The Application of Architecture Frameworks to Modelling Exploration Operations Costs

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Abstract. Developments in architectural frameworks and system-of-systems thinking have provided useful constructs for systems engineering. DoDAF concepts, language, and formalisms, in particular, provide a natural way of conceptualizing an operations cost model applicable to NASA's space exploration vision. Not all DoDAF products have meaning or apply to a DoDAF-inspired operations cost model, but this paper describes how such DoDAF concepts as nodes, systems, and operational activities relate to the development of a model to estimate exploration operations costs. The paper discusses the specific implementation to the Mission Operations Directorate (MOD) operational functions/activities currently being developed and presents an overview of how this powerful representation can apply to robotic space missions as well.

INTRODUCTION

The Vision for Space Exploration. The Vision for Space Exploration (VSE), announced in January 2004, is intended to extend humanity's presence across the solar system, starting with a return to the moon by the end of the next decade, followed by journeys to Mars and beyond. The VSE requires the development of several new systems, upgrades to a number of existing systems, and the integration of all of these into an affordable and sustainable system-of-systems.

The VSE architecture (the "Exploration Architecture") consists of a spacecraft, launch vehicle, common infrastructure, and destination surface segments. The centrepiece new spacecraft to be developed as part of the spacecraft segment is the Crew Exploration Vehicle (CEV), which will first be used to deliver crew and cargo to the International Space Station (using several variants). Other variants will then carry four astronauts to and from the moon, and support up to six crewmembers on future missions to Mars. Another element of the spacecraft segment is the Lunar Surface Access Module (LSAM), which will carry crew and exploration cargo from low lunar orbit to the lunar surface and back.

The launch vehicle segment consists of two new systems, both of which use some Shuttle technology: the Crew Launch Vehicle (CLV), which will launch the CEV; and the Cargo Launch Vehicle (CaLV), which will launch the LSAM and provide the Earth Departure Stage (EDS).

The common services segment consists of elements for mission operations, ground processing and logistics, and communications and navigation. Finally, the destination surface segment consists of elements for surface mobility (e.g., rovers), long-term surface habitation, reliable power, and other elements as needed to support long-term or permanent surface exploration of the moon and Mars.

Clearly, the Exploration Architecture represents an immense, complex undertaking, involving

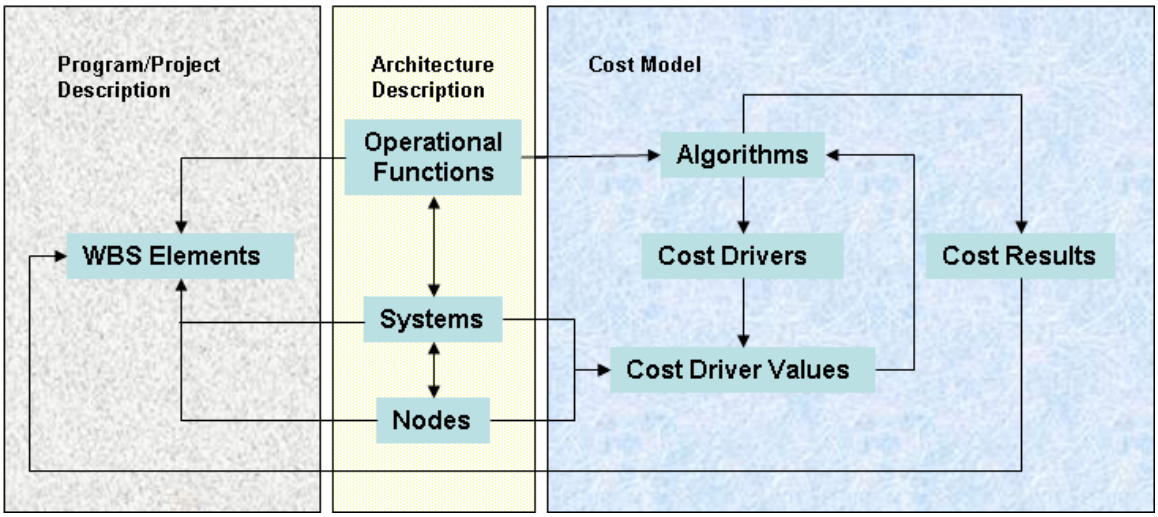
decades of effort, and requiring system engineers to develop models of the architecture elements and of the way they will operate together. Fortunately, over the past years, new ways to describe and characterize evolving complex system-of-systems architectures have been developed and promulgated in various U.S. Government departments and agencies, particularly the U.S. Department of Defense (DoD). DoD policy establishes the use of the DoD Architecture Framework (DoDAF) in capital planning, acquisition, and joint capabilities integration. This paper describes the effort within NASA to use DoDAF general concepts, language, and formalisms to conceptualize an exploration operations cost model that will serve VSE systems engineering needs.

