The 1989 NASA Space Exploration Initiative Cost Risk Estimate and Related Issues

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Introduction

This paper examines cost related issues that arose during and after performing the 1989 90-Day Study (NASA, 1989) cost risk estimate for returning to the Moon and going on to Mars (The Space Exploration Initiative (SEI)). It describes how the cost risk estimate was performed and addresses issues that arose from that process. It also describes issues that arose from follow on personal research driven by performing that estimate. For this paper, an issue is something that requires effort to be expended. Because effort is expended there is an associated cost. Thus, issues are cost drivers.

The observations and perspective contained in this paper are personal and may differ from the perspective of the SEI project and NASA.

Cost Risk Estimate Background

In 1989, Langley Research Center (LaRC) was the only NASA center using Monte Carlo simulation to provide a cost risk estimate for every cost estimate. In the 1980's LaRC used the PRICE models (Price Systems) for cost estimates, but these models did not have a cost risk capability at that time. To perform the cost risk estimates, LaRC had developed a model using PRICE-like parameters that had a Monte Carlo simulation capability. An early version of the LaRC cost risk model was described in (Dean, Wood, Moore and Bogart, 1986). The NASA Johnson Space Center (JSC) was using the Advanced Mission Cost Model (AMCM) for the Moon-Mars cost estimate, but it did not have a cost risk capability. However, JSC desired a cost risk estimate for SEI. I pointed out to JSC that applying Monte Carlo using the parameters of a completed project did not represent the risk at the conceptual stage of the project and that the LaRC cost risk process used parameters that represented the project at the conceptual stage. Thus, in 1989, I was asked by the Johnson Space Center (JSC) to perform the 90-Day Study cost risk estimate of returning to the Moon and going on to Mars (SEI).

The Cost Risk Estimate

I spent approximately two months at JSC performing this estimate with the able support of the team at JSC architecting the mission, the team at JSC estimating the cost, ECON and Kelley Cyr of JSC putting together the Advanced Mission Cost Model (ECON and K. Cyr), and Bob Fairbairn back at the Langley Research Center extending and testing the software (Fairbairn, 1990).

There were a number of challenges putting together the cost estimate, not the least of which was getting travel from LaRC for a cost person to participate in the 90-Day "engineering" Study. A big challenge for me was to understand the scope of the estimate. I read a number of books in preparation. Willey Ley, Wernher von Braun's right hand man, wrote a prescient book envisioning the conquest of space (Ley, 1951) well before Sputnik and the formation of NASA. Wernher von Braun wrote a prescient book envisioning a return trip to Mars (von Braun, 1953). Willey Ley wrote a book detailing a number of large engineering projects that had failed (Ley, 1964). Freeman Dyson wrote a short story about the Mormon exodus from Nauvoo, Illinois to Utah and the Mayflower pilgrimage (Dyson, 1979). In it he detailed costs and, based upon those costs, he estimated the cost of an Island One L5 Colony and for mining the asteroids.

There were additional challenges. The estimate used PRICE-like parameters that were foreign to most of the engineers participating in the 90-Day Study. Interviews of the engineers had to be prefaced with a lesson on the definitions of the parameters. The AMCM data and results had to be transformed to manufacturing complexities for 1989 and beyond. Based upon the work of Darryl Webb (Webb, 1990), we used a model I described in (Dean, 1989) to perform the combined calibration and temporal extension of manufacturing complexities. I had to scrounge computing resources at JSC by using four Macintosh SE/30 computers (Macintosh, 1989) in the evening that were used by JSC secretaries during the day. The biggest challenge was extending and testing the software to perform the calibrations and the estimate (Fairbairn, 1990). Another big challenge was understanding and estimating operations cost. The engineers had architected hardware for the surfaces of the Moon and Mars; however, there was very little understanding of actual operations. The greatest understanding of Moon operations came from several University of Texas graduate students and a software game they wrote. The AMCM had operations data associated with launch vehicles, etc; however, data with an analogy to the surfaces of the Moon and Mars was nonexistent. The lack of definition on surface operations led me to read (Miller, 1987) which provided an interesting perspective on living in space. That reading led me to begin studying (Miller, 1978) - a tremendous basis for understanding living on the Moon and Mars - more on that later.

