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**A Life-Cycle Cost Estimating Methodology
for NASA-Developed Air Traffic Control
Decision Support Tools**

Jianzhong Jay Wang and Koushik Datta

Prepared for NASA Ames Research Center
under Contract NAS2-98074

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A LIFE-CYCLE COST ESTIMATING METHODOLOGY FOR NASA-DEVELOPED AIR TRAFFIC CONTROL DECISION SUPPORT TOOLS

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SUMMARY

This paper describes the development of a life-cycle cost (LCC) estimating methodology for air traffic control Decision Support Tools (DSTs) under development by the National Aeronautics and Space Administration (NASA), using a combination of parametric, analogy, and expert opinion methods. There is no one standard methodology and technique that is used by NASA or by the Federal Aviation Administration (FAA) for LCC estimation of prospective Decision Support Tools. Some of the frequently used methodologies include bottom-up, analogy, top-down, parametric, expert judgement, and Parkinson's Law. The developed LCC estimating methodology can be visualized as a three-dimensional matrix where the three axes represent coverage, estimation, and timing. This paper focuses on the three characteristics of this methodology that correspond to the three axes.

INTRODUCTION

Insufficient capacity, limited access, and excessive restrictions have escalated operation costs and delay for all users of the National Airspace System (NAS). The National Aeronautics and Space Administration (NASA) Advanced Air Transportation Technologies (AATT) project is developing Decision Support Tools (DSTs) that are computer-based analysis, prediction, and display aids for air traffic controllers. These tools will facilitate substantial increases in the effectiveness of national and global air transportation systems. The AATT project is responsible for defining, exploring, and developing advanced air traffic management system concepts through preproduction maturity. From there the technology is transferred to the Federal Aviation Administration (FAA), which, if it decides to deploy the DST, carries out full-scale development and deployment. During the course of the NASA research and development (R&D) effort, NASA conducts life-cycle cost-benefit studies at several stages of maturity, to indicate whether the DST will have a positive return on investment if deployed by the FAA. These studies require a fairly accurate assessment of the life-cycle cost (LCC) of a DST.

LCCs are the sums of every cost incurred for a particular system over its lifetime, except for sunk costs (ref. 1). LCCs usually include R&D, fabrication and testing, operation, maintenance, and disposal costs. To date, there is no standard LCC estimating methodology and technique that is used by NASA or the FAA for air traffic management systems. Some of the more frequently employed

methodologies include bottom-up, analogous, expert judgement, and parametric estimating. Recently, parametric techniques have gained popularity because they can provide reliable estimates that are generated at a lower cost and shorter cycle time than other traditional techniques (ref. 2).

The AATT DSTs are software tools on Commercial Off-the-Shelf (COTS) hardware equipment. The LCC of the DSTs requires assessing both software and nonsoftware costs. Existing software cost estimating models, such as COCOMO (COConstructive COSt MOdel), fit only a portion of the LCC estimation needs. Because of the differences in software cost estimating models and the large uncertainty associated with software cost estimation, there is also a need to use at least two software cost estimating methods to verify the software cost quantification. The methodology presented in this paper was developed to satisfy these needs in estimating the LCC of NASA-developed DSTs. It is important to note that developing the LCC estimation methodology is only one of many steps in a LCC analysis (ref. 3).

METHODOLOGY

When assessing the LCC for a system, three cost characteristics need to be addressed—consideration of all cost types (coverage), quantification of these costs (estimation), and establishing timing of these costs (LCC phase). The LCC methodology can be visualized in figure 1, which illustrates it as a three-dimensional matrix where the three axes represent coverage, estimation, and LCC phase. The outline of the methodology is provided in the following discussion of the three axes.