Operations Costs Modelling in Systems Engineering. Operations costs (sometimes the term operations and support (O&S) costs is used) have not received as much attention and detailed analysis within the space costing community as development costs have. Within the systems engineering community, however, it is well-accepted that early architecture/system design decisions can exert a tremendous influence on O&S costs, locking in the level of O&S cost required for the remainder of the program. Choosing the architecture or system design based solely on development costs has been detrimental to NASA in the past. The VSE system engineer should therefore ensure that (1) O&S cost drivers have been identified, and (2) the O&S costs of alternative architectures/systems have been considered in the down selection process. When program development costs can be traded against O&S costs and operational risks, the ability to make accurate O&S cost estimates that reflect alternative designs and operations concepts is essential to good systems engineering.

The Exploration Architecture Operations Cost Model (ExAOCM). The ExAOCM is a NASA effort to meet the need for defensible, systematic operations costs estimates for exploration systems engineering. The Exploration Architecture is still evolving, though some major elements and their concept of operations are known. Important details will likely change as the program is formulated and implemented.

To remain flexible in light of such unknown refinements and programmatic uncertainties, the model relies on recent developments in architecture frameworks and system-of-systems thinking; in particular, the DoDAF's basic concepts of operational functions (formally called operational activities in DoDAF), operational nodes, and systems have substantial usefulness in modeling exploration operations costs. Not all DoDAF products have meaning or apply to an exploration architecture[1], but Figure 1 is a representation of how the architecture description, operations cost model, and WBS are related. The graphic's key message is that the relationship among these three domains is fairly straightforward, and can be captured in a few data tables that can be populated to represent a wide variety of architectures and scenarios. This enables systematic architectural and lower-level trade studies, so for this reason, ExAOCM's general structure is based on Figure 1.

[1] The following are examples of DoDAF products that are relevant to ExAOCM: High-Level Graphic (OV-1), Operational Nodes and Connectivity (OV-2), Operational Functions/Activities (OV-5), Systems and System Nodes (SV-1), System Functions (SV-4), Operational Functions/Activities to Systems/System Functions (SV-5), Systems Evolution (SV-8), and Systems Technology Forecast (SV-9).



Note: "Systems" box also encompasses "systems nodes" and "systems functions."

Figure 1. Conceptual Flow from an Exploration Architecture to a Costed WBS.

EXAOCM UNDERLYING CONSTRUCTS

To understand the details of building the Exploration Architecture Operations Costs Model, it is first worthwhile to discuss the three domain perspectives in Figure 1 in the language of architecture frameworks.

Three Perspectives

Architecture Perspective. The Program System Engineer/Architect is concerned with defining the program-level requirements and then meeting those requirements with a cost-effective architecture/system solution. As such, he/she identifies operational functions/activities that need to be performed. The program operations concept plays an important role here in identifying detailed operational requirements and in suggesting their allocation to operational entities (nodes and systems). A different set of nodes and systems, or a different allocation of operational requirements, results in a new architecture. High-level trade studies are typically performed to determine which arrangement provides the best solution.

Operational nodes in the Exploration Architecture may have a terrestrial or destination (lunar or Mars) surface location, or may be particular orbits or Lagrange points. In space, the spatial and energy relationships among nodes are governed by the laws of orbital mechanics, and hence change over time. Further, orbital and Lagrange point nodes may have costly systems assigned to them (such as a telecommunications relay spacecraft in GEO), or they may void of systems and simply be a convenient way of representing the locus of a key operations event (such as a Low Earth Rendezvous Orbit).