As for the cost risk model we used, there are five major technical characteristics of a cost risk model:
(1) The statistical uncertainty associated with the derived cost estimating relationships (CERs). The LaRC cost risk model did not yet include this uncertainty.
(2) The uncertainty of the parameters applied to the CERs. These were determined through interviews with the project engineers and our experience with the typical range of these parameters. This interview process is what captures the risk at the conceptual stage of development.
(3) The definition of the probability distribution used for simulating the cost risk. We used Beta distributions with best case, most likely case, and worst case values as determined from the engineer interviews and prior estimating experience. We also introduced correlation between the distributions (Fairbairn, 1990).
(4) The project risks defined by a risk register. These are events that have a probability and a consequence associated with them. The consequence in a cost risk estimate is cost. In 1989 LaRC projects did not have a risk register. Consequently, the LaRC Cost Estimating Office (CEO) had not developed the methodology to use a risk register for cost risk. The 90-Day Study did not have a risk register anyway; so using a risk register was out of the picture. Note, however, that a parameter distribution on an input parameter has an effect that is similar to that of a risk register. The distribution represents the consequences of all risks on the parameter, with a sampled value being a consequence. The output of the cost model is then the cost consequence.
(5) Process recursion. When the desired result of a process is unsatisfactory, it must be performed again. This can be a major cost driver for development, production, and operations. An example is a major cost driver for operations at JSC. The Shuttle has a structural problem that requires it to slow down as it passes through max G during launch. The effect is very sensitive to payload weight distribution. Each time a payload is changed, the payload weight distribution changes. Thus, a number of reevaluations must be performed again to verify safety requirements. The inclusion of process recursion in a cost risk estimate is similar to that of using a risk register where the consequence would be a repeat of the process. Research required to include process recursion was not ready at that time (Unal, Dean and Moore, 1990). Had it been complete, there were no process definitions and no data to apply it.

Root cause cost drivers are those cost drivers that truly drive the cost, even though they may not be parameters in the cost model. Analysis of the interviews and estimate indicated that the root cause drivers for returning to the Moon and going on to Mars were:
(1) The number of Astronauts drives the size of the community. This number was fixed for all 90-Day Study cost estimates.
(2) Energy is required to move mass to the community and to keep the community alive.
(3) Mean time between failure (MTBF) drives the need for mass to the community - the more failures the greater the mass needed. This is critical for a successful round trip to Mars. A 99% chance of success requires approximately a 250-300 year MTBF for each critical string of the 2.5-3.0 year round trip. To understand the criticality, just ask yourself what the typical MTBF for equipment is – particularly in a dust environment? Also ask yourself: What is the MTBF for an Astronaut? How many Astronauts are required? How much mass is required per Astronaut (Dyson, 1979)?
(4) Ability to live off of the land reduces the need for mass to the community.
(5) Technical complexity drives the difficulty in creating the mass required by the community.
(6) Robustness is the faultless operation over a wide range of parameters. This reduces cost. The Shuttle example above demonstrates that substantial operational cost is generated because the Shuttle has a lack of robustness during launch.
(7) Process recursion requires effort expended to do something over again and substantially increases cost. The Shuttle example above couples the cost of process recursion to a lack of robustness. Unal, Dean and Moore (1990) demonstrate and model the cost of recursion within Shuttle operations.

Operations for the Moon and Going on to Mars

After the 90-Day Study cost risk estimate, I was asked to join the SEI logistics team. Note that when you acquire a system, you are acquiring the whole life cycle of the system, not just its development. As a member of this team I had the opportunity to further study operations and the cost of operations – the weakest component of the 90-Day Study cost risk estimate. There were two highlights during this period.

As a member of the SEI logistics team, I performed a study using submarines as a model for Moon and Mars community logistics. Each submarine is a community. Each submarine carries a large part inventory. There is a submarine tender ship for every so many submarines with a large number of machines and parts on board for repairs. Submarines do not stay under water nearly as long a time as space communities will experience – particularly on Mars. My conclusions were that for the Moon and Mars (1) The planned number of astronauts for initial communities on Mars was inadequate. To arrive at this conclusion ask yourself: What is the MTBF of an Astronaut? How long in time is a round trip to Mars? (2) Logistics costs would be far more than we had estimated. To arrive at that conclusion ask yourself: What is the mass required per Astronaut? What happens to the cost if the number of Astronauts is increased? What are the critical components required by the community? What will the dust environment do to the equipment MTBFs? How large a spare part inventory is required? In general, what are the risks for the community and the consequences of those risks? The 90-day study did not have a risk register.

Note that I have used the word “community” a number of times. During the logistics study, I substantially increased my understanding that we would be establishing communities on the Moon and Mars. Initial communities on the Moon and Mars are analogous to the establishment of Jamestown, Plymouth, The Lost Colony, and Mormon Utah. Humans will be delivered by a transportation mechanism through a medium requiring time to arrive and return. Supplies must be adequate for their survival and the growth of their community. Because humans are involved, these communities are living systems (Miller, 1978). Thus, we must fully understand these living systems to estimate their cost. What are the operations within these communities?

Miller (1978) provides a work breakdown structure (WBS) for all living systems - in this case the communities on the Moon and Mars. There are 20 subsystems for each living system.
(1) The **input transducer** brings information into the system.
(2) The **ingestor** brings material-energy into the system.
(3) The **internal transducer** receives and converts information brought into system.
(4) The **channel and net** distributes information throughout the system.
(5) The **internal transducer** receives and converts information brought into system.
(6) The **timer** (Miller, 1990) maintains the appropriate spatial/temporal relationships.
(7) The **associator** maintains appropriate relationships between information sources.
(8) The **memory** stores information for system use.
(9) The **decider** makes decisions about various system operations.
(10) The **encoder** converts information to needed and usable form.
(11) The **reproducer**, with information, carries on reproductive functions.
(12) The **boundary**, with information, protects the system from outside influences.
(13) The **distributor** distributes material-energy for use throughout the system.
(14) The **converter** converts material-energy into suitable forms for use by the system.
(15) The **producer** synthesizes material-energy for use within the system mass-energy.
(16) The **storage** stores material-energy used by the system.
(17) The **motor** handles mobility of various parts of the system.
(18) The **supporter** provides physical support to the system.
(19) The **transducer** handles information output of the system.
(20) The **extruder** handles material-energy discharged by the system.

