Forming and Selecting Flight Concepts for the New Millennium Program: Addressing a Failure in Quantitative Analysis Methods

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Abstract – Quantitative analysis methods are generally employed in making complex decisions about system selection for design and development. NASA's New Millennium Program (NMP) from its inception applied this principle until it failed in the selection of new technologies for DS3. The NMP has since redressed this issue by updating their selection process and has thereafter been able to successfully choose new technologies for flight validation on a yearly basis. To understand what failed in the DS3 analysis and how in was addressed, a field study was performed on the NMP to capture the processes and issues surrounding the formation and selection of technical concept areas during the selection of new technologies for space flight validation. The NMP processes were captured and analyzed using ethnographic methods. The study found 1) setting high-level, break-through technological requirements leads to flight concepts that can potentially address a significant application domain, 2) producing multiple concepts are necessary to address disparate science interests, 3) promoting competitive choices fosters innovation, while not prejudging the outcome, and 4) obtaining prioritization of flight concepts by the science community balances their interests. These results lead to a deeper finding: the understandings, insights, and consensing from design, sensemaking, and negotiation processes that occur during the selection process were lost by quantitative models designed to produce a technology choice, hence making the sole use of quantitative models for technology selection inappropriate.

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1. INTRODUCTION

Highly complex project decision-making is normally done using quantitative methods, often employing econometric and alike statistical techniques. Examples of quantitative work that apply to project selection include Felli, et al's, project selection model at the Monterey Bay Aquarium [1]. Butler, et al, applied multiple attribute approach to ranking sets of technology configurations against one another for project fit [2]. Cook and Green used data envelope analysis to perform project prioritization [3]. Jiang and Klein studied project selection based on organizational strategy criteria [4]. Parnell, et al, use a more general approach to multivariable decision analysis in evaluating the need for technology for air and space forces [5]. From examination, the method employed by originally the NMP was most similar to the methods employed by Felli and Parnell.

In 1997, the New Millennium Program (NMP) was investigating how to select which technologies to space flight validate for DS3. To do this, they employed a quantitative decision analysis method to compare the choices and determine which proposed system to fly. This choice of analysis method is in alignment with current research in project decision analysis. The NMP group gathered specific technical capability needs and constraints details from various NASA mission theme technologists. Concept areas were determined in response to these requirements. Through much discussion and negotiation, a set of ratings where developed.

A chart was created that contained the general ratings for each and every technology being considered for space flight validation. During the review process, a seemingly simple question was asked. A reviewer, while scanning the ratings, asked, "What does the number 3 mean?" All of the technologies were rated from 1 to 3 (low to high). Yet, after consideration, no one could adequately answer the question.

Upon review, it was determined that meaning of the number was lost during aggregations that were used to make the ratings. In addition, important technical and economic details were lost. These were crucial to making the selection decision. Also, significant differences in technologies, such as disturbance reduction systems, ion engines, autonomous control, and so forth were also lost in the translation to single value ratings. From this, it was determined by the NMP that the lost critical information could not be rectified with a general quantitative decision model. A different approach had to be built to help manage and determine the flight validation technology selection.

This paper is a report on how the NMP accomplished this. From detailed, reflective examination of the current NMP concept creation and selection process, it was found that in addition to technical and economic information losses during the creation of a quantitative ranking, there were also losses in processes needed to make sense of the concepts and the political negotiations needed to forge consensus on the selection. The results of the investigation presented here are 1) a detailed explanation of the new NMP concept selection process developed in response to the quantitative model selection problem, and 2) the lessons learned while resolving this issue.

2. Research Methods

One procedure to gain insight into what new methods and processes the NMP created to deal with their selection problem is to reflectively examine a current NMP selection process in-depth. A qualitative field study of the team performing a selection process would capture the activity as a whole. Then, utilizing qualitative analytic techniques, the notable important differences in the methods and process from previous practice to current practice are revealed. This method allows for the identification of key insights that were discovered in the qualitative review. In addition, examining how problems in the selection process were addressed *in situ* provides a first step in establishing theories, models and procedures as to how to address the questions more generally.

Hence, we decided to use ethnographic fieldwork methods [6] to capture a detailed understanding of a complex process used for project selection. This approach has been used in similar research to understand how complex organizations deal with designing, maintaining or repairing technology [7] and to understand new system design [8, 9]. The study of the New Millennium Program was performed at the Jet Propulsion Laboratory (JPL), which is a NASA (National Aeronautics and Space Administration) research laboratory located in southern California. 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 principal) 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, of which there were two key internal documents: the New Millennium Program Plan [10] and a conference paper authored by the NMP group [11].

All interviews and many of the small group discussions were digital audio recorded and transcribed. The data was analyzed using open and axial coding [6]. 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" [12]. Using an autodriving method of data review [13], 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 researchers learned and understood the technical and procedural details correctly and precisely, as they repeatedly quizzed and corrected the researchers on the process details during many onsite visits.

3. NMP Selection Process

The New Millennium Program (NMP) was started in 1994. The main mission of the NMP is to perform space flight validation of new technologies [10]. It was created to address a problem with the lack of utilizing new technologies in space science missions. The primary reason science missions need new technologies is to reduce mission cost, allow a measurement, or enable a new function or capability. But, new technology is considered to risky for space use, and hence off-limits to science missions.

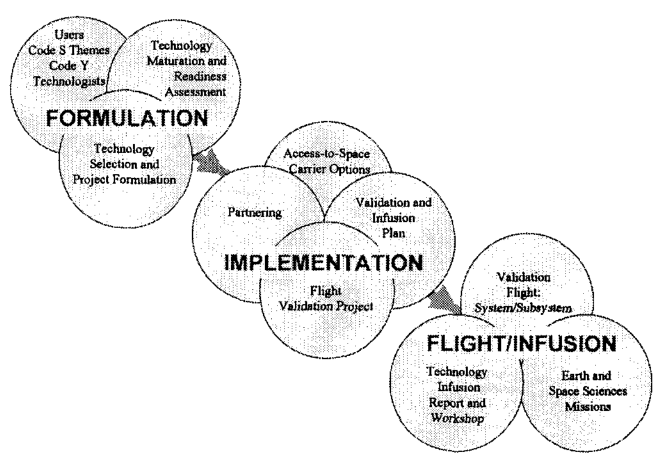


Figure 1. NMP Process Triad

The NMP space flight validation process has four primary objectives: 1) to select technology with a wide enough domain of applicability to space flight validate, 2) to mature the selected technology(ies) from TRL 3/4 to TRL 7, 3) to perform space flight validation with the aims of gathering enough data to capture the technology's functional

Table 1. Field Site Participants and Their General Requirements

Organizational Participants	General Requirements
NASA Headquarters (Principals)	⇒ Want new technologies to be flight test validated so that they can be applied to as broad an array of science mission's as possible, i.e. to meet as many NASA mission themes' needs as possible. ⇒ Want to maximize scientific return on investment for all of NASA. ⇒ NASA level requirements tend to be general, hard to define, somewhat vague, and often conflicting (within and between themes and divisions). ⇒ Constrained by budgetary and policy guidelines from the US Congress.
Themes Technologists (TT)	⇒ Search for new technology that lowers their future science mission system costs or functionally enable a mission. ⇒ Want to maximize their specific scientific mission return, while minimizing cost and insuring technology timeliness (being available when it is needed). ⇒ 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 very tight budgets and project deadlines.
Technology Providers (Providers)	⇒ 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 Managers (Managers)	⇒ Want to insure NMP is flight selecting the best technologies by the best providers at the smallest cost that satisfies the broadest of NASA's mission needs. ⇒ What to satisfy NMP customer (mission themes') needs, NASA principals' requirements, while minimizing the costs and attracting and supporting providers. ⇒ Have project level requirements for new technologies, i.e. must determine and address all issues concerning how a technology flight validation will succeed as a NASA project. ⇒ Constrained by tight budgets, deadlines, and scarce, yet shared, resources. Must maintain appearance or openness and fairness in the selection process.
NMP Technologists	⇒ Want to balance and satisfy the needs of the principals and themes, while validating as many providers' technologies as possible under allotted budgets and given deadlines. ⇒ Want new technologies to be space flight validated. ⇒ Need to insure that new technologies are ready and need space flight validation.

performance characteristics, improve mathematical models of these characteristics, discover the technology's limitations, and verify that the technology is at TRL 7, and 4) to infuse the new technology into NASA science mission use. The general process relationships between these objectives are show in Figure 1.