For the Exploration Architecture, operational nodes may have to exchange information (commands, engineering telemetry, voice, video, positioning data, and science data) and materiel

(forward and reverse logistics). These exchanges can be represented in the architecture view as "needlines" of different flavours.

Program/Project Management Perspective. Although the Program/Project Manager has many views, the Work Breakdown Structure (WBS) is among the most important ways of looking at the program. The WBS is a hierarchical breakdown of the work necessary to complete the program/project. During operations, "work" usually means generating operations products (e.g., operations plans, data, trained personnel), or providing operational services (e.g., maintaining systems, managing inventory). These operational functions/activities have a certain tempo and/or level of service that drives costs. The WBS represents the finest level of detail in these operational functions/activities that makes sense to track from a planning and management perspective. From an architecture/systems engineering perspective, it should also reflect all the functions that must be done in operations so as to verify that the detailed operational requirements have been allocated to some operational node or system and that all the functions have been accounted for somewhere in the program. In other words, each operational function/activity should map to one or more "leaf" elements of the operations WBS. An operational function/activity (for example, maintaining systems) may be performed at several facilities (operational nodes). In practice, it is often useful to have a separate WBS "leaf" element for each such facility and/or system.

Cost Modeller Perspective. The cost modeller is concerned with producing a complete, accurate, and defensible estimate of the costs based on information available at the time of the estimate. Because operations consist of many diverse functions/activities, the operations cost modeller applies cost estimating equations and algorithms for each operational function/activity to obtain his/her estimate. These equations and algorithms have inputs--**cost drivers** such as system MTBF and MTTR, system software source lines of codes (SLOCs), and service life; and **scenario drivers** such as mission rate. The cost drivers are assigned values based on the information available to the cost modeller about the operational nodes and systems. These values are supplied to each function/activity algorithm to produce the operations cost estimate. Each estimate (cost result) is then placed in the appropriate WBS element determined jointly by the operational function/activity and the associated node and/or system.

Database Representation

To capture the information required by the general structure of the model in a form useful for making cost estimates, a database is needed that relates the various elements in Figure 1. To support the ExAOCM, I constructed the relational database based on the E-R diagram shown as Figure 2. The details of the various tables are described later in this paper, but Figure 2 identifies some key features. First, the database identifies the operational functions to be performed, the operational nodes in the architecture (including IOC and FOC dates), the systems to be employed (including system functions), and the cost driver names (including units and valid ranges).

A different table in the database provides the assignment of systems to each operational node. Some systems are unique to a given node, but others may appear at multiple nodes, for example, the EVA system (extravehicular activity). Another set of tables assigns values to cost drivers for

each operational node and for each system at an operational node. The value of a particular cost driver may be different at each node, or for each system. Yet another table assigns cost drivers to each operational function/activity, which is equivalent to the statement that the cost of operational function/activity i , C_i, depends on the vector $\boldsymbol{x_j}$ of cost drivers. Lastly, there is a table that assigns each resulting calculated cost to its appropriate WBS element.

