" that takes place during sensemaking.

A trade-off these constraints incurred was limiting the amount of sensemaking that could take place during each process. This meant some of the depth and richness of learning, understanding, and judging of the technologies and projects were curtailed in favour of producing timely results. The procedural process was constructed and evolved over time to minimize (but not eradicate) the damage inflicted by these losses, especially by the use of multiple review panels. Still, the balance between the procedural and sensemaking process for the VAL program is under constant review. There is a "lessons learned" process after each VAL process step to examine what occurred and what should change to improved the process. This allows a separate "meta" process level sensemaking to occur over time, which slowly modifies the procedural-sensemaking blending and evolves the overall VAL program processes.

Examining the mixture of procedural and sensemaking processes more richly describes the structure of the VAL selection process. Still, to obtain a better understanding of the need and use of sensemaking during the VAL selection process, some examples are presented in detail.

"No Selection Algorithms"

An observation concerning the desired use of algorithms in the selection process produced this exchange:

Lab member: There is a rule: 'No selection algorithms for selection.'
Observer: Why don't you use algorithms to do selection?
Lab member: No one could agree on what the numbers mean. No one could agree on what the definitions mean. We tried for a long time, but all attempts have failed. So, we adopted the rule.

Over the past eight years, there had been a variety of attempts to assign a number to the technology (system and subsystem) proposal ratings. This number was usually a composite of a variety of other numbers that quantified different aspects of the proposal. This included (at any one time) the readiness of the technology, the functionality of the technology, especially excess, unnecessary functionality, the fit between the technology and the concept requirements, the reliability of the technology and its supporting organization, the risk of failure to the technology or other systems connected to the technology, the reviewer's first-hand knowledge of the technology, expected cost to mature the technology, and the quality of the proposal.

Terms like "risk," "readiness," "fit," "function," and "quality" did not have the same meaning for different types of technologies. Each technology reviewer had to make his or her own sense of what each of the terms meant for the technology being reviewed. For instance, a gravity wave sensor usually had very precise values to fit, risk, functionality and readiness. An autonomous space craft control system did not have precise values. In fact, their values are quite different in meaning and scale. A control system commands the whole spacecraft, and thus is not isolatable like a gravity wave sensor. A control system has higher and more complex risks to the spacecraft itself. A gravity wave sensor's main risk is in the failure to correctly do an experiment. There was no agreement as to how calibrate the metrics or even to define the metrics themselves. A VAL technologist summed this up by saying "*the numbers hide the details and the details hide the numbers*."

This does not mean quantitative values were not used in the selection process. In fact, they were depended upon quite heavily by the review, ratings and recommendation boards. The TA and each proposal was a mass of explicit, precise technical details. Where appropriate, specific numbers and ranges were given for cost, size, functional sensitivities, performance, energy demands, communication requirements, system mass and so on. The VAL technologists created a *quad-chart* to capture the pertinent technical information on a single page. The chart showed a picture of the technology, the space flight validation rational and expect cost range, technology description or functional requirements, and a timeline for expected technology capability improvements over time.

The review board members used the quad-chart information, along with the proposals and reviews to *learn* about each proposed technology. They took this information and *judged* each technology, utilizing their own experience with similar technologies and the explicit demands of the concept the technology was situated in. They *discussed* their judgments with each other to come to a *consensus*. As noted by a VAL technologist, the results of the board were based on the board members' experience and history with the technologies and space system design. Thus, the quad charts were a way to formalize the information used by the reviewers in decision-making. The board participants indeed followed the rules, requirements, timeline and order of proposal review as defined by the procedural process view of the review boards. But, the judgments, ratings and recommendations were determined by a sensemaking process.

Final Selection

Towards the end of the selection process, the reliance on space system expertise, especially space mission risk and cost considerations, became more prominent. At the project recommendation and selection stage, each technology was not directly comparable. Still, using very precise, technical language, each technology was considered from a space flight project point-of-view. Questions of risk took on deeper meaning. For instance, "*Will this technology endanger or destroy the space shuttle?*" "*Does this technology impose a possible radiation risk to the planet [earth]*?" "*Does the gravity of the Earth 300 miles out affect the validity of the fight test?*" "*What do you think is the real cost of getting the technology ready and shot into space?*"

Since each board member (in any of the boards) is an expert in a specific field, the rest of the board members depended on and learned from the other board members about each technology and project proposal. On rare occasions, a board member may mention some mission risks that were unanticipated in a project plan. This can and had swayed the opinions of the other board members in favor or against a specific project.