A main issue for the NMP program faces is how to select the technologies for validation in space, i.e. "Formulation" in Figure 1. There are thousands of possible technologies that need space flight validation, hundreds of which are considered important by NASA directors and science mission technologists at any one time. The technologies tend to cluster into sets of related functionality, such as propulsion, communications, sensors and control systems. Each new technology was viewed by the NMP as a possible project choice.

Field Site Participants

After five months of observation, clear role groupings of those involved in the NMP selection process became evident. These groupings are 1) NASA Headquarters (Principals), 2) Themes Technologists (TT), 3) Technology Providers (Providers), 4) NMP Managers (Managers) and 5) NMP technologists (NMP). Each group had its own goals and requirements in the NMP selection process, which are detailed in Table 1[1].

The NMP principals want to satisfy as many of NASA's general objectives as possible with the introduction of new technology. So, they empowered the NMP to conduct an "open and fair" competition to determine which technologies would be selected for flight validation. The principals support and provided budgets for starting up at least one new space flight validation cycle per year. This way, those technologies not chosen in a previous cycle would have another chance to be selected in an upcoming cycle. This insures a ongoing pipeline of new technologies being validated and made available by the NMP. Altogether, the main job of the NMP technologists (who shepherd the selection process) during Formation is to create and foster an environment in which technology selection can be made by achieving a generally acceptable consensus by the NASA principals and themes.

From examining the general requirements needs of the various participants, it is evident that creating such an environment was nontrivial and fraught with political,

[1] This table was adapted from Bergman and Mark (2002) [14].

economic, and technical risks. The NMP technologists and management have created and evolved a process over the past nine years to deal with this situation. More specifically, how can a technology be selected that meets all of the requirements set down by each of the interested NMP parties? Why, as discussed in the introduction, did applying a quantitative decision matrix fail in doing this? How was this failure addressed? To answer these questions, we examined the NMP selection process for ST8 (Space Technology 8), NMP's latest flight validation cycle, in detail.

NMP Principles of Space Flight Validation

The ST8 technology selection process was started in 2002. In considering a new cycle, the NMP has developed a set of criteria, e.g. *filters*, that they apply to determine whether a technology needs to be space flight validated. The NMP filters are:

Table 2. NMP Filters

1. TRL (Technology Readiness Level)
2. Flight Justification
3. Access to Space
4. Timeliness
5. Need Across Missions
6. Open and Fair Technology Competition
7. Cost
8. Strength of Validation

TRL – A technology must be at TRL 3 (or 4) to be considered by the NMP. If the technology is too new or too fully developed, it will not be considered. NMP is not in the technology research business. Hence, technologies that do not exhibit a reasonable clear and defensible path to TRL 7 are not considered. Yet, NMP will consider a somewhat mature technology as long as in contains one or more critical elements that are rated TRL 3.

Flight Justification – The NMP has a specific set of criteria that a technology must meet to become eligible for space flight, see Table 3. Chief amongst these criteria is: *Must the technology be validated in space?* If a technology can be adequately tested on the Earth, especially by creating artificial environments or accurate simulations, then it is rejected by the NMP. It will be someone else's job to mature such technologies to TRL 7. Still, applying these criteria is difficult and is often the subject of long debates between the NMP technologists. Often, there is an extended discovery and learning process between the NMP technologists and the technology providers to determine the appropriate TRL of an examined technology.

Access to Space – The NMP has flight system engineers that determine if and how a technology will be put into space. The three main issues for this filter are:

- Gaining assess to a launch vehicle ("piggy backing")
- Safety
- Orbital concerns

As part of designing an NMP space system, system engineers keep track of availability of upcoming flights that have the ability to carry the technology safely into its required orbit (GEO, LEO, etc.) for the validation experiment. By doing this, the NMP determines the likely cost, safety risk, and availability of vehicles that can launch the technology into space.

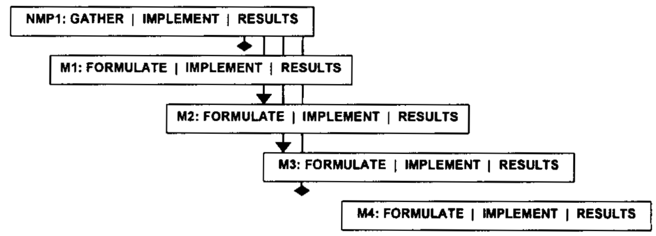


Figure 2. Timeliness of NMP Flights

Timeliness – There is a time horizon for new technologies to be viable for upcoming space missions. Insertion of NMP flight results into missions needs to fit within this window of opportunity. Since the validation process can take 4 to 5 years, the time frame starts at least 5 years from the start of a NMP cycle. For example, in Figure 2, NMP1 represents the current NMP cycle. Any mission planned before the end of NMP1, such as mission M1 in Figure 2, is too soon to use the results of NMP1. Also, if a mission is planned in the distant future (i.e. more that 10 or so years), like M4, then it is too early to validate a technology for that mission. Newer technologies will have been developed in the time span between the beginning of the need of the technology by the mission and the NMP cycle time. In the case of Figure 2, only missions M2 and M3 are in the timeliness window of opportunity for NMP1.

Need Across Missions – An ideal new technology is one that is needed by all the science missions. Since this criterion is hard to fulfill, the NMP wants to select technologies that cover as many future mission needs as possible. In other words, the higher the TT customer demand for a technology, the more likely the technology will be selected. The more and varied missions a technology cover the wider its breadth of functional capability. The NMP labels this flexibility and breadth of functional capability of a technology the "*domain of applicability.*" NMP wants to flight validate technologies with a wide domain of applicability, as shown in Figure 3.

Open and Fair Technology Competition – The NMP, as per NASA (via United States Congressional mandate), must hold open and fair technology competitions when selecting a technology to space flight validate. More specifically, this means that any United States based technology provider, i.e.

Table 3. NMP Flight Justification

FACTORS	SUB-FACTORS	EXAMPLE EFFECTS	EXAMPLE JUSTIFICATION
1. MAJOR IMPLEMENTATION SHIFT **(Never Flown Before)**	1.1 **Fundamental Change** is a revolutionary way of designing, assembling, fabricating, testing, integrating, or operating.	Revolution in Design Procedures or Operations.	Multifunctional structures invoke new assembly, test and rework procedures that depart from existing practice and require flight validation to verify procedures and demonstrate flight worthiness.
	1.2 **Combined Effects** are complex interactions between advanced technology and different parts of the system or launch vehicle.	Contamination, Noise Sources, Survivability, Ionic Contamination, Launch Debris.	Contamination, deposited by thrusters or other sources, is difficult to predict; thus, flight validation needed to confirm contamination models.
2. SPACE ENVIRONMENT **(Ground Test Inadequate)**	2.1 **Persistent Effects** are steady space/planetary environments acting on the technology.	Zero Gravity, Radiation Effects, Noise Sources, Temperature cycling.	Large, light-weight deployable structures need zero G flight validation because an accurate ground test is impossible.
	2.2 **Transient Effects** are impulse space/planetary environments acting on technology.	Cosmic Rays, Temperature spike, Particle and Fields, Noise, Microphonics	System level faults, such as cosmic-ray induced single-event upsets in integrated circuits. Validation flight needed to confirm software error handlers.
	2.3 **External Interactions** are environments used by the technology to accomplish something.	Cometary Surfaces, Planetary Atmospheres, Solar Wind.	Aeroassist technologies using planetary atmospheres and solar sails using solar wind for propulsion. Both require flight validation to build an experience base and to determine the performance envelope and operating safety margins.
	2.4 **Reliability Hazards** are space/planetary environments that degrade performance.	Micrometeorite, Dust Accumulation, Atomic Oxygen, Radiation Effects.	Micrometeorite, orbital debris, dust accumulation, atomic oxygen, and radiation effects are difficult to predict and simulate.

industry, university, or government laboratory, can submit a technology that meets the stated requirements in a call for technologies created by the NMP. This call is in the form of a Technology Announcement (TA) or NASA Research Announcement (NRA). All of those who meet the qualifications stated in a TA or NRA are encouraged to send proposals, which are to go through a "fair and open" review process used for selection. Due to this policy, NMP technologists may only shepherd technology proposals through the selection process, but not participate directly in the proposal teams. This allows the NMP technologists to maintain "third party objectivity" as required for an open and fair competition.

