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X-51 scrams into the future

Conversations with Werner J.A. Dahm

Critical times for India's space program

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Controlling launch vehicle

Over the course of 40 years, we have devolped safe, reliable—but expensive—space transportation systems. By considering life-cycle cost as a fundamental driver early in any future designs, we may be able to develop vehicles that are also both sustainable and affordable.

Space transportation systems historically have been designed for maximum performance based on the design history of the 1950s and 1960s, and to throw the maximum weight to orbit while minimizing the propellants required. Payload and vehicle unit cost and development costs were "managed" to meet the performance goals.

Except for the Air Force's evolved expendable launch vehicle program, a cost-sensitive design goal was not the overall driver. The Thor, Atlas, and Delta launch vehicles, the Saturn V Moon rocket, the mostly reus-able space shuttle, as well as some foreign systems were all performance-driven designs, without serious consideration of overall life-cycle cost (LCC) as a design driver. These vehicles lifted extremely expensive payloads and demonstrated safe and dependable delivery—but at high cost.

A sustainable low-LCC delivery system has been a goal for more than four decades. Fully expendable and partially reusable systems have been developed and operated, but neither approach has achieved this goal. Today, we have an even greater need for safe, dependable, affordable, and sustainable systems. New entries by commercial spaceflight providers promise to change the focus, but will they be life-cycle-cost driven or profit driven, which may not be the same thing.

At present, access to space is very expensive, and will remain so until there is a breakthrough in the way we do business.

The Space Propulsion Synergy Team

Recognizing the gap in previous development efforts, the Space Propulsion Synergy Team (SPST), chartered in 1991 by NASA, took on the task in 2004 of analyzing and defining an LCC control approach to launch vehicle design, focused on affordablity and sustainablity.

The SPST is a national volunteer organization of government, industry, and university experts in space propulsion and propulsion- and other system-related technologies. The members' diverse expertise was used to develop new engineering management decision-making tools—specifically, developing innovative engineering processes in the architectural design, development, and operation of space transportation systems. These tools permit quantification of the requirements of both the system operators and the payload customers.

The team maintains an active dialogue among the personnel involved in all phases of the technology, design, development, and operation of space transportation systems. Since its inception, the SPST has reviewed and assessed the lessons learned from all of the major U.S. programs, past and present, focusing on what has been learned from the assessment and control of LCC.

A new approach

From its analysis of previous programs, the SPST determined that a development process *must* focus first on developing system requirements. These include the usual flight performance and functional requirements as well as the total relevant infrastructure on Earth, in space, or on the Moon/Mars surface, as appropriate. These requirements determine the overall LCC.

Specific innovative engineering and management approaches and processes were then developed that included a focus on flight hardware maturity for reliability, ground operations approaches, and business processes between industry and government.

Achieving sustainable LCC will require a major change in program cost control. That cost control must be used as a program metric in addition to the existing practice of controlling performance and weight. Without a firm requirement for cost control and a methodically structured process to achieve it, it is unlikely that an affordable and sustainable LCC will ever be realized.

The basic approach was to adapt the management process for weight control that NASA used on the space shuttle program to control LCC. The process would be used for technology development; advanced development; system design, development, test, and engineering (DDT&E); manufacture; operation; and recycle/disposal. This requires a major cul-

life-cycle costs

tural adjustment in the way the government in general and NASA and the aerospace industry specifically do business. The approach is clearly feasible; commercial enterprises already use it. They are required to budget and control the LCC of their programs—otherwise they fail and go out of business.

All requirements that address a program's major objectives (performance, affordability, safety, and sustainability) must be in place from concept definition through flowdown to the unique element requirements level. The recommended approach is the use of structured engineering management processes to budget and control those functions that are the primary LCC drivers of the program.