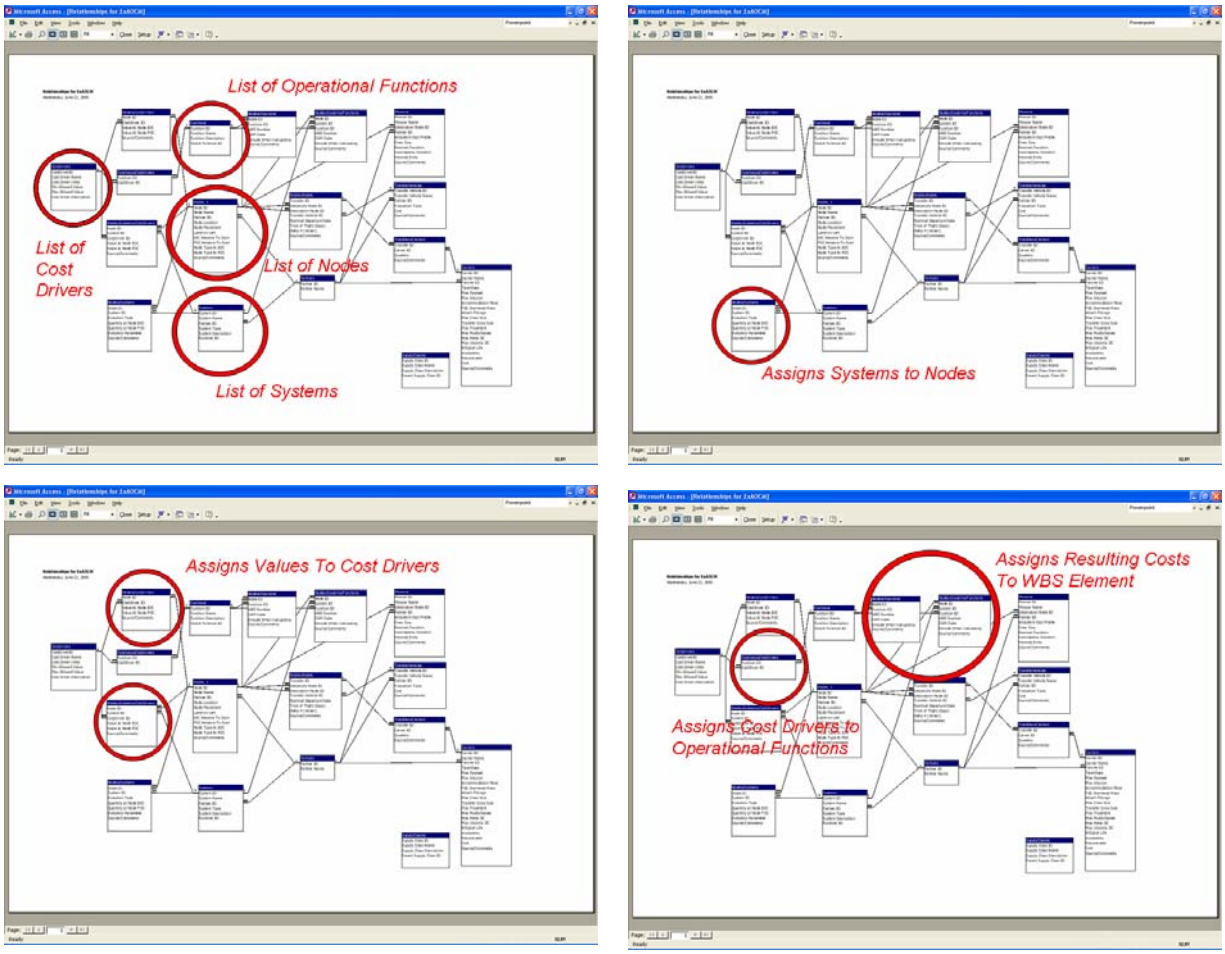


Figure 2. Entity-Relationship Diagram for ExAOCM Database

Relationship to CADM. The ExAOCM general structure and database have a close relationship with the Core Architecture Data Model (CADM), which is designed to capture DoDAF architecture information in a standardized structure. Figure 3 shows some of the key parallel constructs. The figure suggests, as well, that CADM support to operations cost estimation could be enhanced by the explicit addition of tables for cost drivers and cost driver values for each node or system. The counterpart to CADM within NASA is the NASA Exploration Information Ontology Model (NeXIOM), which is designed to capture and expressively describe the engineering and programmatic data that drives exploration program decisions. NeXIOM is

intended to be a repository that can be accessed by various simulation tools and models that need to exchange information and data.

