A Return to the Moon: A System Engineering Management Framework and the Success of Lunar Prospector

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Introduction

Most of the project, engineering, and systems management literature has traditionally taken the approach of "one size fits all," assuming that a universal set of management procedures can apply to all projects. The complexity of a project alone alters the management style and strategy of a project; therefore, it should become clear that no one approach can solve the problems of project management, and thus no one strategy is best for any one project (Drejer 1996). This has become even more important as there has been increasing attention on complex systems projects in the economic activities of firms, industries, and nations (Hansen and Rush 1998).

Hobday, Rush, and Tidd (2000) state conventional innovation wisdom is derived from research on high volume consumer products; new evidence, models, and concepts are needed to properly understand the innovation process in complex products and systems. These complex systems are commonly characterized by customized, interconnected subsystems; carry high cost; designed for one customer; produced in low volume; require broad and deep knowledge and skills; engage multiple collaborators; involve the customer and suppliers throughout the life cycle; and have strong political considerations (Floricel and Miller 2001; Miller and Lessard 2000). The knowledge base of these systems projects is limited in the area of systems engineering, how they develop, and how they are managed. To explore this body of knowledge, this case study will use a system engineering management framework to describe the success and lessons learned of a complex systems project at the National Aeronautics and Space Administration (NASA) (i.e., Lunar Prospector).

Framework for Systems Engineering Management

Based on classical contingency theory, Shenhar (2001) has worked toward the development of a theory to address the strategic, operational, and human issues of systems innovation and add strategic direction to a project. He theorizes that not all projects are the same and thus they should not be managed the same. Shenhar and Dvir (2004) have expanded this theory to a typology based on an elemental foundation in contingency theory for managing different types of projects (e.g., large system projects). This typology theorizes a framework for project and systems engineering managers for the planning and execution phases of a project.

Assessing the environment and the task, a project is classified on four dimensions, and the right management style to fit to the project type. Shenhar (2001) states that projects carry contingencies based on these four dimensions of novelty, complexity, technology, and pace (NCTP).

Novelty

Novelty is defined by the product's uniqueness to the market and existing technology, and has an impact on the project definition and market-related activities. To categorize product novelty, Shenhar (2001) uses Wheelwright and Clark's (1992) definition of new product development as the following:

1. Derivative—Extensions and improvements of existing products (e.g., a new color option in a MP3 player, the addition of a search feature in a software program)
2. Platform—New generations in existing product families (e.g., new automobile model, new commercial airplane)
3. Breakthrough—Introduces a new concept or a new idea, or a new use of a product, which customers have never seen before (e.g., the first Post-it Note, the first microwave)

Complexity

Complexity is defined by the way a project is organized, its scope, and the interconnection between project elements. As the complexity of a project increases thus does the project size, extent, and detail of planning, coordinating, documentation, and bureaucracy. Shenhar (2001) classifies project complexity as the following:

1. Assembly—A collection of components and modules in one unit, performing a single function (e.g., CD player, cordless phone)
2. System—Involves a complex collection of interactive elements and subsystems, jointly dedicated to a wide

range of functions to meet a specific operational need (e.g., spacecraft, cars)

3. Array—Deals with large, widely dispersed collections of systems (sometimes called system-of-system) that function together to achieve a common purpose (e.g., New York transit system, air traffic control)

Technology

Technology is defined as the initial uncertainty centered on a technologies development, maturity, and knowledge. As technical uncertainty increases, so do requirements for technical and professional skills, development efforts and time to completion, communication, and the impact and significance of project results. As both technological uncertainty and system complexity increase so does the employment of systems engineering techniques, problems of systems integration, the employment of configuration management, and risk management techniques. Shenhar (2001) classifies projects on technical uncertainty as the following:

1. Low-tech—Relies on existing and well-established technologies (house, city street)
2. Medium-tech—Uses mainly existing or base technology, yet incorporate some new technology or new feature that did no t exist in previous products (automobile, appliances)
3. High-tech—Represents situations in which most of the technology employed are new but nevertheless exist when the project is initiated (satellite, fighter jet)
4. Super high-tech—Based on new technologies that do not exist at project initiation (stealth bomber, Apollo moon landing)

Pace

Pace is defined by the urgency and criticality of time goals for a project. Time constraints on a project can dictate varying project structures and management attention. Shenhar (2001) classifies projects on pace as the following:

1. Regular—Efforts where time is not critical to immediate organizational success (community center, wetlands development)
2. Fast/Competitive—Time-to-market is directly associated with competitiveness, and although missing the deadline may be fatal, it could hurt profits and competitive positioning (satellite radio, plasma television)
3. Time-Critical—Project completion is time critical with a window of opportunity (mission to Mars, Y2K)
4. Blitz—Emergency or crisis project (Apollo 13, September 11, 2001)

Once a project is classified based on these four dimensions, it defines certain characteristics of that project that make it unique in how it is managed. Figure 1 shows how the four dimensions are reflected on a graph, and that connecting the NCTP classification with a straight line to form a diamond gives a representation of the level of risk associated with a project. The greater the diamond's area, the greater the degree of risk.

