Lessons Learned from the Space Station Program: The Role of Life-Cycle Cost

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Abstract
In November 2001, the ISS Management and Cost Evaluation (IMCE) Task Force found that the imposition of annual budget caps was counterproductive to controlling total Space Station life-cycle costs. Program management focus on annual budgets has resulted today in significant cost overruns for the Space Station and the forfeiture of research opportunities for an unknown period of time due to crew limitations. This paper states that in doing so, NASA suffered a loss of cost credibility that is likely to affect the future of human spaceflight, and further, it lost opportunities to meet program objectives while staying within a credible total resource estimate. The proximate cause goes back to the lack of a strong commitment to life-cycle cost management (LCCM) since Space Station Freedom (SSF). This paper describes SSF's early attempt at LCCM and the lessons learned for the next major human missions beyond Earth orbit.

1. Introduction

In November 2001, the ISS Management and Cost Evaluation (IMCE) Task Force expressed concerns about NASA's ability to meet original ISS expectations at assembly complete without further cost overruns and/or radical reform. These concerns focused on NASA's apparent emphasis on meeting annual budget caps imposed by Congress during ISS development, rather than on total cost management. ISS systems were selected primarily "on technical excellence and crew safety with emphasis on near-term schedules, rather than total program costs" [Reference 1]. The Task Force found that "to stay within the annual budget caps, basic program content slipped and the total program cost grew". Only now that NASA is operating these systems have the total program costs become apparent, along with the profound implications for ISS research, should the crew size remain at three.

Beyond ISS, it is likely that NASA, in cooperation with other space agencies, will propose to undertake another large-scale human exploration initiative. Although no decision has been made, that initiative might be a Lagrange point space station, lunar base, or Mars mission. Regardless of the destination, it is critically important to reestablish life-cycle cost management (LCCM) credibility and avoid the conundrum that has befallen the Space Station Program (SSP).

Human exploration is, for the foreseeable future, different from weather, remote sensing, and communications satellites, where the private sector benefits (and hence willingness-to-pay) are sufficient to make them profitable businesses. Human exploration of space offers insufficient private sector benefits to justify its expense. Only the public benefits accruing from exploration and the expansion of human presence in the solar system can provide sufficient reason to marshal the considerable resources required. Thus, we believe that human space exploration will require sustained governmental expenditures for the foreseeable future. Human exploration and development of space programs must therefore be demonstrably well-managed and system-engineered to secure that necessary political support.

We use the term LCCM to mean the disciplined use of life-cycle cost information to guide design and development decisions. (LCCM may be known to some as Design-to-LCC.) Ideally, the objectives and requirements of a LCCM program are to:

- Identify a common set of ground rules, assumptions, and data for LCC estimation (In this regard, the use of a Cost Analysis Requirements Document (CARD) has become fashionable.)
- Ensure that best-practice methods, tools, and models are used for LCC analysis
- Track the estimated LCC throughout the program life cycle, and most important
- Integrate full LCC (not merely development cost) considerations into the design and development process via trade studies and formal Engineering Change Request (ECR) assessments.

This paper presents some of the history of the application of LCCM to the Space Station Freedom Program (SSFP), discusses the technical aspects of doing LCCM, and outlines the requirements and opportunities for a LCCM program for future human exploration initiatives.

2. LCCM in the Space Station Freedom Program

In early 1985, the then-acting SSFP Program Manager, John Hodge, asked JPL to create a LCCM program, and develop the needed tools and models to support it. The clear intent was to ensure that operations issues were addressed during the design and development of the station, and that operations costs were properly traded against development costs. Two models were developed at JPL over the next several years: the Station Design Tradeoff Model (SDTM), and the Model for Estimating Space Station Operations Costs (MESSOC).

Together, these models produced quantitative results sufficient to support trade studies by coupling engineering design information with LCC. The analytic approach that produced these quantitative results is described in Section 3.