Cost – Each NMP cycle is allocated an awards budget to be used in validating either a single system (for odd number ST's, i.e. ST5, ST7) or multiple subsystems (for even numbered ST's, i.e. ST6, ST8) by the NASA principals. The total budget for either case is approximately the same. Only those technologies that can be flown under budget will be considered. The task of technology proposal cost estimation is ultimately the responsibility of the providers. If a cost estimate appears unreasonable, unlikely, or excessive, the technology proposal will be culled from the current NMP selection cycle. Hence, being able to accurately predict costs, and associated risks, is critical in determining whether a technology remains in consideration for NMP validation.

Strength of Validation – As previously stated, a technology should be important across multiple missions. To do this, often the technology needs to apply to different missions. Hence, the technology validation needs to be flexible enough to adapt to multiple different types of mission needs. Single point solutions do not meet this criterion. The NMP does not attempt to flight certify a particular article that will be used unchanged in future science missions. In such a case, the domain of applicability is too small and the strength of the validation too limited. Instead, the selected technology must demonstrate a wide level of scope and flexibility. For example, the ion engine validated in DS1 is now being proposed for a number of missions, each of which require different forms of the ion engine than the one originally used. Altogether, strength of validation indicates how broadly and well a technology can likely be adapted into different forms, sizes, and applications, as well as capturing how well it operates in a range of different environments. More generally, to cover a wide domain of applicability, a technology needs a strong strength of validation, as shown in Figure 3.

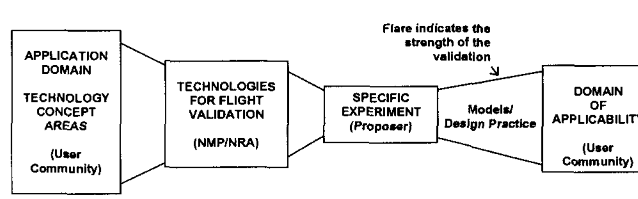


Figure 3. Relationship between NMP Flight Filters

The challenge for the NMP technologists is to describe a technology in sufficient detail that a provider can design an effective space validation experiment ("specific experiment" in Figure 3) that addresses a significant number of the technical issues. In this regard, NMP provides an unparalleled opportunity for a provider to conduct a space experiment that can quantify (generate numbers for) critical technological parameters. This process is seen as *maturing the technology* and thus reducing the risk to future users.

Altogether, the technologies that best meet and satisfy these NMP filters, as well as the requirements of the NASA principals, Theme Technologists, and Technology Providers, should be selected for validation. To see that this indeed occurs, the NMP constructed and refined its selection process over 7 different validation cycles (ST8 is the 8^{th} NMP cycle), as shown in Figure 4. Already, one can begin to induce why a single quantitative decision value is problematic. It obscures how all of these filters and requirements are being met per technology. To better understand the implications of this, the initial aspects of the ST8 selection process, i.e. from initiation up to producing the ST8 NRA, will be examined in more detail.

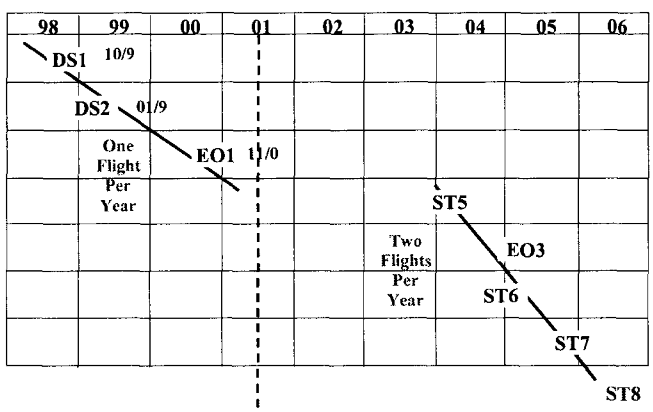


Figure 4. NMP Flight Validation Schedule[2]

4. CONCEPT FORMATION AND SELECTION PROCESS

The ST8 NMP mission was initiated in November 2001. Since this was an "even" numbered cycle, the ST8 focused on identifying, selecting and validating subsystems, i.e. a (usually isolatable) part of a spacecraft. From experience, ST6 funded 3 subsystems [15]. Currently, the plan is to fund three systems for ST8, but that can change as per cost models and which technologies are deemed suitable for flight validation.

Requirements and Technology Gathering

Once the ST8 cycle was started and funded, the NMP team members went to the different NASA centers to gather the technological requirements from the mission theme technologists (TT's). Table 5, Activity 1 represents the process followed by the NMP in gathering theme requirements. In general, NMP members met with and performed semiformal interviews with the TT's who had needs within a NMP technologist's professional area, such as microelectronics, software, and so forth. We assert by observation that professional skills matching, along with previous familiarity with one another (NMP technologists and theme technologists for the most part know one another), reduced the amount of time it would be needed to convey the TT's requirements. The NMP technologists gathered all of the TT's expected and known technology needs for missions that fit the NMP's and the TT's "timeliness window" of ~5-10 years in the future (2007-2012 for ST8). Table 4 represents the results of the NMP requirements gathering phase.

From examining Table 4, it can be seen that the TT's needs, as a whole, are very diverse. It is not reasonably feasible technically nor economically to flight validate all of these technologies. Instead, as per 40+ years of JPL-NASA experience, it has been found wiser to propose technology designs that incorporate related aspects of the requirements, those which are functionally compatible and economically (in time, cost, and risk) supportable. Altogether, a large and broad enough set of proposed technology designs can cover most to all of the TT's technology needs. To begin to understand, i.e. make sense of, how to create these proposed designs, it is import to first understand the likely technologies that currently exist or are underdevelopment, yet at TRL3/4, to guide the design activity.

After the list of TT's technological needs was compiled and agreed to (by the TT's), the NMP technologists embarked on visits to the NASA centers to discover new technologies, at TRL 3 or 4 (see Table 5, Activity 2). To determine which technologies, and hence which NASA centers and projects to visit, the NMP technologists relied upon their years of experience and understanding of the TT needs to make a preliminary selection, as well as upon their history and interest in new technologies in their respective professional fields (via conferences, journals, and JPL/NASA colleagues), the NASA technology database, and ongoing social interactions with project leads and engineers in projects related to their field of work. Through a series of meeting, interviews, phone calls, emails, and so forth, the NMP technologists recorded in detail what current technologies were available and their specific functionalities and constraints. NMP technologists focused of technologies that appear to reasonably fit the NMP filters as well address part or all of one or more TT's technological needs. Altogether, 89 technologies were collected from the NASA centers during the NMP technology gathering process for ST8, as noted in Table 5, Activity 2.

Initial Concept Formation

89 different technologies are too many to flight validate in a single cycle. Some of these technologies are too expensive to flight validate. Those are eliminated from consideration,

[2] There have been 11 proposed NMP missions including ST8. Three missions (EO2, DS3, ST4) were cancelled and are not included in the figure.