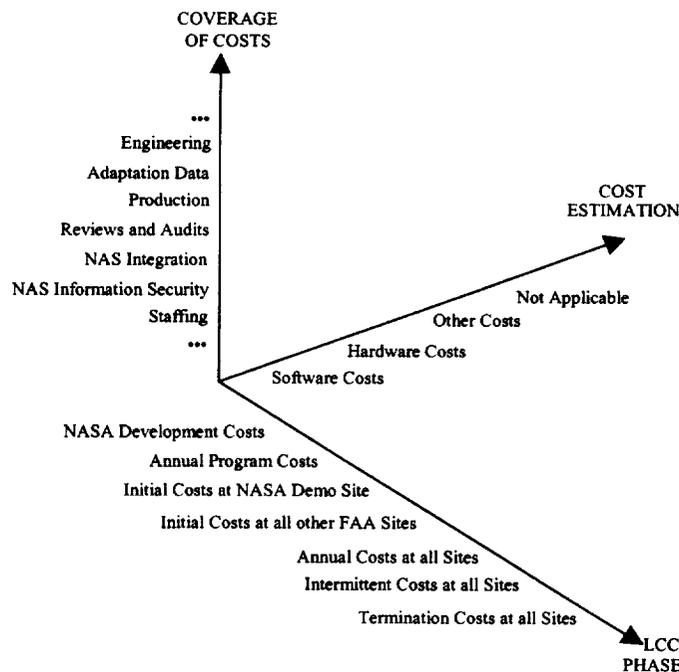


Figure 1. Cost characteristics for LCC assessments.

Coverage Axis

The elements on the coverage axis ensure that all types of costs associated with the life cycle of the system are included. Various types of coverage structures have been used in LCC analyses—work breakdown structure, cost element structure, and subdivisions of work structure. In application of the methodology developed in this paper, the cost element structure is used for the coverage axis. The cost elements and cost factors reflect the accounting subdivisions of program costs, and include research, development, transfer, operations, and maintenance. Some of these cost factors are shown in figure 1. Given the knowledge base at the time of the assessment, every effort should be made to make this a comprehensive coverage of all cost factors. It is best to have a large list of cost factors so that they can be used as a checklist to help analysts achieve a comprehensive assessment.

Estimation Axis

The elements on this axis represent the assessment methodologies for the various cost elements on the coverage axis. Each element on the coverage axis must have at least one corresponding element on the estimation axis. In this paper, the cost factors are either not applicable (hence, not assessed) or they are assessed in one of three methodologies—software, hardware, or other (ad hoc). Many software and hardware cost estimating techniques and models are available. In this analysis, the NASA DST software costs were estimated using an internally developed Activity-Based Cost (ABC) model and the COCOMO II model. The cost of the COTS hardware was assessed based on manufacturer quotes. The rest of the cost factors were assessed using a combination of analogy, parametric, and expert opinion methodologies based on available knowledge.

LCC Phase Axis

Every quantified cost on the coverage axis occurs at some point in the life cycle. The timing of these costs is indicated on the LCC phase axis. During conceptual designs, the timing may be known only by phase (concept, demonstration and validation, technology transfer, production, deployment, operations and support, retirement, etc.). If the cost estimating process includes a work breakdown structure, the timing may be known more precisely (by month). Evaluation of the timing of the costs is important for Net Present Value (NPV) calculation. Figure 1 shows the timing of costs broken down into categories that were useful for the LCC assessment of NASA DSTs.

As part of the LCC methodology, it is also important to determine the base year of analysis, the economic service life of the system, and the discount rate for NPV calculations. The base year is usually the current year or the year in which the first cost associated with an alternative is incurred. In an economic analysis, all costs are discounted to the base year. If the estimated costs are not assessed at the base-year dollar values, then conversion to base-year costs requires knowledge of the deflation/inflation rate.

LCC PHASE

To estimate the DST life-cycle costs, we must first understand the sequence of events in a DST program's life cycle. Figure 2 schematically describes a road map of a DST's life cycle from NASA R&D to the end of the DST program.

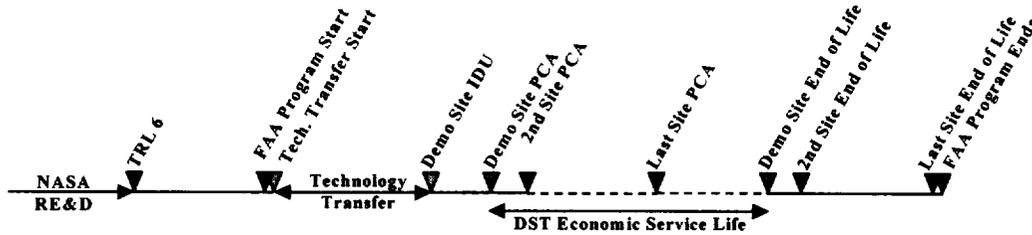


Figure 2. Example of a DST life cycle.