Shuttle shortfall study and analysis

The SPST conducted several analyses to uncover the areas that caused the significant cost shortfalls of the space shuttle program from 2000 to 2004. The shuttle shortfall study first identified the major cost drivers that affected shuttle cost. The team found that design decisions that affected development and acquisition costs also drove the operations costs, which then dominated the LCC. The SPST proceeded to identify all the major operations cost drivers.

The study reformatted the major lessons learned from previous programs as technical performance metrics (TPMs). To the degree that these can be implemented, both the design and the operations elemental cost will then cause a decrease in the LCC. Performance and weight can be adversely impacted by the pursuit of these TPMs in some missions and architectures. Consequently, a balance must be struck between these cost TPMs and the performance and weight TPMs in order to meet any LCC goal.

The optimization process will form the framework of the architecture development. Of the 64 TPMs identified in the study, 18 were determined to be major cost drivers. The design and operations aspects of LCC can then be decreased by establishing minimum values of the TPMs consistent with mission objectives and then flowing down the values of the TPMs as actual requirements.

by **John W. Robinson**
Chairman, SPST

After defining an architecture using these TPMs, structured engineering management and a disciplined program development process would be implemented throughout the design and development phases of a program.

Functional breakdown structures

Complete requirement definitions are a necessity at the onset of a program. The SPST developed a unique approach to formulating requirements, one that provides full accountability of all the functions needed to define an architecture's capability to perform missions. That approach is to develop a top-level functional breakdown structure (FBS) with modular subsets that can be used as the basis for defining the functional requirements in any system.

The FBS is a structured, modular breakdown of every function that addresses the capability within an architecture to perform the mission's transportation function. It is also usable for any subset of the mission. It is not tied to any particular architectural implementation because it is a listing of the needed functions (not elements of the architecture). The FBS offers a universal hierarchy of required functions, including ground and space operations and infrastructure. It provides total visibility of all the elements needed to perform an entire mission. This is a new approach that will provide full accountability/traceability of all functions required to perform a mission. It serves as an integrated checklist so no functions are omitted, especially in the early architectural design phase. The approach allows upfront visibility to achieve the desired TPMs required to meet the objectives of affordability and sustainability.

Without a firm requirement for cost control and a methodically structured process for achieving it, it is unlikely that an affordable and sustainable LCC will ever be realized.

One significant characteristic of an FBS is that missing or redundant elements of options within architectures are identified. As a result, valid LCC comparisons can be made between architectures. For instance, one architecture option might not need a particular function (for example, vertical launch with vertical landing does not need the same controls a winged vehicle would need). Or one option may have specific elements perform multiple functions while another option uses one element to perform the multiple functions.

Once the architecture is selected, the FBS will serve as a guide in development of the work breakdown structure, highlight those technologies that need further development, and help identify the discipline resources required to develop and operate that architecture. It also will allow the systems engineering activities to totally integrate each discipline to the maximum extent possible and optimize at the total system level rather than at the element level (stovepiping). In addition, it furnishes a framework that will help prevent incorrect requirements or specifications because all functions are identified and all elements are aligned to functions.

The FBS should be used to ensure that the architecture options are compared fully and validly. After the selection of an architecture that can meet the performance and LCC requirements, these requirements must be allocated and flowed down to all lower tiers. All the requirements and elements of an architecture must be identified at the beginning of a program if the LCC is to be controlled.

Steps to achieving low life-cycle cost

•Establish cost credibility through the use of extensive system-level and component-cost databases. Develop anchor values and LCC models to assure the credibility of initial early estimates and explore the alternatives within the architecture.

•Assess annual funding constraints while exploring alternative system concepts.

•Use a design-to-LCC management process that is an integral part of a performance management system, thereby assuring an integrated cost management system that is coupled with the technical performance measurement system to enhance the early detection of unfavorable trends.

•Use a design-to-LCC manager who reports directly to the program manager, thereby providing a high-level single point of contact.

•Trade cost reduction design solutions through system engineering control of the technical performance and operations cost assessment.