Table 4. Theme Technologists' Technology Needs

Theme Technologists	TECHNOLOGY
TT1	Gossamer Telescope Systems
	Active wavefront sensing and control of lightweight optical systems
	10-100mN class precision control thrusters for distributed aperture observatories
	Energy resolving detector arrays for submillimeter and UV astrophysics
	5-10K instrument cryocoolers
TT2	Aeroassist and entry descent systems
	Advanced radiation tolerant computing
	Optical communication for outer solar system missions
	Inflatable/deployable structures for solar arrays and antennas
	Power sources and thermal management
TT3	*Solar sails: Deployment test*
	Picosats: 5kg, 5W sats—platforms for Ionospheric, Magnetospheric, Heliospheric science, flight experiment to include science validation of platform
	Ultra-low power electronics and avionics
	Guidance, navigation and control: Sun and earth sensors for spinning s/c, Position information to 100m well above GPS constellation
	Instrument technology: Compact plasma analyzers w/o large, complex electrostatic optics; Low-threshold, particle detector/analyzer (ions/neutrals, as low as 1keV energy)
TT4	Drag-free inertial sensor
	Actuators for formation flying – tethers
	Autonomous spacecraft control, coordination, and pointing
	Light, large, deployable, high-precision structures
	Cryocoolers: Mirrors and sensors
	Gossamer X-ray optics

but this still left a considerable number of technologies. Each technology, by itself, covered only a part of one or more the technological needs of the TT's. This would create a weak match for the NMP "need across missions" filter. In addition, these individual technologies tended to be unique point solutions and thus, would not meet the NMP's criteria of strength of validation. Finally, there needed to be an open and fair competition for technologies at some point in the selection process (i.e. once a Technology Announcement or NASA Research Announcement was produced), which would allow for reasonably competing technologies to be proposed by US providers. The NMP must guard against highly prescribed technologies that would overly limit competition.

In response to these conditions, the NMP developed their own approach to available technology determination. This activity (Table 7, Activity 1) corresponds with the need to create a set of high-level technology designs that altogether would cover the stated TT needs, as previously alluded to. The NMP technologists considered different combinations of the proposed technologies (along with known reliable technology, as necessary) to best address the highest combination of TT needs, and NASA principals' requirements, while maintaining NMP filters. A new combination of existing technologies that well met these criteria became a *technology concept area* (TCA), e.g. a *concept*. A NMP concept is thus, a high-level design of a technology that covers two or more needs of one or more TT's.

A TCA quadchart example in Figure 5 illustrates the approach to concept design. The purpose of the TCA is to: (a) identify the critical elements for the NMP technologists in gathering needed technical information, (b) provide a one-page description of the technology to allow assessment and decision making, and (c) provide the starting point for the preparation of the call for technology described in a NASA Research Announcement.

The concept contains three types of communication elements: pictures, words, and numbers. These three elements seem to provide an effective mix that facilitates rapid communication and decision-making. The elements contained in a TCA, as shown in Figure 5, are:

(a) A picture of the requested technology
(b) Customer needs as described by the Mission Applicability A flight concept as described by the Validation Objective, Flight Validation Rational, Suggested Flight Concept, Technology Requirements, and the current State-of-the-Art
(c) Technology Roadmap that places the technology within its development progression
(d) Cost Range

The features that distinguish the flight validation of NMP technology from other mission technologies are (a) the need to validate a piece of a technology, not the complete technology and (b) the need to provide characterizations that will allow the technology to be used by a number of missions in the future. The example in Figure 5 indicates that only a portion of the solar sail is to be deployed. This is deemed sufficient to validate the many issues associated with deployment of a solar sail.

The complexities associated with solar sails are illustrated in Figure 6. There are a significant number of interacting factors that, in this case, cannot be characterized on the ground. For example, a difficult technical issue is trapped gas during solar sail packing that affects space deployment. The effect is difficult to model and depends, in part, on the skill of the technician who packages the sail. There is no known method to simulate or test this effect on the ground, thus qualifying it for flight validation.

Using the TT's needs and 89 initial technologies, the NMP technologists applied their professional technical design capabilities, based on their fields of expertise in conjunction with NMP filters, to develop an initial set of TCAs (Table 7, Activity 1). For ST8, 21 concepts were created. These initial technology concept areas are listed in Table 6.

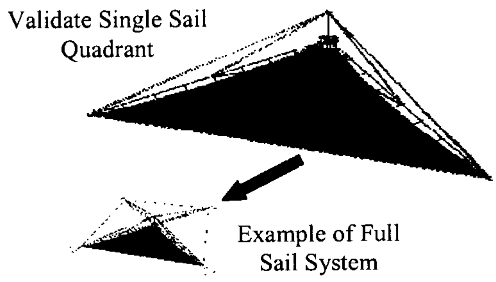
Table 5. Process 1: Gathering

Activity	Inputs	Mechanisms Applied	Outputs
1.Theme Technologists contacted: a. NMP requests a list of technologies needed by the Themes b. Themes notified about the planned solicitation at NASA Centers	▪ NMP ST8 budget	▪ E-mail ▪ Theme Letter ▪ NMP Senior Technologist Phone Call ▪ Meetings and teleconferences with Themes	▪ A list of technological capabilities needed by the Themes
2. NASA Centers Visits: a. Centers informed about NMP process and Theme needs b. Centers supply a list of technologies/ presentations c. NMP asks Centers to produce Center Technology Quadcharts (see Figure 5)	▪ A list of technological capabilities needed by the Themes ▪ NASA database of technologies ▪ NMP technologists' knowledge on ongoing projects	▪ POC: NMP and Centers ▪ Center Letter ▪ Email and POC phone calls ▪ Meetings at Centers	▪ 89 technologies being developed at Centers ▪ A TCA per technology (89 TCAs)

Table 6. ST8 Initial Technical Concept Areas (TCA#)

Concept Title	Validation Objective
TCA1: Ultra-Lightweight Deployable Booms	Validate deployment and structural characteristics of ultra-light inflatable structures for future mission use
TCA2: Solar Sail Deployment (Figure 5)	Validate deployment, and characterize effect of space environment on deployed sails for future mission use
TCA3: Lightweight Deployable Solar Array	Verify deployment and characterize effect of space environment on performance of ultra-light weight solar arrays.
TCA4a: Ultra-Low Density Optics – Large Membrane Optics TCA4b: Ultra - Low Density Optics – Flexible Optics	Validate membrane optics performance, control, and active distortion compensation in the space environment. Validate active control and distortion compensation for thin-shell or other flexible lightweight optics in the space environment.
TCA5: EDL: Aerodynamic Drag Technologies	Validate atmospheric entry technologies that slow spacecraft prior to landing
TCA6: EDL: Aeroshell and Thermal protection Technologies	Validate atmospheric entry technologies and effect on Thermal protection materials
TCA7: Cryocooling for Lightweight Optics	Validate effect of thermal and microgravity environment on cooling of lightweight optics
TCA8: Large Deployable Antennas	Validate deployment, and characterize mechanical and RF and performance of large antennas in micro-g environment
TCA9: Space-to-Space Optical Communications: Acquisition, Tracking and Pointing	Validate acquisition, pointing and tracking, with a micro-radian level pointing accuracy, of optical communication in space to space, over distances in the order of 40,000 km and scalable to 1AU
TCA 10: Miniaturized Telecomm System for Nanosatellites	Validate performance of communications protocol and subsystem in micro-gravity environment

Concept Title	Validation Objective
TCA11: Tethered Spacecraft Formation Flying	Validate dynamic measurement and control techniques for maintaining/changing separation distance (baseline) between tethered spacecraft
TCA12: Miniature Energy Saving Thermal Control Subsystem	Validate a miniature thermal management system and demonstrate substantial spacecraft energy and mass savings.
TCA13: Multifunction Integrated Power and Attitude control Systems	Included in TCA15
TCA14: Distributed Attitude Control of Large Structures	Validate ACS, targeting, and solar torque compensation for large space structures that use distributed thrust elements.
TCA15: Long-life Integrated Power and Attitude control Systems	Validate performance of magnetic levitation system, spacecraft dynamics and integrated subsystem in microgravity environment
TCA16: COTS Based High Performance Computing For Space	Validate fault rates, response characteristics, reliability and throughput of a fault tolerant, COTS-based, high performance computing system in a space radiation environment.
TCA 17: Miniaturized Technologies Enabling Intelligent Constellations	Validate the ability to perform coordinated activities autonomously using inter-constellation communications
TCA18: Continuously Operating Cryocooler	Validate operability, microgravity effects, autonomous operation, performance, and scalability of continuously operating, milli-Kelvin cryocoolers.
TCA19: Interference-Free, Low-Energy-Threshold Particle Detector	Validate capability of detectors to provide accurate counts and characterization of low-energy particles in the presence of UV radiation
TCA 20: Model-Based Fault Protection for Complex Systems	Validate the ability to diagnose faults and recover autonomously in all modes of operation
TCA21: Navigation Above the GPS Constellation	Validate hardware and software for receiving/ processing of GPS signals in real time onboard a spacecraft in GTO or other HEO.