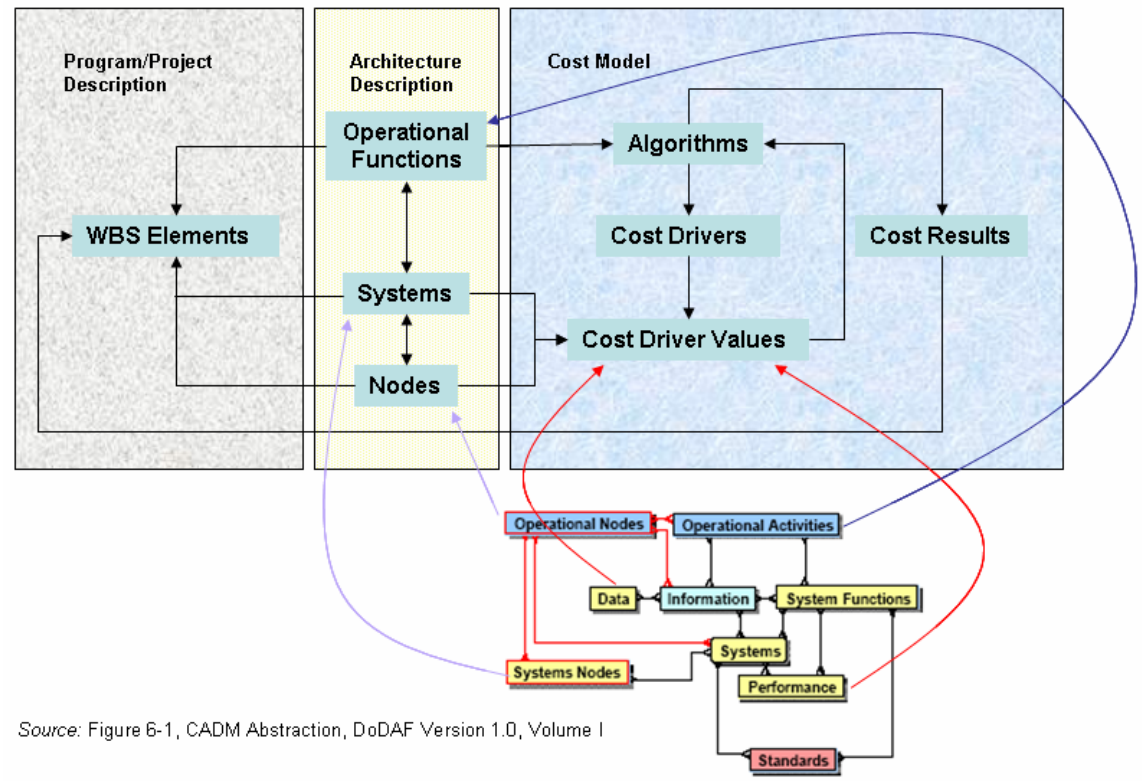


Figure 3. Relationship to DoDAF Core Architecture Data Model (CADM)

An Example

Example Database. To illustrate the workings of the ExAOCM, I have selected a number of mission planning functions/activities and flight controller and astronaut training functions/activities. First, the table in Figure 4 shows the assignment of the key systems operated by the training node and the mission control node. The table describes also how each system evolves over time at each node in terms of quantity. (In this particular table, system quantity does not change for the Integrated Planning System, but system cost drivers might. Other kinds of systems at other nodes, such as the EVA system at the International Space Station and the lunar base, may change in both quantity and quality.) This table allows evolution from Block I to Block II designs by treating them as separate systems.

Next, the table in Figure 5 shows how the value of a cost driver might change over time. For example, the number of SLOCs may increase as the Integrated Planning System evolves from its IOC configuration to its FOC configuration. This table allows for each cost driver to evolve differently for each system at each operational node.

Systems Assigned To Each Node

Describes How/When System Quantity Evolves At Each Node

Node ID	System ID	System Name	System Qty Evolution Type	Quantity At Node IOC	Quantity At Node FOC	Evolution Parameter	Source/Comments
1	2	Integrated Planning System	0	1	1		
1	3	Mission Control Center Facility		1	1		
1	6	FDD Infrastructure System		1	1		
8	4	Flight Controller Training Facility		1	1		
8	5	Shuttle Mission Training Facility		1	1		
7	1	Extra-Vehicular Activity System	1	4	7	12	
2	1	Extra-Vehicular Activity System	1	4	8	3	