One important trade study that used these models pitted the baselined photovoltaic (PV) power system against a less developed, but promising Solar Dynamic (SD) technology. The large effective frontal area of the station's PV arrays meant that drag forces would be large - much larger than for SD. That, in turn, implied that the reboost requirements of the station would be much greater, and the cost during operations of delivering propellant for such reboosts would be much higher. Offsetting that was the surely higher and uncertain development costs of SD. The trade study showed a LCC advantage for the SD, while development budget constraints favored the PV.

Another important trade pitted a H_2 - O_2 propulsion system against a more traditional hydrazine system. The cyrogenic H_2 - O_2 propulsion system would have a much higher specific impulse than the alternative, and could make use of water produced by each visiting Shuttle from its fuel cells. The development costs of such a system would be higher, and the amount of electrical power for electrolysis of the water and cooling of the cyrogenic fuel would be greater as well. Offsetting this was the enormous cost of delivering (highly toxic) hydrazine via the Shuttle to the station over its operational life. The trade study showed a LCC advantage for the advanced propulsion, but again development budget constraints favored the hydrazine system.

While these major trades were being conducted in the mid-1980s, SSFP contractors at each Work Package were encouraged to institute their own LCCM programs. At Work Package 2, many smaller issues kept coming up that could be decided on a LCC basis, if the long-run cost of "station resources" were known. For example, should a particular power system box be located externally on the truss, or internally in a system rack? If located externally, then expensive EVAs would be needed for maintenance, but located internally, less costly (and safer) IVA maintenance could be performed. Offsetting the lower IVA cost was the cost of consuming precious pressurized rack space over the station's operational life. More system racks meant less room for science payloads as well as less living and working space for astronauts.

The two JPL models produced the kind of long-run marginal costs for station resources needed to complete such trades. Indeed, a relatively simply process emerged by which such trades could be conducted: NASA would regularly publish updated long-run marginal costs of about 40 station resources (known as resource "shadow prices"), which contractors could use in making design decisions that didn't require a formal ECR. At the same time, the two models would be distributed to contractors so that larger, more complex trade studies could be performed before initiating a formal ECR. Supporting analyses would then be verified by an independent systems engineering group reporting to the station's Configuration Control Board.

In March 1990, NASA approved this approach to LCCM,[1] and such station resources prices were subsequently published [Reference 2]. Shortly thereafter, the SSFP was cancelled.

3. Technical Aspects of LCCM

At the heart of JPL's approach to the technical aspects of LCCM were models that would determine " optimal" sizes for SSF's many subsystems based on user requirements and LCC. At the time, the station was still a "paper" design, and the subsystem performance requirements were yet to be decided. There were, however, mandated top-level user requirements for SSF, such as 35 kW of power for payloads, 16000 crewhours/year of IVA, 150 crewhours/year of EVA, and 12000 kg/year of pressurized payload upmass. The technical issue was to determine the performance requirement ("resource size") for each subsystem that minimized LCC while meeting these user requirements.

Subsystems must be sized so that they produce their respective resources not only for users, but also to satisfy the demands of other station subsystems. For example, of all the EVA crewhours produced in a year, some are consumed by the power subsystem for maintenance. Both the power subsystem and the EVA subsystem consume pressurized upmass for spares and consumables. These cross-station resource impacts were called "cross-consumptions", and had to be modeled accurately. Balancing station user requirements and cross-consumptions means:

$$X_i = \sum_j A_{ij}(X_j) + U_i \quad \text{for } i = 1, 2, \ldots, N \qquad (1)$$

where:

X_i = Gross production (supply) of resource i

$A_{ij}(X_j)$ = Cross-consumption of resource i used to produce X_j

[1] NASA Memorandum "Design to Life Cycle Cost (DTLCC) Implementation Plans" from Director, Program Control, SSFPO, Reston, VA, March 22, 1990.

U_i = Desired utilization amount of resource i.