Validation Objective: Validate deployment, and characterize effect of space environment on deployed sails for future mission use

- Characterize structural mechanics and dynamics of the deployment of a solar sail.
- Characterize the behavior of a deployed sail section
  - Assess the combined effects of space environment on sail shape. Environmental effects include microgravity, solar radiation pressure, static charging, and thermal deformations.
  - Validate models to enable scalability for larger sail sections in complete sail systems.

Flight Validation Rationale: Microgravity deployment dynamics cannot be simulated in ground testing.

Suggested Flight Concept: Deploy a sail section from ELV upper stage or carrier spacecraft in GTO.

Cost Range: ~\$12M to \$18M

Missions Applicability:

SEC: SPI, Sub-L1S (Geostorm)

Technology Requirements:

- Sail section area > 350 m^2
- A real density 10-20 g/m^2, including sail film, booms, tensioning hardware, and any other hardware that must remain with the sail after deployment.
- First mode frequency > 0.03 Hz
- Film stress > 0.7 N/cm^2
- Thrust reduction from wrinkling < 5%
- Successful deployment in space to full section shape without ripping, tearing, or excessive deformation

State of the Art:

- Russia has deployed 20m-diameter sail in space
- DLR has developed prototype 20m sail
  - A real density 25 g/ m^2

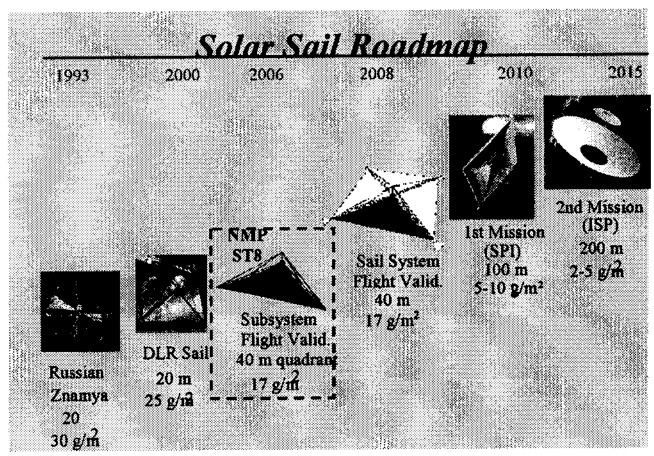


Figure 5. TCA2: Solar Sail Deployment Quadchart

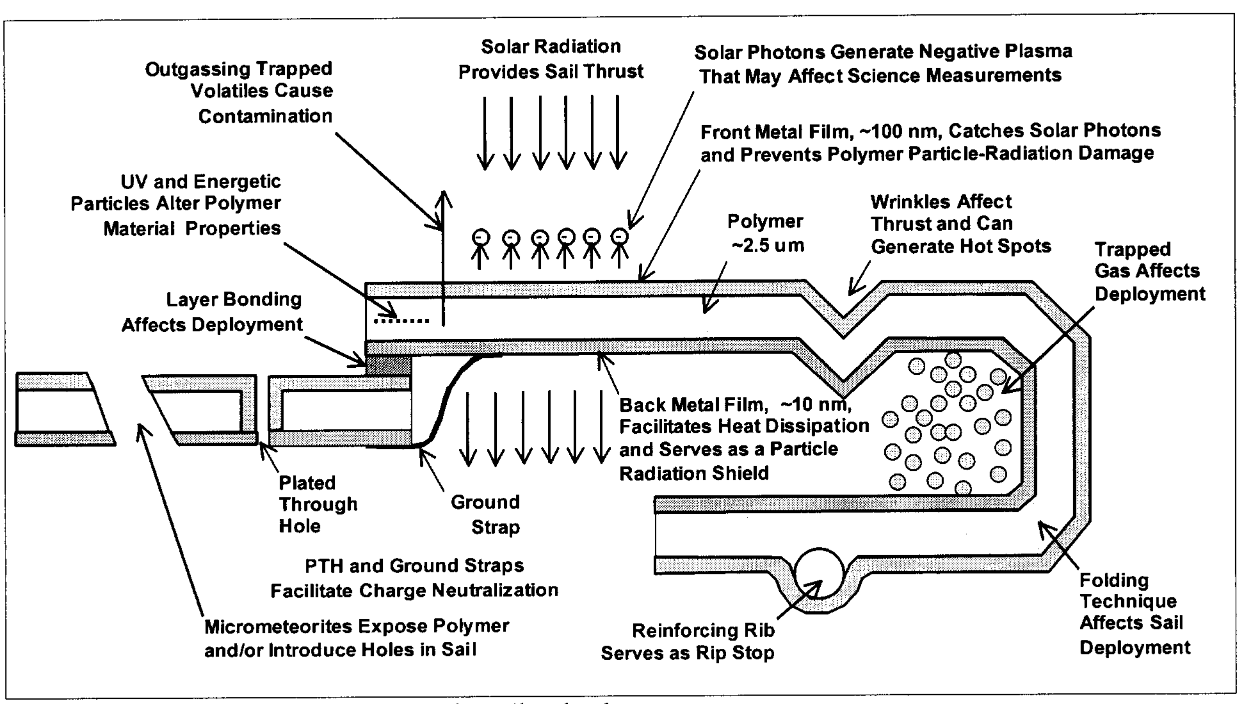


Figure 6. Examples of factors affecting solar sail technology

Table 7. Process 2: Forming and Ranking

Activity	Inputs	Mechanisms Applied	Outputs
1. NMP combines Center Quads into 21 TCA (Concept Areas) a. TRL b. Mission impacted c. Validation need d. Cost	▪ 89 Center Technologies TCAs ▪ NASA Technology Database ▪ NASA Principals requirements ▪ TT needs ▪ NMP technology knowledge and professional technical design expertise	▪ NMP works with Centers and technologists ▪ NMP Filters ▪ High-level concept design	▪ TCAs for 21 TCAs ▪ Rationales ▪ Flight concepts ▪ Cost ▪ Applicability ▪ Requirements ▪ SOA

Concept Ranking and Review

Each of the 21 NMP concepts was described by a quadchart, as illustrated by the one shown in Figure 5. These concepts were then compared, using the information available in the quadcharts, as well as the background notes of the NMP technologists, with the TT's "needs across missions" to determine the breadth of each concept. The very diverse set of needs inspired an equally diverse set of concepts to cover them, as seen in Table 8. This table shows the process by which many different themes needs were covered by each concept. An *x* in a theme need row means that the need was addressed by concept area in the column. The more *x*'s a column has, the boarder its coverage of TT needs, i.e. the higher its needs across missions. Few concepts, such as TCA1, cover at least one of each TT's needs. While other concepts, for instance TCA3, TCA7, TCA11, and TCA17, cover multiple needs of a one or more TT's. Most of the rest of the TCAs covered two or more different TT's needs. For concept ranking, it is considered preferable for a concept to cover multiple TT needs over those that cover fewer or a single TT's needs, even if multiple individual TT needs is met. In other words, the NMP was looking for concepts with high breadth of mission coverage across multiple themes.

In parallel with the "needs across missions" assessment, the TT's individually reviewed and rated each concept by importance. As seen in Table 10, each TT rated each concept as per their own view of how well it fit their needs, initially using a high/medium/low scale. If known, the preliminary cost estimate of each concept was supplied. The TT's did the initial ratings by themselves. They utilized the TCAs as their main source of technical data. NMP collected the ratings from the TT's and constructed the chart Table 10. They assigned number values to each ranking, as shown in Table 10, and performed a standard average across the scores per concept.