Lunar Base Alpha

Training Center, Houston

Quantity Evolution

Mission Control Center, Houston

Figure 4. System and Node Relationships Over Time

System Assigned To This Node

Describes How System Cost Driver Evolves At This Node

Node ID	System ID	Cost Driver ID	System Name	Cost Driver Name	Cost Driver Value At Node IOC	Cost Driver Value At Node FOC	Cost Driver Units	Source/Comments
1	6	3	FDD Infrastructure System	sw_kslocs	5203	5203	real, dimensionless	
1	6	6	FDD Infrastructure System	mission_complexity	1	1	real, dimensionless	
1	2	5	Integrated Planning System	prog_volatility	1	1	real, dimensionless	
1	3	8	Mission Control Center Facility	grd_system_complexity	1	1	real, dimensionless	
1	3	10	Mission Control Center Facility	telemetry_automation_factor	1	1	real, dimensionless	
1	3	11	Mission Control Center Facility	command_automation_factor	1	1	real, dimensionless	
7	1	1	Extra-Vehicular Activity System	hw_invest_cost	25	35	$FY05M	
7	1	2	Extra-Vehicular Activity System	mass_effective	225	450	kg	
8	5	3	Shuttle Mission Training Facility	sw_kslocs	8510	8510	real, dimensionless	

Training Center, Houston

Cost Driver

Mission Control Center, Houston

Figure 5. Cost Driver Values by System and Node Over Time

The operational functions/activities associated with each system at each operational node have a unique assigned WBS designation. This assignment is shown in the table in Figure 6. For example, the software maintenance function/activity for the Integrated Planning System within the Mission Control Center node has a different WBS designation from that function for the Flight Design and Dynamics Infrastructure System at the same node. The table also allows for

the designation of the organization responsible for managing that WBS element from a budgetary (formulation and execution) point-of-view.

Systems Assigned To Each Node

Assigned WBS and CAM Code

Node ID	System ID	System Name	Function ID	Function Name	WBS	CAM Code	Include When Calculating (T/F)	Source/Comments
1	2	Integrated Planning System	2	Facility/System Management	4.3.2.1.1	DA	TRUE	
1	2	Integrated Planning System	3	Facility/System Operations	4.3.2.1.3	DA	TRUE	
1	2	Integrated Planning System	4	Facility/System Hardware Maintenance	4.3.2.1.4.1	DA	TRUE	
1	2	Integrated Planning System	5	Facility/System Software Maintenance	4.3.2.1.4.2	DA	TRUE	
1	2	Integrated Planning System	6	Facility/System Sustaining Engineering	4.3.2.1.5	DA	TRUE	
1	3	Mission Control Center Facility	2	Facility/System Management	4.3.2.2.1	DA	TRUE	
1	3	Mission Control Center Facility	3	Facility/System Operations	4.3.2.2.3	DA	TRUE	
1	3	Mission Control Center Facility	4	Facility/System Hardware Maintenance	4.3.2.2.4.1	DA	TRUE	
1	3	Mission Control Center Facility	5	Facility/System Software Maintenance	4.3.2.2.4.2	DA	TRUE	
1	3	Mission Control Center Facility	6	Facility/System Sustaining Engineering	4.3.2.2.5	DA	TRUE	
8	4	Flight Controller Training Facility	2	Facility/System Management	4.3.3.2.1.1	DA	TRUE	
8	4	Flight Controller Training Facility	3	Facility/System Operations	4.3.3.2.1.3	DA	TRUE	
8	4	Flight Controller Training Facility	4	Facility/System Hardware Maintenance	4.3.3.2.1.4.1	DA	TRUE	
8	4	Flight Controller Training Facility	5	Facility/System Software Maintenance	4.3.3.2.1.4.2	DA	TRUE	
8	4	Flight Controller Training Facility	6	Facility/System Sustaining Engineering	4.3.3.2.1.5	DA	TRUE	
8	5	Shuttle Mission Training Facility	2	Facility/System Management	4.3.3.2.2.1	DA	TRUE	
8	5	Shuttle Mission Training Facility	3	Facility/System Operations	4.3.3.2.2.3	DA	TRUE	
8	5	Shuttle Mission Training Facility	4	Facility/System Hardware Maintenance	4.3.3.2.2.4.1	DA	TRUE	
8	5	Shuttle Mission Training Facility	5	Facility/System Software Maintenance	4.3.3.2.2.4.2	DA	TRUE	
8	5	Shuttle Mission Training Facility	6	Facility/System Sustaining Engineering	4.3.3.2.2.5	DA	TRUE	
1	6	FDD Infrastructure System	2	Facility/System Management	4.3.4.3.3.1	DA	TRUE	
1	6	FDD Infrastructure System	3	Facility/System Operations	4.3.4.3.3.3	DA	TRUE	
1	6	FDD Infrastructure System	4	Facility/System Hardware Maintenance	4.3.4.3.3.4.1	DA	TRUE	
1	6	FDD Infrastructure System	5	Facility/System Software Maintenance	4.3.4.3.3.4.2	DA	TRUE	
1	6	FDD Infrastructure System	6	Facility/System Sustaining Engineering	4.3.4.3.3.5	DA	TRUE	