Case Study Approach

A case study research methodology was used because it allows for the characterization of real-life events, such as organizational and managerial processes, and there is no requirement for control over behavioral events, thus allowing for the capture of holistic and significant experiences (Eisenhardt 1989; Gillham 2000; Yin 1994). This method works best when alternatives must be evaluated to

Figure 1. The NCTP Framework

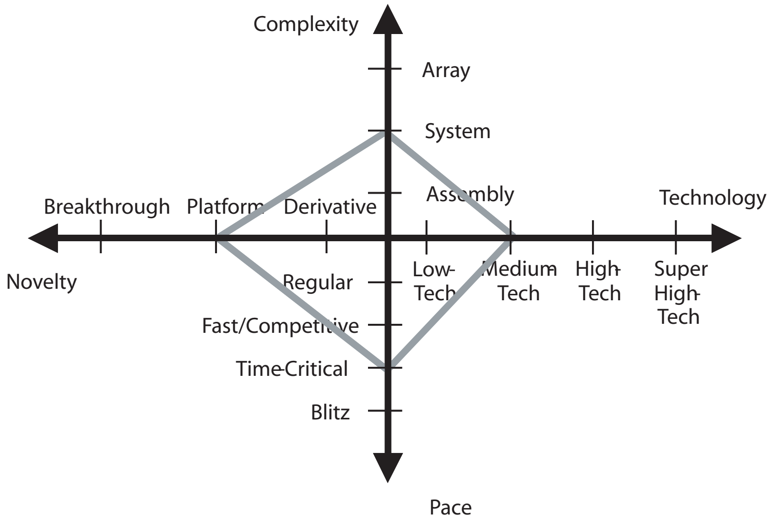


Table 1. Sources of Evidence (Yin 1994)

Data Type	Source
Interviews	Semistructured, open-ended conversational format to allow interviewees to speak freely and openly about their experiences. Interviews ranged from 30 minutes to 2 hours based on the interviewee's availability and depth of information. A single interview session was performed with each subject, with follow-up interviews on an as-needed basis. Six key personnel related to the project were interviewed. These people represented program management, project management, administration, systems engineer, team member, and customer. Each interview was recorded on audiotape and transcribed.
Documentation	Formal studies, evaluations, journal articles, survey data, mass media, and physical artifacts (samples of work done).
Archival and Historical	Letters, memoranda, policy statements, regulations, proposals, guidelines, procedures, summary reports, organizational records, and personal records.
Participant Observation	NASA gave permission for participation in its Academy of Program and Project Leadership training programs. This included project management training classes.

determine which alternative performs best. It allowed for comparison among what people do, what people intend to do, and what they should do. The case study approach was to use a descriptive case study methodology where the case is defined by a descriptive theory (i.e., NTCP framework) (Yin 1994). To address any threats to validity as defined by Yin (1994), multiple sources of evidence supported by data source triangulation was used (see Table 1 for sources of data) (Denzin 1984; Stake 1995; Yin 1994) and a study protocol was established for future replication and to reduce any bias in the collection of data (Shenhar 1999). Case development and analysis was performed by the following:

1. *Case Definition and Selection*: Defined the case to be evaluated, and the framework in which the case was to be described.
2. *Data Collection*: Data collection was performed using interviews, documentation, archival and historical information, and participant observation.
3. *Analysis*: The analysis of the case followed an iterative process where the completion of an interview or coding of evidence was followed by an analysis to gain familiarity with the data and evaluate or reevaluate the theories. This involved the establishment of an attribute-versus-alternatives matrix (Scholz and Tietje, 2002) for evaluating the project (e.g., an attribute in the NCTP framework would be Technology and the alternatives would be Low-Tech, Medium-Tech, High-Tech, and Super High-Tech).
4. *Evaluation and Discussion*: Once the final analysis was completed, a final iteration was performed to develop and refine a final theoretical statement about the findings.