It was observed by a few VAL technologists that, so far, there had been 1) no algorithm that can reasonably replicate the judgment process of the boards, 2) there was no agreement as to the precise meaning of the project comparison metrics, such as "project risk" and 3) it was not predictable as to what a board will and will not recommend (it is possible that *no* project is recommended). An algorithm did not allow for the technical, economic and political consensus building that occurred in the board meetings. Indeed, it was a requirement that any recommendation must be made by unanimous consensus. Board discussions allowed for the expected "political positioning" that each member will likely take to promote a personally desired concept or technology. Through "hashing it out," these positions were attended to and a stable socio-technical agreement [6] can be reached.

Altogether, the process used by each board is a sensemaking process, which relies on access to and use of very accurate, precise technical information. In addition, until the important aspects of the sensemaking process used to make ratings and recommendations are known and can be quantitatively modelled, it is unlikely that a quantitatively based algorithm will be creatable and acceptable in the selection process.

Sensemaking with Space Flight Validation Filters

Another example of using sensemaking processes during the selection process was in the creation and application of a set of *space flight validation filters* used to determine whether a proposed technology should be considered for space flight validation at all. Space flight validation filters were created and refined over the past eight years and over ten VAL cycles. They were originally a set of heuristics the technologists applied to be sure inappropriate technology did not get into, and thus slow down, the selection process.

None of the filters had precise quantitative definitions. This is due to, in part, the complexity and diversity of technologies these filters were applied to. Most of the filters dealt with the qualitative aspects of the technology or the environment in which the technology can be validated. For instance, the "in-space" flight validation filter specified whether a new technology can be validated on the Earth or must be validated in space[3]. Any technology that can be validated on the Earth (even with only the use of simulation) was dropped as a space flight validation candidate.

The application of "in-space" filter had led to many long and complicated discussions. Most of the proposed technologies were usually a system of many component technologies. There was (and still is) an ongoing discussion whether each component technology needs to be space flight validated individually as well as together in a system. The following statements show some of the typical discussion points:

[3] The other space flight validation filters tended to be applied and refined in a similar way to the "in-space" flight validation filter. But, there were too many other filters to go in to detail in this paper.

Do the flex cables that connect the boards need to be validated? We don't know how they perform in space. Still, they are just ribbon cables. Do we have to wait to validate the whole system on the next cycle until after the flex cables are validated?

Each of the components in this communication system has been validated, but the combination of the components has not been. Does it need to be validated?

An Aerocapture system needs to validated in the environment it has to work in. It is not possible to recreate the Martian atmosphere, its density and chemical composition, and planetary gravity, and have the capture system move fast enough in this environment on Earth.

Each proposed technology goes through this debate. The less obvious the answer, the longer the discussion between the technologists, and between the technologists and the providers. These filter discussions tended to be "invisible," i.e. not outlined in the VAL stated procedural processes. It was observed that some of these discussions went on for weeks or months (such as for software autonomy systems and inter-satellite communication systems), but most were usually resolved quickly (such as for gravity wave detectors).

Filters could be applied at any time during the selection process, although they were usually applied before or during the first review board. A review board could ask for a report from a VAL technologist as to their opinion on how well a specific technology passed or failed the filters, or they could apply the filters themselves. Altogether, these acts of applying the filters to the proposed technologies required judgment, learning, reliance on history and expertise, presentation, argumentation by and between multiple participants.

Sensemaking using Social Networks

Although much of the process of selection is done by the review, rating and recommendation boards, there was a lot of work going on "behind the scenes" by the VAL technologists to be sure there were technologies to select from. VAL technologists relied on their technical, social networks to find out about possible new candidate technologies. Much of this work occurred in one of the Lab's lunchrooms.

The lunchroom is my main place of work.

The VAL technologists tended to eat starting at noon. Each VAL technologist had an office in a different building within the Lab. So, lunch was one time during the day they all tended to come together.

Most of the few hundred people eating during this time seemed to know one another. Repeatedly, it was observed that a Lab member knew quite a lot of information about his or her lunchroom colleagues. This included a person's name, organizational work area, expertise and some of what s/he were currently working. If a person was not directly recognizable by another in the lunchroom, there was usually a third person at a table that would know both of the other people. The observer was introduced and instituted into the "lunchroom network" in this way.

This repeated expression of technical and social knowledge showed the existence of a rather tight technical, social network in that lunchroom. During any one lunch, a technologist would either seek out someone s/he would need to communicate to about a specific problem and converse with them. Many short (5 minute of less) conversations occurred during the time a technologist walked towards his/her table to eat or walked from his/her table to drop off his/her tray. There would be longer discussions with those the technologist sat down and ate with. As observed, the content of these conversations would usually be one of: reminders of work that needed to be done by a certain time (usually yesterday); request to do a favor; request for information about a system, project or person; or general "catch-up" project, technology design or personal status discussions.