Equation (1) says that for each resource i, total production, X_i, must equal the total amount consumed in the production of all the other resources plus the amount to be made available to users ("utilization"). The matrix **A**, known as the Station Description Matrix (SDM), represents all the self- and cross-consumptions as functions of the resource amounts produced. The SDM is then a set of N engineering equations with N unknowns, representing the flow of station resource inputs and outputs. Building the SDM requires a detailed understanding of the workings of the station's subsystems.

Using the developed SDM, JPL's SDTM solved the following constrained minimization problem: choose $X_1, X_2, \ldots, X_n$ so as to

minimize $C(X_1, X_2, \ldots, X_n)$

subject to $U_i = X_i - \sum A_{ij}(X_j) \geq U_i^*$

and $X_i \geq 0$ for all $i = 1, 2, \ldots, N$

where U_i^* is the station's utilization requirement for resource i — that is, the amount to be made available to users, and C is the station LCC.

The shadow price for each resource is the corresponding Lagrangian multiplier in the above constrained minimization problem. Switching to vector notation, the set of shadow prices, **p**, is solved from the first-order conditions of the constrained minimization as:

$$\mathbf{p} = (\mathbf{I} - \mathbf{H}^T)^{-1}\,\mathbf{C}' \qquad (2)$$

where **H** is the n x n matrix of marginal cross-consumption rates with n station resources and **C'** is the vector of direct marginal costs. That is,

$$H_{ij} = d\,A_{ij}(X_j)\,/\,d\,X_j \qquad (3)$$

and

$$C_i' = d\,C\,/\,d\,X_i \qquad (4)$$

The **H** matrix is likely to contain many zero elements, indicating no marginal cross-consumptions. MESSOC, an operations cost and performance model, provided quantitative values to the matrix for many of the resources consumed in station operations, logistics, and maintenance. Table 1 shows some of the primary on-orbit resources for which shadow prices were initially developed. (Prices are US $ FY88 from Reference [2], revised December 1990.)

Resource	Shadow Price	Units
IVA (Intravehicular Activity)	US $ 17,500	Crewhour
EVA (Extravehicular Activity)	US $ 83,000	Crewhour
MRS/SSRMS/MT	US $ 52,000	Robot-hour
Energy	US $ 330	kW-hr
Pressurized Logistics	US $ 7,275	kg
Unpressurized Dry Cargo	US $ 6,600	kg
Pressurized Volume	US $ 780,000	Rack-year

Table 1. Primary On-Orbit Resource Shadow Prices

All station resource shadow prices depend on the marginal cost of a Shuttle launch. Table 1 was calculated using the NASA-mandated value of US $ 62.0M per launch. If a higher marginal cost were used, then the shadow prices would all be higher (all "consume" launch services), though the percent increase of each depends on how intensively they consume launch services.

The use of LCCM techniques results in the selection of different technologies and designs at all levels of design decision making—from broad selections of technology to the details of parts and materials.

When these decisions are guided primarily by development costs, the resulting systems often have much higher operations costs than necessary. Within fixed budgets, these high operations costs have the additional pernicious effect of displacing even the most desireable product improvements and expansions of capability. Once inefficient systems are developed and placed in operation, further life-cycle cost trades become heavily biased in favor of the inefficient technology—its development costs and risks having been retired. Compared to new technologies that must still be developed, an existing capability has a huge advantage. Thus, once investments are made in inferior designs, they tend to have a very long life.

4. LCCM for Future Human Exploration Programs

The approach to LCCM described above produced estimates of the program LCC and station shadow prices. In human exploration programs beyond the International Space Station (ISS), a similar approach can restore LCCM credibility. The role of the shadow prices is to guide the design toward a cost-minimizing optimum through trade studies, while the program LCC provides information to assess whether user and system requirements can be met within the budget constraints that may be imposed. As the design, operations concept, and programmatic assumptions of such future programs change, the LCC and shadow prices are updated and tracked through the program control and systems engineering processes respectively.