With Table 10 constructed, the NMP held a consensing meeting with the TT's to determine joint rankings (Table 9, Activity 1). An NMP technologist provided the forum for the meeting, as well as produced the initial ranking chart, but did not participate in the meeting except to answer questions about the concepts. In essence, the meeting with the TT's was designed to discuss their rankings and address their concerns about the concepts in Table 6.

Initially, it only one consensing meeting for the TT's was planned. Yet, the process of TT's performing TCA ranking and review ended up spanning 3 meetings, each one held a week apart. To better understand the implications of why this occurred, the activities and issues addressed by these meetings are examined in detail.

Consensing Meeting 1 – The initial consensing meeting was the first time each TT saw the other TT's rankings. During this time, the different TT's began to share why they ranked a concept H, M, or L. Based on what was heard from other TT's, a TT can and did change his rating on one or more concepts. The main reasons elicited for the changes were:

- Make a clearer differentiation between which technologies they really wanted (highs) versus ones they did not care about (lows).
- To make deals with the other TT's where they all rated a concept medium or high so it had a better chance of being selected.

Hence, the initial meeting became a forum for deal construction used as a mechanism to reach early consensus amongst the TT's. During this first meeting, the TT's felt they needed to expand the rankings to include a "no interest" rating. This rating was to be used to cull out the technologies each TT clearly did not need. In addition, they wanted more time to consider what was discussed at the meeting.

Between the meetings, other changes were made to the ratings chart, via phone calls and emails, most notably to the technology concept areas. Some of the concepts were combined (TCA13 into TCA15). Some concepts were dropped (TCA6 and TCA17) due to cost considerations. They are retained for ST9, the next NMP cycle. The TT's re-ranked all of the concepts using the new scale and called or emailed in the results to the NMP host.

Consensing Meeting 2 – At the next meeting, the NMP technologist hosting the meeting provided the newly updated chart. During this meeting the TT's decided that an average did not really represent what they rated the concepts as a group, so the TT's added a joint ranking column that reflect their consensus rating of a concept, again using high, medium, low, or no interest (NA was for the concepts that

Table 8. "Needs of Missions" Coverage by Concepts[3]

Themes	Theme Needs	Concept Area																				
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
TT1	Gossamer Telescope Systems	x			x			x														
	Active wavefront sensing and control of lightweight optical systems				x																	
	10-100mN class precision control thrusters for distributed aperture observatories														x							
	Energy resolving detector arrays for submillimeter and UV astrophysics							x														
	5-10K instrument cryocoolers																		x			
TT2	Aeroassist and entry descent systems					x	x															
	Advanced radiation tolerant computing					x	x															
	Optical communication for outer solar system missions									x												
	Inflatable/deployable structures for solar arrays and antennas	x		x					x													
	Power sources and thermal management			x									x	x		x		x				
TT3	Solar sails: Deployment test	x	x																			
	Picosats: 5kg, 5W sats—platforms for Ionospheric, Magnetospheric, Heliospheric science, flight experiment to include science validation of platform											x	x		x			x				
	Ultra-low power electronics and avionics										x						x	x				
	Guidance, navigation and control: Sun and earth sensors for spinning s/c, Position information to 100m well above GPS constellation															x		x				x
	Instrument technology: Compact plasma analyzers w/o large, complex electrostatic optics; Low-threshold, particle detector/analyzer (ions/neutrals, as low as 1keV energy)																			x		
TT4	Drag-free inertial sensor																					
	Actuators for formation flying – tethers											x			x							
	Autonomous spacecraft control, coordination, and pointing									x	x	x					x	x			x	
	Light, large, deployable, high-precision structures	x			x			x	x						x							
	Cryocoolers: Mirrors and sensors							x											x			
	Gossamer X-ray optics																					

Table 9. Process 3: TT's TCA Ranking and Reduction

Activity	Inputs	Mechanisms Applied	Outputs
1. Theme Technologists Prioritization: a. Reduce the 21 TCAs into 13 TCAs b. Criteria: Ranking and Relevance to Themes	▪ 21 TCAs ▪ NMP technologists notes, as necessary	▪ Ranking by individual TT ▪ Joint prioritization via teleconference ▪ Negotiation and Sensemaking between TT's ▪ Ranking Chart from NMP	▪ 13 TCAs for 13 TCAs

were already dropped). In general, the joint ratings matched well with the averages, yet there are notable exceptions. Most of these exceptions, for instance TCA5 and TCA15, were giving ratings of zero because they were not as highly valued as other concepts. During this discussion, the TT's decided they needed a special vote, i.e. a "silver bullet," to protect concepts they thought were very important to a TT individually, even if it is not considered important to the group as a whole. As a forcing function, they, as a group, decided that they could only have one "silver bullet" each. They decided to stop the meeting and go off to decide which concept would get the special vote. They decided to meet again in another week with this information decided.

Consensing Meeting 3 – The special votes were sent to the NMP technologist coordinating the meetings. He updated the rankings and ratings chart to its final form, as shown in Table 10. The "silver bullets" are shown in the joint ranking column using the H(TT#) notation. All special voted concepts were automatically ranked high regardless of the average or individual ratings. For example, TCA4 was rated high using a "silver bullet" from TT1.

Summary – Altogether, consensing process created a reflective, detailed ranking of the concepts by the TT's. By allowing the process to take the time to adapt to the new understandings of the TT's, it fostered the ability for the TT's to:

[3] Two theme needs from TT4 were not addressed because they were too expensive to be included in the ST8 cycle.

Table 10. ST8 TT Concept Rankings

ST8 Concept Area	Individual Rankings Scale: 3=High, 2=Med, 1=Low, 0=No Interest					Joint Ranking Scale: H=High, M=Med, L=Low, 0=No Interest	NMP Preliminary Cost Est.
	TT1	TT2	TT3	TT4	Av		($M)
TCA1: Ultra-Lightweight Deployable Booms	3	2	3	3	2.75	H	9-15
TCA2: Solar Sail Deployment	2	2	3	0	1.75	M	12-18
TCA3: Lightweight Deployable Solar Arrays	0	3	1	0	1	L	6-10
TCA4: Ultra Low Density Optics	3	1	1	2	1.75	H(TT1)	10-20
TCA5: EDL: Aerodynamic Drag Technologies	0	3	0	0	0.75	0	
TCA6: EDL – Aeroshell and Thermal Protection Technologies	NA	NA	NA	NA	NA	NA	
TCA7: Cryocooling for Lightweight Optics	2	1	1	0	1	0	
TCA8: Large Deployable Antennas	2	3	1	2	2	M/H	15-20
TCA9: Space-to-Space Optical Communication: Acquisition, Tracking and Pointing	2	3	1	2	2	H(TT2)	10-15
TCA10: Miniaturized Telecomm System for Nanosatellites	1	1	1	0	0.75	0	
TCA11: Tethered Spacecraft Formation Flying	1	3	2	2	2	H(TT4)	20-25
TCA12: Miniature Energy-Saving Thermal Control Subsystem	1	3	2	2	2	M	3-5
TCA13: Included in TCA15	NA	NA	NA	NA	NA	NA	
TCA14: Distributed Attitude Control of Large Structures	2	2	2	3	2.25	M/H	6-8
TCA15: Long-Life Integrated Power and Attitude Control Systems	1	0	2	2	1.25	0	
TCA16: COTS-Based High Performance Computing for Space	1	3	2	1	1.75	M/H	5-10
TCA17: Miniaturized Technologies Enabling Intelligent Constellations	NA	NA	NA	N/A	NA	NA	
TCA18: Continuously Operating Cryocooler	2	1	0	3	1.5	M	15-20
TCA19: Interference-Free Low-Energy-Threshold Particle Detector	0	1	3	0	1	L	
TCA20: Model-Based Fault Protection for Complex Systems	1	2	1	0	1	0	
TCA21: Navigation Above the GPS Constellation	0	1	3	2	1.5	H(TT3)	9-12
Total	24	35	29	24			
The NA concepts were either merged with another concept or recommended for ST9 due to high cost						TCA6, TCA13, TCA17	

Table 11. Process 4: NMP Managers Rating and Selection

Activity	Inputs	Mechanisms Applied	Outputs
1. NMP management rank the 13 TCAs	▪ 21 TCAs Ranked by Themes ▪ 13 Remaining TCAs ▪ Needs of Missions Coverage Chart	▪ Meetings ▪ Negotiation and Sensemaking between the NMP managers	▪ 13 TCAs ▪ NMP Assessment of the 13 TCAs