Over time, it was observed that quite a lot of work was being performed in the lunchroom utilizing this localized technical, social network. During some of these discussions, new technologies or projects would be brought up. If the new technology seemed appropriate for space flight validation, a technologist would actively seek out the person or group who was working on the technology, i.e. a technology provider. Often, a technologist would know who this person was and set up a face-to-face meeting. It was observed that a VAL technologist often knew who the person was by name, where s/he worked, his/her expertise and what other projects, missions and technologies s/he had worked on. This indicated that each technologist had a private, personal technical, social network that extended beyond the lunchroom network.

New technology meetings were normally conducted at the technology provider's office, even if the office was outside the Lab. Sometimes a VAL technologist went to a conference to observe many new technologies at one time and meet with each of the technology's providers. Whether at an office or a conference, these meetings tended to be focused on 1) gaining a deeper understanding of what exactly the new technology's capabilities, constraints and readiness level were and 2) the initial application of the space flight validation filters. If a technology looked like a good fit, its provider would be encouraged to watch the TA's and submit a proposal for the technology when it matched a concept's requirements. It was observed that many of the validation technologists keep personal lists of likely candidate technologies. These lists were used to contact the new technology providers when a likely concept match was about to appear in a TA, and sometimes to help define a TA. No provider was obligated to submit a proposal. Still, those who received personal attention tended to submit proposals.

Altogether, each technologist's technical, social network was utilized to perform sensemaking activities. These activities included, amongst others, discovering, learning about, and soliciting new technologies for the selection process. Many activities were the "unseen" process work that was necessary to implement the selection process.

DISCUSSION AND IMPLICATIONS

In what ways does technology and project selection, as discussed, affect the design of interactive systems? Although space systems are an extreme form of interactive systems, the main lessons learned can be generalizable beyond space systems. The selection process itself, and how it addressed deciding which problem-technology set to choose can be considered common to many, if not all, designs of interactive systems. The selection decision 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 [28].

Sensemaking and Procedural Processes in Tandem

The selection process was designed to occur in many well defined, repeatedly followed steps, as earlier discussed. Any change in the stated process must be renegotiated with the providers and the NASA administrators. Hence, there tended to be few changes or deviations. Altogether, the general organization of the selection process can be defined as a procedural process.

Yet, our data show that the selection process steps actually rely upon sensemaking. Most of the important selection work, i.e. reviewing, rating, recommending and soliciting for technologies, were sensemaking activities. Yet, it is how the sensemaking activities were combined with the procedural process for each step that allowed for the technology and project selection processes to be performed repeatedly, efficiently, and to create acceptable socio-technical selection agreements.

Sensemaking on its own does not conform to organizational economic constraints. It is not well bounded in time or cost, by definition. Procedural processes, when well defined, repeatable and well understood, do tend to conform to organizational economic constraints. But, procedural processes cannot insure the discovery, learning and consensus building that a sensemaking process can produce. By examining the eight main procedural steps, one can see that each step isolates one type of sensemaking activity, bounds it in time, cost, and defines acceptable outcomes. Instead of one large, overly complex and ill-manageable sensemaking selection process, there are many small, well-understood sensemaking subprocesses. Each sensemaking step is isolated from the other steps and must be completed within its own specific governing framework (i.e. rules, policies and success/ending criteria). The front-end review process focuses solely on the technologies, i.e. the intra-concept selection problem. The back-end process focuses on the project selection, i.e. the project selection problem. The procedural processes also use standardized artifacts (i.e. documents and slides) that allow for the smooth flow of information between the process steps. This also tends to "clean up" and "focus" the sensemaking activities and their outputs.

The complexity of the selection problem was reduced, and the detailed information about the proposed technologies and their providers was increased, as the selection process progressed. From a general point of view, learning, discovering and consensus building via competition, confrontation, discussion and examination were occurring throughout the whole selection process. Therefore, the selection process was, as a whole, a sensemaking process. It was built upon a procedural process foundation, which in turn isolated and utilized sensemaking activities. As such, this structure had the power to be able to repeatedly perform selection determination amongst a very complex, heterogeneous set of technologies and projects.

Overall, the selection process resulted in defining which project or projects to design and implement. Depending on the allotted budget and TA specification, multiple projects could be funded. Hence, any one selection cycle could create multiple projects (unless only a single project outcome is stipulated in the TA). Indeed, multiple project outcomes have been observed in many cycles.

In addition, during project and technology(s) selection, the detailed requirements of the project(s) were determined as well. This was mainly due to the need to determine the concept requirements as well as the different technologies' fit and constraints during the selection process steps. One of the final results of the selection process was, therefore, a technically detailed project plan, which defined the requirements that the spacecraft design, implementation and flight were to follow.