Why are we optimistic that such an approach, given adequate resources, can work? Three developments since the 1980's give us hope: (1) the recognition that LCC and LCCM credibility matter in human space exploration programs, (2) dramatic changes in the way conceptual studies of space missions are performed, and (3) ISS experience.

4.1 *LCC and LCCM Credibility Matter*

While it seems obvious, the reason that LCCM credibility is important is that someone must ultimately pay the bill for human space exploration. Whether that someone is a set of governments (and their taxpayers) or commercial investors, the demand for exploration programs is not price-inelastic. An approach which overpromises on initial capability and associated operations costs damages NASA's credibility in the long run—once programs' true costs and capabilities are revealed. The recent appointment of Sean O'Keefe as NASA Administrator was accompanied by clear direction from the President to restore credibility to the ISS and human space exploration programs. Thus, we believe NASA will make a major effort to identify and correct the problems that led to the IMCE's admonitions.

Associated with this restoration of credibility, Congress and the Administration need to adopt a realistic view of the future promise and costs of human space exploration. First, there is little reason to hope that the private sector can or will assume a significant part of the burden of funding human space exploration beyond LEO—there is simply too little hope of a profitable return. Second, a realistic view of what can be accomplished with a given budget profile must be adopted. In particular, Congress must accept that LCC-efficient programs usually require higher upfront expenditures for any given set of performance requirements.

4.2 *Collaborative Engineering Environments (CEEs)*

In the mid-1990s, new CEEs such as JPL's Project Design Center, JSC's HEDS-Integrated Design Environment, and ESA's Concurrent Design Facility have changed the way conceptual space missions are studied.

These facilities function as homes for standing design teams using integrated space mission design tools and models. In Houston, the JSC Advanced Design Team has been elaborating architectures for returning humans to the Moon. One such architecture envisions a gateway station at the Earth-Moon L1 Lagrange point, with crews departing to and from both the ISS and a landed lunar laboratory.

With only a little imagination, one can translate the LCCM approach developed for the SSFP to such an architecture. This would allow a team of system and subsystem experts to thoroughly explore the design space, looking for designs that are LCC-efficient. However, a sustained effort is needed to develop the needed LCCM tools and models like SDTM and MESSOC that link with traditional mission and system design tools.

4.3 *The International Space Station*

The ISS program is an invaluable source of actual data for LCCM models supporting future human space exploration. Again, a long-term program of data collection and preservation is needed to reap the benefits.

5. Conclusions

Experience with ISS has raised awareness of LCCM in NASA and the Administration. If Congress can be persuaded of the benefits to the nation and its taxpayers of LCCM, NASA has an opportunity to restructure and reinvigorate its decision making and communication processes so as to restore the credibility of the human space exploration program, allowing a sustained and expanding human presence in the solar system. The emphasis placed on annual budgets and schedule has led the ISS program to largely ignore life-cycle costs in favor of minimizing development costs and cost risks. The result is that the ISS program, while a recognized technical success, is now in a position of having to make some very difficult decisions.

This result can be avoided by a rigorous LCCM program whose implications and results are supported by the Administration and Congress. There is little doubt that such a process is technically possible given the advancements in concurrent engineering over the past decade. This process includes models that estimate life-cycle cost and marginal costs (shadow prices). Life-cycle cost models are needed to address the issue of whether system requirements can be met within the budget constraints that may be imposed. Long-run marginal costs-- that is, the gradients of the cost function-- are needed to perform trade studies that move the design in LCC-effective directions.

With these capabilities, realistic projections of future system costs, cost risks, and performance metrics can be made. On the basis of these projections, more informed decisions can be made about the future of human space exploration. Properly performed, LCCM promises smaller total program costs, though spending profiles may require higher upfront investment. Communicating these implications to the Administration and Congress such that they are understood and accepted will go a long way toward restoring the credibility of the human space exploration programs with respect to cost management.

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