Each of these subsystems performs one or more functions [verb phrase, noun phrase]. By breaking out the functions one can arrive at a slightly expanded process based structure (PBS) for living systems. I did this and presented it to a very small audience at JSC. As I expected, the presentation went over the heads of the very concrete engineers composing the audience. A major disconnect exists in that NASA engineers architect hardware and assume that software exists to complete the hardware, but there is little understanding of the abstract functions that the hardware performs. The abstract functions performed for a Moon or Mars community are the functions performed by the 20 Living Systems subsystems (Miller, 1990).

As with all work breakdown structures, the Living Systems WBS may have many levels.
(8) Supranational systems are organizations of societies with a supraordinate system of influence and control.
(7) Societies are loose associations of communities, with systematic relationships between and among them.
(6) Communities include both individual persons and groups, as well as groups that are formed and are responsible for governing or providing services to them.
(5) Organizations involve one of more groups with their own control systems for doing work.
(4) Groups contain two or more organisms and their relationships.
(3) Organisms: there are three kinds of organisms: fungi, plants, and animals. Each has distinctive cells, tissues and body plans and carries out life processes differently.
(2) Organs: the principle components are cells, organized in simple, multi-cellular systems.
(1) Cells: a basic building block of life.

My use of the word communities throughout is defined as above. Note that all Living System WBS levels can be associated with a Moon or Mars mission, however, the focus must be on the community. The community is also the focal point for cost associated with a Moon or Mars mission. The conceptualization, evaluation, marketing, design, prototyping, testing, production, deployment, operation, support, evolution, retirement, and management of the community (Dean, 1993), not the hardware, should be the focus of any project concerned with returning to the Moon and going on to Mars.

90-Day Cost Related Issues

Why do we not yet have communities established on the Moon and Mars? The answer is the cost of doing so.

There is a cost estimating disconnect. We estimate the cost of the hardware and the software, but the cost arises from the process of creating, sustaining, and retiring a community.

There is a design disconnect. We do not design to reduce cost. Until cost can be substantially reduced, creating communities on the Moon and Mars will be impractical.

These observations drove my research from 1990 through the end of 1998 when I retired from NASA. As long as we estimate hardware and software with no insight into how the cost arises, our estimates provide no guidance to design teams for reducing cost. Cost arises through the execution of processes. They arise because of an action upon an object [action upon, object]. They arise because someone does something [do, something]. Currently, much of the substantial cost of the living systems is allocated to wraps with no insight as to how they arose.

Until system developers focus on reducing cost, we will get what we have always got. Until we can estimate how cost arises and can explain that to the developers, developers will be flying blind if they attempt to design for cost (Dean and Unal, 1991).

There are tools that can be used to reduce cost. Nine years of my research into how to reduce cost is summarized at Design for Competitive Advantage (Dean, 1994-1998) – the republication of a substantial part of my NASA Design for Competitive Advantage web site. In recent years Lean (Womack and Jones, 1996), Six Sigma (Yang and El-Haik , 2009) and Lean Six Sigma (Jugulum and Samuel, 2008) have added additional tools. To become a part of the focus on reducing cost, cost estimators need to develop accurate target costing (Cooper and Slagmulder, 1997 and Monden, 1995), to focus on root cause cost drivers, and to focus on the cost of processes (Emblemsvag, 2003 and Smart, Reese, Adams, Batchelor and Redrick, 2007) from which costs arise.

Research Required to Establish a Community on Mars

In order to eliminate the severe cost constraint on returning to the Moon and going on to Mars, the following are needed: more cost effective energy, increased MTBF in a Mars environment, means to live off of the land in the Moon and Mars environment, an improved understanding of living systems and related costs in the Moon and Mars environment, more cost effective processes to bring into being, to maintain, to evolve, and to retire the systems required by a colonial community. There is a strong need to learn to design for robustness, quality, cost, and value. Without appropriate target cost models, the cost community can be of no value to the development community and the development community cannot get us back to the Moon and on to Mars.

Conclusions

Cost estimating is far more than applying someone's cost model – it requires that we understand, at a substantial level of detail, both what we are estimating and how we are performing the estimate. There is a substantial amount of research required before we return to the Moon and set foot on Mars. This includes cost understanding, cost estimating, cost reduction, genopersistation (Dean, 1993), Living Systems, and appropriate technology.

Resources for Further Understanding

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