Design by Concept

This study provides some insights on how project and technology selection is managed in multiple, competing heterogeneous domains of technological capabilities to meet divergent sets of customer demands. Domains of technological capabilities could be technology families from the original introductory scenario (i.e. mobile personal data appliances (PDA's), internet infrastructure middleware, database) or technology families for spacecraft design (i.e. propulsion systems, sensors, communication systems and alike).

As seen in the study, concepts represented 1) a related set of customer requirements and 2) a domain technological capabilities. In this way, customer demand and technological supply were paired at the beginning of design. This insured, in part, that customer requirements would be addressed in a design that selected their particular concept. This does not guarantee customer demand will be satisfied during design though, since many changes could still occur during the process. Yet, by better coupling requirements and technological capability early in the design process, it reduces the risk of requirements to design errors.

In addition, the identification and selection of concepts, technologies, and projects, does not usually mean complete project design occurs upon selection. Instead, only some of the technical components of project design were pre-selected during the selection process. In the study, the selection process outcomes dealt with only a small, yet vitally important, fraction of the design of a space system. In general, the selection of the technologies constrains, but does not fully define, design. Examples of the similar selection process outcomes can be observed for interactive information systems design as well. This includes early project consideration and selection of open source code, COTS and middleware systems, web applets, JAVA libraries, and so on. By observation, it can be argued that doing concept identification and selection at the start of a project is likely a norm for design rather than the exception.

Competition and Consensus

The selection process also showed that there can be many stakeholder groups who are in competition with one another as to who will get their requirements addressed. This is alignment with group power struggles in organizations [17, 30, 40]. The idea that there is a single stakeholder group at the beginning of a project is an illusion. In any organization that builds many different products for customers, there is always contention as to which customers' interests will be served [29]. This is in addition to any contention there is for resources by the various engineering groups that want to design and implement the proposed projects. Although competition was mandated at the site of the study, the need to do competitive analysis existed anyway.

Hence, the question is not whether there is conflict and competition in front-end technology and project selection, but rather it is how to manage this competition and come to a selection consensus. This study showed how the VAL selection process was able to repeatably reach selection consensus by incorporating competition, formal procedure, and sensemaking.

The technology selection outcomes in this study affected the distribution of tens of thousands to millions of dollars. Hence, the selection process mirrored a high-stakes market, which was made up of a wide variety of participants. It could be argued that the main job of the VAL technologists who shepherded and managed this process was to create and foster an environment in which a selection can be made and achieve enough consensus by the NASA administrators to be acceptable. Also, the providers needed to believe they had a "fair chance" at presenting their technology proposals and being selected. And, if they were not selected, there needed to be clear, precise, detailed reasons as to why not. The VAL technologists needed to be accountable for their actions.

Sensemaking in the design of interactive systems

Although we discovered sensemaking to occur at the "front-end" of system design, we expect that sensemaking activities occur throughout the entire design process. Technology selection and requirements determination form the start of a system design process. There are great deal of other design implementation concerns that require the judicious use of learning, understanding, and judging. Despite the best attempts to define formal and reproducible processes in design, we maintain that such well "definable" processes will always be interspersed with sensemaking activities. Sensemaking is a way to interpret phenomena in light of the current conditions. A predefined specifiable process, while meeting certain organizational goals, e.g. fairness and reproducibility, can never function to completely define the situation at hand. Sensemaking is needed to fit formal procedures to the situated nature of the current state of the design process. The implications of this to the CMM and design process modelling is a subject for further research.

CONCLUSION

The study showed the use of a selection process that blended sensemaking activities within a procedural process framework. Procedural processes were designed for the organization to perform formally repeatable, definable, and measurable actions. Yet a common set of selection metrics was not possible, as terms did not have the same meanings for different technologies. In actuality, the formal procedures were interwoven with sensemaking activities so that technologies could be understood, compared, and a decision consensus could be reached.

As the selection process progressed, the complexity of the selection domain was reduced and consensus building was fostered. By the end of the selection process, there was a clear data trail of how the decision was reached. It was observed that the VAL program at the Lab has had an ongoing record of success in performing front-end selection analysis for highly complex, competing sets of technologies. After eight years and ten selection cycles, the final decisions have held up unchanged.

Indeed, the VAL process is likely to be excessive when a selection decision can be reasonably reached by one or a few people or by an agreed-upon algorithm. From this study, it was observed that a selection algorithm must:1) have results that are at least as good as the results of the "manual" sensemaking process, 2) deal with the technical, economic and political implications of the selection and 3) have the ability to create a sustainable socio-technical agreement, e.g. consensus, as to the outcome. Hence, if the selection domain requires too many participants to allow for a "simple" consensus to be reached, and a selection algorithm cannot be created that adequately addresses the selection domain, then a design group might benefit from using a similar selection process as presented in this study, but adapted to the host organization,.

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