•Establish realistic but rigorous cost objectives early on and emplace highly visible management processes that include the design-to-LCC approach and follow a disciplined process to achieve them.

Designing to life-cycle cost

Controlling life-cycle costs also requires the use of a structured mechanism to implement a design-to-LCC process. This should be a rigorous, disciplined process and must be implemented and demonstrated early in the definition of an architecture and the conceptualization of its elements, including its ground infrastructure, and then refined continuously. It is a process where tradeoffs among development, operation, performance, technical risk, schedule, DDT&E cost, and life-cycle

Recommendations

The improved life-cycle-control processes developed by the SPST will provide the necessary cost controls when properly applied in the future advanced systems. The SPST recommendations are:

- *Make both nonrecurring and recurring costs a required metric, coequal with weight and performance, and flow it down to the individual element developments, with rewards and penalties, in the same way this is done for weight and performance control. Do not allow life-cycle cost to become a goal.*
- *Fully and clearly define competing architectures and alternate implementations of architectural elements. Use an FBS to accomplish this full definition.*
- *Fully and clearly define the requirements at the program's beginning. Use an FBS to accomplish this full definition.*
- *Define architectures using the TPMs and implement a structured engineering management process to budget and control the TPMs throughout the design and development phases of the program.*
- *Develop and implement a very active process of reallocating requirements to lower levels to achieve overall system requirements throughout the DDT&E program. This should be done across multiple requirements.*
- *Balance the safety, reliability, and maintainability requirements to provide controls on recurring maintenance burden to provide operational effectiveness and LCC control.*
- *Develop a thorough understanding of the cost dependence on reliability and maintainability tradeoffs.*
- *Develop a thorough appreciation of the coupling of maintainability and reliability.*
- *Use a methodology or process for developing and balancing quantitative safety, reliability, and maintainability requirements.*
- *Develop and use a structured mechanism for design-to-life-cycle cost.*

costs must be addressed on an ongoing basis. LCC must be the primary TPM used to make decisions within these trade studies. An ability to control costs within stringent total program and fiscal constraints must be demonstrated early in the design development phase and carried throughout the last day of operation of the vehicles.

The design-to-LCC management process should allow definition and implementation of cost-effective design improvements early in the design phase. Implementation early on assures visibility into production and life-cycle cost trends. It also facilitates credible cost, schedule, and technical performance feedback. Moreover, coordination with responsible design engineers and functional managers gives them the capability to provide effective and timely cost-reduction decisions when they have the most impact on LCC.

The system engineering discipline would employ the design-to-LCC management process as a guide to allocating resources and performance requirements, identifying high-risk or high-cost components that are major LCC drivers, managing system-level cost/capability/risk tradeoffs, analyzing technology selection impacts on program costs, and monitoring design engineering technical performance against identified system goals. There should be a focus on both development and operational cost containment. If system LCC projections exceed target values, design trades should be initiated to redefine system design characteristics to meet the LCC TPM and still meet the minimum requirements.

As the design phase progresses, the emphasis should shift to producibility and maintainability improvements that will benefit production and life-cycle costs. An operations cost model should be used during the design process to provide operations cost impact data for design option selections. Operational life-cycle costs must be continuously and rigorously evaluated as an integral component of overall system design.

Outlook

Based on study and analysis of several programs, including the space shuttle, it is clear that past and current efforts to control LCC have been inadequate and ineffective.

The "lesson learned" from these studies is that vastly improved, innovative processes must be developed and rigorously applied to adequately control life-cycle costs. These processes must be enforced by program managers throughout the design, development, production, and operation of a system. The objective is to establish LCC as a true requirement that is flowed down to all tiers. Requirements not flowed down become "goals," and are rarely met.

Proper application of these processes can provide the necessary cost controls, resulting in sustainable low life-cycle cost space transportation systems.

An ability to control costs within stringent total program and fiscal constraints must be demonstrated early in the design development phase and carried throughout the last day of operation of the vehicles.