Lunar Prospector

Lunar Prospector was the first competitively selected mission in the NASA Discovery Program developed to produce frequent, low-cost missions to explore the solar system. Lunar Prospector was a spin-stabilized spacecraft designed to map the surface composition and magnetic field of the Moon and begin investigating some of the 80 percent of the Moon's surface features, structure, and composition not investigated during Apollo.

As a product, Lunar Prospector was a single vehicle (orbiter), and several instruments designed to demonstrate a low-cost system for orbiting the Moon and expanding its scientific knowledge. Additional objectives included the deployment and operation of various scientific instruments: neutron spectrometer, gamma ray spectrometer, magnetometer-electron reflectometer, doppler gravity experiment, and alpha particle spectrometer. Although much of the technology was known, its application and what Lunar Prospector was planned to accomplish made it different than anything that had been done before.

As a project Lunar Prospector was to design, test, and develop an orbiter that would obtain scientific data and demonstrate the philosophy of “faster, better, cheaper” (FBC). With a development time of almost three years and a project cost that included development ($34 million), launch vehicle ($25 million), and operations ($4 million), for a total of $63 million, Lunar Prospector was chartered with being the first competitive selected Discovery Program mission to demonstrate FBC. Lunar Prospector involved 75 to 100 people from NASA Ames Research Center (ARC), NASA Goddard Space Flight Center, NASA Jet Propulsion Laboratory, University of California – Berkley, University of Arizona, Lockheed-Martin, Lunar Research Institute, and Los Alamos National Laboratory.

Lunar Prospector ended on 31 July 1999, when the spacecraft was jettisoned into a crater near the south pole of the Moon as part of an experiment to confirm the existence of water ice. The mission ran for nineteen months and successfully completed all its objectives. The data collected has allowed for the construction of a detailed map of the surface composition of the Moon and results have been ten times better than ever planned. The information gathered was far more comprehensive than any data ever collected.

Lunar Prospector’s NCTP Classification

The NCTP classification represented in Figure 2 is the analysis of Lunar Prospector in respects to its novelty, complexity, technology, and pace. Connecting the NCTP classification with a straight line to form a diamond gives a representation of the level of risk associated with a project. The greater the diamond’s area, the greater the degree of risk. Although there is not a linear relationship between the diamond’s area for correct and incorrect project risk, it can represent a difference in the degree of risk.

Novelty

“Things that we did were unheard of, all goes into my saying that nobody believed that we could do this.”

Lunar Prospector was a breakthrough product. The technology used in Lunar Prospector was a new use for existing technology that aerospace had never seen before, and it pushed the boundaries of cost-effective space exploration. Although there was much to be learned from Apollo, these early lunar missions only opened 20 percent of our understanding of the Moon, and little had been accomplished in lunar exploration since Apollo. Therefore, Lunar Prospector was based largely on scientific fundamentals, with limited experience in similar products and history of trial and error. This meant fast prototyping, keeping a close, honest relationship with its customer, and late design freezes.

Complexity

“You fly what you test and test what you fly.”

Lunar Prospector was a system project. As a complex integration of scientific instruments and spacecraft subsystems, a main program office, NASA ARC, directing a prime contractor, Lockheed-Martin, led Lunar Prospector. There were several other subcontractors to produce the scientific instruments with a mix of in-house and external development. While Lockheed-Martin managed the project, it was ARC’s ultimate responsibility to be accountable for the spacecraft.