NASA is developing the DSTs from Technical Readiness Level (TRL) 1 (Basic Technology Research) to TRL 6 (Prototype System Demonstrated in Relevant Environment). Each of these DSTs is being developed at a demonstration site in the United States. At completion of TRL 6, the FAA has the option to pick up the NASA-developed technology. If the FAA chooses to do so, then a technology transfer from NASA to FAA occurs. The FAA then develops the DST to a state of operational readiness at the demonstration site, with an initial daily use (IDU) leading to a planned capability available (PCA). The FAA may choose to deploy the DST at other sites; this is shown in figure 2 as the second-site PCA through the last-site PCA. The economic service life of the DST was determined from reference 4—it is the period of time during which the DST is expected to provide a positive benefit. After the economic service life, one by one the DST is taken out of service from each site, and the FAA's program ends soon after the removal of the DST from the last site.

Based on the timeline of events in figure 2, DST costs were categorized into one-time-only program costs, recurring annual costs, recurring intermittent costs, initial costs specific to certain sites, and termination costs for each site. For clarification, the following symbols are assigned to each category.

- One-time-only costs: OC
- Annual program costs: AP
- Initial costs at the first DST site: I1
- Initial costs at the i^{th} DST site ($i > 1$): I2
- Annual costs at all DST sites: AC
- Intermittent costs at all DST sites: IC
- Termination costs at all DST sites: TC

After all the cost factors were associated with a LCC phase (see table 1), the timing (year of occurrence) of the costs related to each cost factor was determined based on the timing of the LCC phases. The methodology to establish the timing of the LCC phases was based on information from previous implementations of similar DSTs by the FAA.

COVERAGE OF COSTS

In this paper, the cost element structure has been used for the coverage axis. The methodology requires a two-level hierarchical arrangement of cost factors and cost elements. One or more cost factors combine to make a cost element.

A list of generic NASA and FAA project cost elements and factors over the life cycle of a DST was studied. The chosen factors were based partially on information provided in reference 4. They were representative of what may be needed by NASA and the FAA to fund and implement a DST acquisition program. The list was intended to be comprehensive so that it applied to all the DSTs. Consequently, not all cost elements and cost factors considered were applicable to every DST. Only those that were quantified for the example DST are listed in table 1. Table 1 also shows the LCC phase and the cost estimating models used. The abbreviations for the cost estimating models follow:

- Software-related cost estimating: S
- Hardware-related cost estimating: H
- Other (ad hoc) cost estimating: O

Table 1. Cost elements and factors quantified in an example DST life-cycle cost evaluation

Coverage of costs		Estimation	LCC phase
Cost element	Cost factors		
NASA's R&D	R&D	S or O	OC
FAA's program management	DST investment decision	O	OC
	Program management	O	AP
	Contract award process	O	OC
	Site feasibility studies	O	I2
Technology transfer (TT)	TT knowledge acquisition	O	I1
	TT production	S	I1
	TT reviews and audits	S	I1
DST software development	Development	S	I2
	Engineering	S	I2
	Knowledge base: adaptation data	O	I2
	Production	S	I2
	Reviews and audits	S	I2
Physical integration	Space	H	AC
	Power system	O	AC
	Telecommunications	O	AC

Table 1. (Continued)

Coverage of costs		Estimation	LCC phase
Cost element	Cost factors		
Functional integration	NAS integration	S	I1, I2
	Standardization	S	I1, I2
Human integration	Human/product interface	S	I1, I2
	Special skills and capabilities	O	I1, I2
Security	NAS information security	S	I1, I2, AC
In-service support	Staffing	S & O	AC
	Technical data	S	AC
	Training and training support	O	AC
	First- and second-level repair	S & O	AC
Test and evaluation	Test plans, procedures, reports	S	I1, I2
	Test equipment/tools, including aircraft	S	I1, I2
	Test staff and training	S	I1, I2
Initial operational test and evaluation (IOT&E)	IOT&E test plans, procedures, reports	S	I1, I2
	IOT&E test equipment/tools, including aircraft	S	I1, I2
	IOT&E test staff and training	S	I1, I2
Configuration management	Functional baseline	S	I1, I2
	Product baseline	S	I1, I2
	Physical configuration audit	S	I1, I2
	Functional configuration audit	S	I1, I2
	Configuration change management	S	I1, I2, AC
	Documentation management	S	I1, I2, AC
Quality assurance	Contractor quality management	S	I1, I2
	Cost/schedule/performance management	S	I1, I2
Implementation	Planning	S	I1, I2
	Preinstallation checkout	S	I1, I2
	Installation and checkout	S	I1, I2
	Site integration and shakedown	S	I1, I2
	Dual operations	O	I1, I2
In-service management	Monitoring, assessing, optimizing product performance	S	AC
	Evaluating capability versus projected demand	S	AC
Sustainment engineering	Replacing obsolete hardware components	H	IC
	Sustaining performance - OS changes	S	IC
Program support services	Program management/technical support	S	I1, I2, AC
	Hardware and COTS software acquisition	H	I1, I2
	Procurement activities	O	I1, I2, AC
Operation and maintenance (O&M)	O&M resources required by the Integrated Product	S	AC
	Team for fielded products		
Termination	Software disposition	O	TC
	Hardware disposition	O	TC
	Telecom and cable disposition	O	TC
	NAS reintegration	S	TC