Mission Control Center, Houston

Describes the Operational Function

Training Center, Houston

Figure 6. Assignment of WBS Elements by Systems and Nodes

Example Cost Algorithms. For many of the operational functions/activities in mission planning and training, the annual costs depend on the number of missions per year. The cost estimating equation in ExAOCM for these particular operational functions/activities has been formulated as a linear function of the CEV/CLV flight rate (in the range of flight rates now anticipated). See Eq. (1), where $C_i(T)$ is the cost in year T of operational function/activity i and $Q(t)$ is the flight rate in year t.

$$C_i(T) = a_i(x_1, x_2, ..., x_n) + \sum_{t=T,T+1,T+2} b_i(x_1, x_2, ..., x_n; t)Q(t) \qquad (1)$$

Because some of the effort associated with these operational functions must be done years in advance, the equation reflects a “lookahead” feature that captures the allocation of the current total effort to current flights and to flights in subsequent years. The coefficients a_i and b_i for each “leaf” operational function/activity, i, are themselves functions of several cost drivers such as mission design complexity, mission duration, crew size, and schedule volatility. In this way, both the intercept (quasi-fixed cost) and slope (marginal cost) terms can be very different for each

operational function/activity. (As an extreme example, the number of SLOCs is the primary cost driver for the software maintenance function. The slope term is set to zero and the intercept term depends only on the SLOCs to be maintained.)

For each operational function/activity, system, and node combination, the cost estimate can be computed for a given flight rate scenario using the cost driver values drawn from the table in Figure 5. These results are then associated with the WBS designation taken from the table in Figure 6.

CONCLUDING OBSERVATIONS

This paper has tried to demonstrate how operations cost modelling and estimation for complex system-of-systems can be integrated with architecture frameworks like the DoDAF. The general concepts, language, and formalisms of the DoDAF are being used to develop an operations cost model for NASA's Exploration Architecture. The same ideas can also be used on less complex undertakings. There appears to be no obstacle to developing a similar model for NASA's robotic missions, such as a pair of Mars rovers. The architecture for that type of mission consists of several terrestrial nodes, two Mars surface nodes, and one or more low Mars orbital nodes, depending on the exact telecommunications assets and strategy employed.

A second observation concerns the importance of developing the program/project operations WBS in concert with the architecture development. It is essential that the program/project system engineer be involved so as to ensure that the operations WBS captures all the operational functional/activities, and that these are overlaid on the operational nodes and systems. Failure to do so will, if past experience holds (regarding gaps in scope and double counting), lead to a failure to understand the program/project's full operations costs.

REFERENCES

DoD Architecture Framework Working Group, "DoD Architecture Framework, Version 1.0, Volume I: Definitions and Guidelines", August 15, 2003.

National Aeronautics and Space Administration, "The Vision for Space Exploration", February 2004, www.nasa.gov/pdf/55583main_vision_space_exploration2.pdf

Office of the Secretary of Defense/Program Analysis and Evaluation, "Cost Analysis Guidance and Procedures", DoD 5000.4-M, December 1992.

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BIOGRAPHY

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