Figure 2. Lunar Prospector’s Mission Trajectory

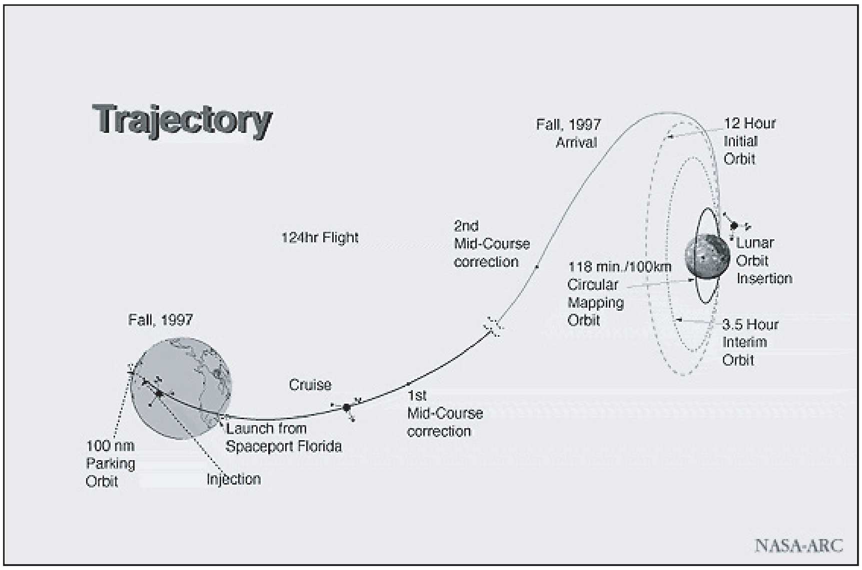
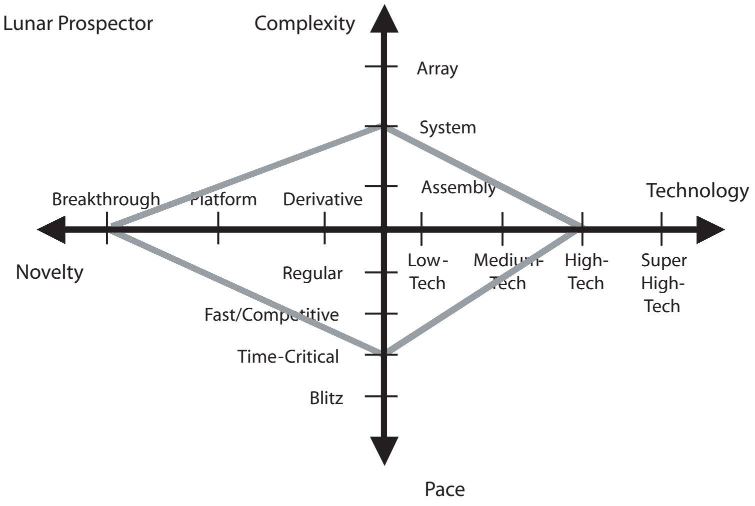


Figure 3. Lunar Prospector NCTP Classification



Although the documentation was kept minimal, with any complex NASA project, the documentation is extensive compared to most projects. As an organization, Lunar Prospector was a pure project structure with tight control over the project and extensive reviews with the customer. Lunar Prospector had multiple key customers from industry, public, government, and the scientific community that were all vested in Lunar Prospector's development and success. As a systems project Lunar Prospector was a complex project that required extensive planning, computerized tools and software, hundreds or thousands of activities, tight and formal control, financial and schedule issues, and reviews with customers and management.

Technology

"This is what we are going do and we don't change anything we build."

Lunar Prospector was a high-technology project. As a product, Lunar Prospector was not revolutionary but maintained a simple design using proven technology with only a few new iterations of those technologies. Although most of the technology was commercial-off-the-shelf or borrowed from other proven spacecraft, it was innovative in its application. With a simple design (by NASA standards), the project still involved long periods of design, development, testing, and redesign with multiple design cycles that had to start before the project started. With the extensive testing that was required for a high-tech project like Lunar Prospector, in-depth, technical reviews were mandatory to make a project of this complexity successful. In conjunction with these reviews, communication had to be frequent and active. The complexity and communication demands required management to be of good technical skills and intimately involved in the project. They also had to recognize the unique challenges of Lunar Prospector and be flexible to extensive testing and design changes. Therefore, design freezes had to be scheduled and as late as possible. Lunar Prospector had a clear understanding of the complexity of the technology they were dealing with, and applied the right level of design constraints to the project to assure success.

Pace

"Well this was a super skunkworks"

Lunar Prospector was a time-critical project. All Discovery Program missions are under a contained development time, and any delays in that would mean cancellation of the mission. As a pure project, the team was specially assembled because of their unique and valued capabilities, and team members were only retained because they brought value to the project. When a crisis arose, it was dealt with in a quick and effective manner. People were open with any crisis, realizing the end goal was more important. With a shortened development time, many bureaucratic policies were lifted and procedures were kept to the core minimum. Project managers were very involved in the project from beginning to end, and were never afraid to "pick up a wrench" to guarantee project success. In addition, management up the chain never questioned the status of the project. They were kept informed while allowing the project team the freedom to get the project done.

Summary

Lessons Learned from Lunar Prospector

Lunar Prospector was successful because it was understood well before the project started that simplicity would be the key to project success. Lunar Prospector was well-defined with a clear understanding of the scope, technical uncertainty, and pace. This guided management toward design constraints that kept Lunar Prospector on budget and on time. Lunar Prospector determined their strategy early with customer-defined objectives that were simple, attainable, and valuable. A focused, unspoken, and common commitment from a collocated team laid a foundation for limited top-management involvement and a dedication of people from project start to finish. Lunar Prospector understood the value of informal and formal reviews, how they related to when to freeze designs, how they impacted requirements, and that only a good test program can reduce uncertainty.