Table 12. Process 5: NASA Principals Rating and Selection

Activity	Inputs	Mechanisms Applied	Outputs
1. NASA Principals reduce the number to 5 TCAs for inclusion in ST8 NRA	▪ 13 TCAs ▪ 21 TCAs Ranked by TT's ▪ NMP Assessment of 13 TCAs ▪ Needs of Missions Coverage Chart	▪ Meeting ▪ Negotiation and Sensemaking between the NASA Principals	▪ TCAs for 5 TCAs ▪ TRL ▪ Cost ▪ Access to Space

- Create new rating and ranking criteria to better support their view of the process
- Make sense of the technical and political implications of the available TCAs – including being able to merge and drop concepts as needed
- Negotiate and make deals with the other TT's
- Reach joint consensus on rankings, while preserving individual TT's important concepts

This process resulted in the adoption of the top 13 jointly ranked concepts (Table 9, Activity 1). The unselected concepts are likely to resurface again in a future NMP cycle. Some of the 13, notably TCA3 and TCA19, were kept because at least one TT rated the concept high.

NMP Concept Recommendations

The NMP managers met to apply their subset of the NMP filters to the 13 concepts (Table 11, Activity 1). The results of this meeting are shown in Table 13. The TCA rankings were based on a subset of the NMP filters listed in Table 2. The reason for choosing this subset is that all of the other filter criteria were already met or passed by the remaining TCAs. The three filters shown in Table 13 required NMP management insights, which were not available to the NMP technologists.

The managers assessed the remaining 13 TCAs on TRL, projected cost, and access to space. There was very little discussion, bantering, or negotiation between the NMP managers to come to joint ratings per concept. In general, the ratings were determined quickly, based on the available data on the TCAs and the managers' own NMP project level experience. After each concept was assessed in the three factors, the managers rated each of these factors: G (go), Y (unsure), or R (no go). Then, they produced an overall NMP rating, i.e. recommendation, for each concept. They were + (keep), ? (unsure), and – (drop). As seen in Table 13, 7 concepts were rated keep.

Concept Selection for the ST8 NRA

The needs of mission coverage, TT rankings, NMP assessment, and the quadcharts for the remaining 13 concepts were sent to the NASA principals. The principals formed a meeting to discuss, debate, and eventually select which concepts will be chosen for the ST8 NRA (Table 12, Activity 1). They viewed the 13 concepts (yet considered all 21 concepts) from the point-of-view of their requirements, i.e. how well each TCA, if selected, assisted NASA as a whole as well as per division (in the Space Theme for ST8). Hence, their views were quite different than NMP and the TT's views. In addition, the principals could re-add a concept onto the list of recommend concepts or remove a concept from the list at their discretion, although this did not occur for ST8.

Table 13. NMP TCA Down Select

Concept	TRL	Cost	Access to Space	Rating +/?/-
TCA1: Ultra-Lightweight Deployable Booms	G	G	G	+
TCA2: Solar Sail Deployment	G	G	G	+
TCA3: Lightweight Deployable Solar Arrays	G	G	G	+
TCA4: Ultra Low Density Optics	Y	Y		?
TCA8: Large Deployable Antennas	G			
TCA9: Space-to-Space Optical Communication	G	Y		?
TCA11: Tethered Spacecraft Formation Flying	Y			?
TCA12: Miniature Energy-Saving Thermal Control Subsystem	G	G	G	+
TCA14: Distributed Attitude Control of Large Structures	Y	G	G	+
TCA16: COTS-Based High Performance Computing for Space	G	G	G	+
TCA18: Continuously Operating Cryocooler				
TCA19: Interference-Free Low-Energy-Threshold Particle Detector		G	G	
TCA21: Navigation Above the GPS Constellation	G	G	Y	+

From discussions of the meeting with NMP members[4], it was clear that many of the same activities that the TT's used were present in the meeting. Most notably, sensemaking to understand the concepts and their various ratings, negotiation and deal making as to which concepts should be supported to represent division needs, and the ability to change the rating or voting mechanism or process as deemed necessary.

Table 14. Selected TCAs for ST8 NRA

A. TCA1: Deployment of Ultra-Light Booms
B. TCA2: Solar Sail Deployment
C. TCA3: Deployment of Lightweight Solar Arrays
D. TCA12: Energy Saving Thermal Control Subsystem
E. TCA16: COTS Based High Performance Computing

The principals in charge of ST8 selected 5 concepts for the NRA. They are listed in Table 14. These five are deemed to represent the best balance of the NASA principals', theme technologists', and NMP's requirements and filters. They form the basis for the ST8 NRA call for technologies to technology providers.

The NMP selection process from this point on, i.e. the Technology Selection and Project Formulation process from

[4] Due to the sensitive nature of the principals' meeting, the details of the meeting cannot be directly discussed. The details of the meeting were reported from secondhand sources, i.e. NMP members.

Figure 1, is explained in detail in [14] and is beyond the scope of this paper. In addition, an earlier version of the overall NMP process is discussed in [11].

5. DISCUSSION

Process Insights and Lessons Learned

Table 15 summarizes the ST8 TCA formation and down selection process. In general, 89 initial technologies were collected from the NASA centers. The NMP compared these initial technologies with their filters and the TT's needs to create 21 TCAs. The TT's ranked the TCAs through a series of meetings, which left 13 TCAs. The NMP mangers took the TT rankings and rated the remaining TCAs against project level NMP filters (TRL, cost, access to space). This action reduced the list to 7 acceptable TCAs. All of the collected data and charts were given to the NASA principals. They applied NASA level filters to determine the 5 TCAs chosen for the ST8 process, as presented in Table 14.

Table 15. ST8 TCA Down Select Process

Process	Number of TCAs	Actors	TCAs
Table 5. Process 1: Gathering	89 initial technologies	NMP technologists	Not Shown
Table 7. Process 2: Forming and Ranking	89 → 21	NMP technologists	Table 6
Table 9. Process 3: TT's TCA Ranking and Reduction	21 → 13	TT's	Table 10
Table 11. Process 4: NMP Managers Rating and Selection	13 → 7	NMP Managers	Table 13
Table 12. Process 5: NASA Principals Rating and Selection	7 → 5	NASA Principals	Table 14

As shown in the study, performing TCA formation and selection is based on a series of detailed and intricate procedures. The following general observations capture the highlights of these procedures:

- Setting high-level, break-through technological requirements leads to flight concepts that can potentially address a significant application domain (Table 4, Table 6)
- Producing multiple concepts are necessary to address disparate science interests (Table 8)
- Promoting competitive choices fosters innovation, while not prejudging the outcome (Table 6, Table 10, Table 13, Table 14)
- Obtaining prioritization of flight concepts by the science community balances their interests (Table 10)

There are likely other important observations that can still be derived. Still, these lessons learned capture much of the procedural complexity that is the essence of forming and selecting TCAs. In considering these outcomes, we re-examine the initial question of why a quantitative measure is insufficient to base TCA selection upon.

Addressing the DS3 Question

The question posed in the DS3 concept selection process, ("What does the number 3 mean?") indicates the reviewer was pointing out that a generalized quantitative metric was unclear, ambiguous, or missing something important. From examining the NMP's ST8 TCA formation and down selection process as well as the lessons learned, the issues implied by this question begin to emerge. Based on the ST8 process, the reviewers needed to better understand the actions and outcomes of the "hidden activities" [12] that went into forming, ranking, and culling the TCAs. In general, these hidden activities can be classified into three categories:

A. Design
B. Negotiation
C. Sensemaking

Design – Simon views design as the devising of artifacts to obtain goals [16]. It is an art that is concerned not with the way things are, but how things ought to be. Design work is all of the activities that are applied in devising and implementing technologies that satisfy the goals as set by those with the power to create and resources to implement these goals [17]. It is clear from examining the ST8 process that a great deal of design work had occurred throughout the process. The most visible design activity was in the creation of the 21 TCAs (Table 6, Table 7) by the NMP. Still, the initial gathering of technologies, determination of theme technologists' requirements, reflective examination of the TCA rankings by the TT's, NMP managements' ratings, and NASA principals' down selection were all forms of design work. These activities a) affected the designs espoused in the TCAs and b) determined which TCAs were allowed to continue the design path. At the end of the process, one could retrace the design steps to understand how and why each TCA was created, refined, ranked, and selected or rejected. These details (quadcharts, rankings) were seen as critical to those who participated in the process, and ultimately by the NASA principals, i.e. those in the NMP who have the power to set goals and apply resources to achieve them. The design details were viewed as crucial in understanding the choices made available and supporting informed decisions, or, conversely, NMP selection of TCAs could not occur without detailed, traceable, understandable design information and artifacts. A single quantitative ranking (i.e. "3") does not capture these details or how these details were determined, and thus fails to be sufficient basis for NMP selection.