Lunar Prospector was unique in that it was one of the few NASA-sponsored missions at the time that was truly principal investigator-led. This environment worked for Lunar Prospector because it was small and had an experienced and directed principal investigator. Unfortunately, this principal investigator also brought an immense amount of tacit knowledge, thus, it was difficult to document and transfer the project success to other projects.

At the time of Lunar Prospector, the Discovery Program and FBC were in their infancy. Documenting the how and why should have been more important to determining Lunar Prospector's success. Lunar Prospector was a focused project whose success, while measurable, was not captured. Lunar Prospector was the vision of one man, who was focused, directed and driven to make Lunar Prospector successful. Although these may be some of the traits of a good leader and what was needed to make Lunar Prospector successful, the style and processes that were used to help Lunar Prospector be successful were not well documented. Management believed that to make Lunar Prospector successful, documentation had to be limited. Although this streamlined processes, it left Lunar Prospector as a project that relied on the people as the keepers of the knowledge. This knowledge and lessons learned were never captured or documented during or post-project.

The Success of Lunar Prospector Defined by Lunar Prospector

Because this case study resulted from interviews with key personnel, it should go with mentioning how Lunar Prospector defined its success. When the principal investigator was asked what the strategy for Lunar Prospector was he answered simply, "You are responsible, you're responsible to me, no passing the buck, keep it simple, and do it on time. If there is a problem we sit down together and fix it right then and there. That was the whole strategy." He lived by the motto: "Keep It Simple Stupid" (KISS), and this is how he ran Lunar Prospector. This meant no redundancy, modularity, backup, or test model; it meant going "single string." His philosophy on single string was that "If you know you've got a backup, you're not quite as careful in construction. If you have no backup, you are damned careful about what you are doing." His strategy could not have been reality without a reduction in the insight and oversight. The program manager believed that this was critical to a focused strategy and keeping the team focused.

Before Lunar Prospector started there were a series of meetings with the program manager, principal investigator, project manager for Lockheed Martin, and senior management of Lockheed Martin to lay out what they were going to try to do and how they were going to try and do it. These meetings were then extended to the project team to make sure that they understood the strategy and how it was going to be accomplished. There were strategic corrections throughout the project, but Lunar Prospector wanted to be very sure that people did not misinterpret faster, better, cheaper as being a license to be "sloppy." This meant defining the requirements early and sticking to them. With such a short development time and limited resources, Lunar Prospector believed they could not afford or allow requirements to grow. Lunar Prospector wanted to make sure that everyone understood that they should focus on things that were truly value-added or contributed to mission success and not on things that provided minimal value. Additionally, Lunar Prospector management built a strategic focus on the following:

- *Clear Set of Requirements*: Requirements were not only clearly defined but people adhered to them.
- *Defined Roles and Responsibilities*: Team members and management knew their roles and responsibilities from the beginning and there was never any question.
- *Mix of Experience*: Experienced people at the top were combined with energetic young engineers.
- Willingness to Do Things Differently: Lunar Prospector was unique in how it was selected, managed, and developed. People were willing to try a different way of doing business.
- *Strong Sense of What Was Mission Success*
- *Strong Commitment from Top Management*: Consistent funding stream from top management, which did not waiver from the commitment.
- *Extensive Pre-project Definition*: A long history of studies and missions to the Moon, which gave a solid basis of the science requirements.
- *Focused Management Team*: The focus of all the managers was on making Lunar Prospector successful. When problems arose, management set aside differences to keep the project directed with a common goal of doing it appropriately and timely.

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Biography

Brian J. Sauser holds a B.S. from Texas A&M University in Agriculture Development with an emphasis in Horticulture Technology, a M.S. from Rutgers University in Bioresource Engineering, and a Ph.D. from Stevens Institute of Technology in Technology Management. He has worked in government, industry, and academia for more than 10 years as both a researcher/engineer and director of programs. He has managed an applied research and development laboratory in life sciences and engineering at NASA Johnson Space Center, was Program Director of the New Jersey – NASA Specialized Center of Research and Training, where he managed a multi-institutional, multi-disciplinary science and engineering research center working to generate new knowledge and technology for life support systems, and was a Project Specialist with ASRC Aerospace responsible for managing technology utilization and assessment, and commercial partnership development at NASA Kennedy Space Center. He is currently a Research Assistant Professor at Stevens Institute of Technology in the Systems Engineering and Engineering Management Department.