Negotiation – Negotiation is the act of resolving the differences between two or more interested parties in the creation of an agreement or contract [18]. The ST8 selection process had many instances of negotiation. In general, conflicts over how to rank and down select TCAs were resolved using negotiation. For instance, during the TT's ranking of the 21 TCAs, there was observed deal making in the way that the individual and rankings were changed and adapted during the consensing meetings. More specifically, the observed fact that deal construction occurred during TCA ranking is indicative of technical and power conflicts that needed to be resolved. Indeed, coming to consensus can be seen as a successful outcome of negotiation.

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

Although a deeper treatment of negotiation is beyond the scope of this paper, is important to understand the relationship between negotiation and the DS3 question. In general, quantitative models take the ratings and weights of all the agreed to relevant factors as inputs and applies an analytic model to determine an overall ranking and decision [1, 4, 5]. As viewed in the ST8, part of coming to agreement on a decision is working through the understandings and newly exposed differences that come from discussing the choices under consideration with a group of peers (of reasonably equal power and knowledge to make the decision). These new differences are often the result of expert design insight and project experience that is brought forth during negotiation to address specific situations of technical or project level uncertainty, ambiguity, or conflict. For instance, as discussed earlier, to understand and argue the strength of validation and access to space issues for a solar sail, one must bring forth the detailed implications of how the sail is deployed (Figure 6). The technical, economic, and political insights delved during a negotiation process often became critical deciding factors in TCA selection.

Running an analytic model short-circuits this process of expert insight and sensemaking by hiding the conflicts inherit in complex decision making, thus obscuring the areas in which negotiation should occur. Although the application of analytic negotiation strategies, such as game theory [19], can be of aid in the decision process, examination of the ST8 process shows that it this cannot be a substitute for the application of design expertise to the negotiations that are part of complex system design and selection.

Sensemaking – Sensemaking is the art of creating understanding in uncertain or ambiguous circumstances, in an attempt to reduce or eliminate these uncertainties or ambiguities [20]. In general, the NMP is faced with uncertainty in determining which technologies to space flight validate. Hence, the TCA selection process is an intricate act of sensemaking. Still, sensemaking does not stop at the general level of technology selection. As seen in the ST8 process, sensemaking was applied whenever understanding, judgment, and learning were entailed. Each process step in Table 15 is an example of isolating and performing separate, yet interrelated, sensemaking activities.

The NMP TCA formation and selection process, in general, has been refined since DS3 with the recognition of when specific different sensemaking activities need to occur. The NMP process breaks down the uncertainties and ambiguities into "addressable chunks" and begins to resolve them individually. For example, Process 1, Activity 1 (Table 5) applies sensemaking to gathering and understanding the TT's needs. Process 1, Activity 2 utilizes sensemaking in determining, gathering, understanding, and describing the available NASA center TRL 3/4 technologies. Then, these newly formed "chunks" of understandings (i.e. gathered technologies, determined TT's needs) are brought together to create deeper understandings (i.e. creating 21 TCAs, ultimately down selecting to 5 TCAs). These deeper understandings are built using information and artifacts determined through design and negotiation. In return, the new understandings are used to further design and derive issues for negotiation.

Another clear example of different uses of sensemaking was in the TT's ranking and consensing meetings. In this case, the first application of sensemaking was in the TT's understanding the 21 TCAs as presented. Other applications were: learning the method of ranking, using judgment in performing the rankings, understanding each other's positions and responding to them during the rankings, and increased learning, understanding, and adaptation of the ranking process as it progressed. Indeed, at each level of the NMP process (see Table 15), there were applications of all of these types of sensemaking by every actor within the process steps. Each of the process actors had to make sense of what the other actors needed and what was expected from one another. For instance, to create the 21 TCAs, the theme technologists needed to understand (and apply this understanding of) the TCAs, the NMP filters, and their managers and NASA principals' objectives and requirements. Similarly, the NMP technologists had to interpret and apply diverse inputs in performing their activities in the selection process. In addition, the NASA principals needed to understand the NMP technologists, TT's, and NMP managers' views, and so forth.

Summary

At first take, all of these activities – design, negotiation, and sensemaking – appear to the norm of doing engineering of complex systems. But, upon closer inspection, it is details of when these activities need to be preformed and how they are accomplished that provides much of the "hidden machinery" that allows engineering processes to work. Together, this can be viewed as "the essence of system design." It is also during these points were the highest risk of process failure can occur. This is due to the weakness exposed in the processes that can only be addressed by design, negotiation, or sensemaking, which are imperfect arts, yet are the best that can be performed in these circumstances. This is why decision research, in general, is focused on creating formal methods and models to reduce risks associated with the ambiguities and uncertainties inherit in the process [1, 2, 4, 5]. Still, it is precisely that the selection process is a sensemaking process built upon design and negotiation activities that quantitative measures, which lose or are devoid of the understandings and agreements needed to create and interpret these measures, fail. This is what was observed in the failure of understanding the ranking of "3" during DS3. Altogether, this points to the need for quantitative measures to exist in conjunction with sensemaking based understandings to bring meaning, focus, and utility to the selection process, as demonstrated in the ST8 process.

6. Conclusions

The NMP TCA formation and selection process for ST8 relied upon design, negotiation, and sensemaking. It also required a solid process to focus and blend these activities, the negotiated understandings of the artifacts produced by these processes, and a highly competent staff to administer them. An question this study inspires is how should these activities be combined, or more specifically, examining and determining different combinations of sensemaking, negotiation, and design to improve the outcomes of complex system formation and selection is an area that needs further research. This study, which describes in detail how the NMP combined these activities, is a beginning. Further detailed *in situ* studies in other organizations facing similar system formation and selection issues will be necessary to be able to generalize the results of this study.

In addition, as observed in this study, design, negotiation, and sensemaking can utilize quantitative measures, charts, and models to inform and support these activities. Yet, quantitative metrics and models cannot be used as a substitute for these activities. Hence, how to better combine design, negotiation, and sensemaking with quantitative models and metrics is also in need of further study.

Finally, the NMP has created an art of shepherding the TCA formation and selection process. The NMP managers, TT's, providers, and NASA principals relied on the NMP technologists to guide and support them through the ST8 TCA formation and selection process in a timely and cost efficient manner. It is arguable that the NMP process runs significantly smoother due to the focus and momentum provided by the NMP technologists. They provide the process roadmap, gather, create, and supply needed information, host review meetings, and can supply expert insight to detailed technical, economic, and political questions about the technologies they are supporting. Indeed, well matched process activities with process actors abilities and expertise was seen as essential in repeatably producing and selecting technical concept areas that addressed disparate science interests.

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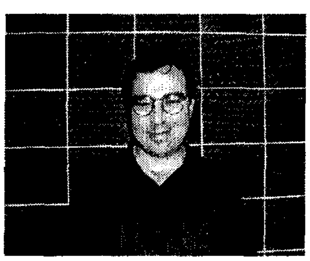

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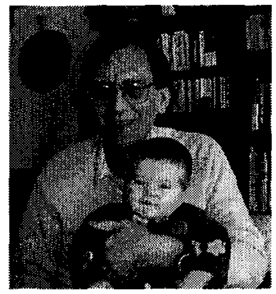

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