Following is a discussion of these various cost elements:

- NASA's R&D costs includes all applicable cost starting from TRL 1 to TRL 6 completion. In this study, NASA's sunk costs prior to the start of the AATT project were not included in the assessment (ref. 1).
- FAA's program management covers the planning and monitoring of all tasks and resources over the entire life of the DST at all sites.
- Activities external to the program (not shown in table 1 because they are not applicable to the example DST) are those that may be needed for rulemaking and interfacing with other organizations in fielding the DST.
- Facilities costs (not shown in table 1 because they are not applicable to the example DST), if required, cover the architecture, engineering, and construction of special facilities.
- The technology transfer cost factor covers NASA and FAA costs related to transfer of the DST technology from NASA to the FAA.
- DST software development covers FAA's development, engineering, and production of the DST from TRL 6 completion to PCA.
- Physical integration concerns the integration of the DST into the physical operational environment by the FAA. Cost factors include acquisition of real estate or space, engineering for environmental compliance, energy conservation, and noise abatement.
- Functional integration is related to the interface requirements associated with integrating the DST into the operating NAS air traffic control and air navigation systems.
- Human integration costs are due to requirements and standards that ensure that the DSTs are designed for the air traffic controllers that will operate it and the human workforce that will maintain it. The cost factors relate to safety, training, staffing levels, and personnel skills.
- Security ensures that the DST does not compromise NAS information or personnel security. Cost factors related to maintaining DST physical security are also part of this cost element.
- In-service support includes cost factors to define supportability requirements associated with maintenance, staffing, supply support, training, etc.
- Test and evaluation relates to all test and evaluation requirements prior to the operational tests for the DST. Cost factors include test plans, procedures, reports, equipment/tools, simulations, staff, etc.
- Initial operational test and evaluation (IOT&E) is similar to test and evaluation, but includes only the operational tests.

- Configuration management is related to identifying and documenting the functional and physical characteristics of the DST, controlling changes to DST characteristics, recording and reporting change processing and implementation status, and verifying compliance with requirements.
- Quality assurance cost factors are those that are applicable because of the definition of quality assurance requirements.
- Implementation costs are those that are caused by the requirements related to transitioning from the current capability to the new DST capability so as not to disrupt ongoing NAS operations.
- In-service management costs are related to monitoring, assessing, and optimizing DST performance, and planning for major upgrades.
- Sustainment engineering is related to maintaining the DST with bug fixes, software enhancements, operating system upgrades, or replacing obsolete or failed hardware components.
- Program support services are related to the activities of the FAA's contractor program management and technical support.
- Operations and maintenance (O&M) resources required by the FAA for a fielded DST are the relevant cost factors for this cost element.
- Terminations cost factors relate to the disposal of hardware and software along with reintegration of the affected systems.

The cost factors that were classified as "not applicable" on the cost estimation axis belonged to one of the following four categories:

- Not required (e.g., DSTs did not require physical integration with roads or sewage).
- Not quantified because the baseline resources were sufficient, so that additional resources were not required (e.g., additional real estate).
- Not quantified based on study assumptions (e.g., the FAA's contract procurement was assumed to be part of the FAA program management costs).
- Not quantified because they were assumed to be small cost contributors (e.g., the cost of heating, cooling, or air conditioning).

COST ESTIMATION

The costs of the remaining cost factors (see table 1) must be estimated. Every remaining cost factor was estimated using some cost estimating models—some were part of another cost factor (subset), others were estimated along with other cost factors (grouped), while others were estimated individually (singleton). The cost estimating models were either software related (software development, adaptation, maintenance, and enhancement), hardware related, or ad hoc models. The cost estimating model used for each applicable cost factor is also shown in table 1.

Software-Related Cost Estimation

As seen from table 1, most of the cost factors were estimated using the software cost estimating models. This is expected because the DSTs are software tools that use COTS hardware equipment.

Activity-Based Cost Model

The activity-based cost model is described briefly here. Through many years of research, Jones (ref. 5) identified 11 activities that comprise a minimum set for activity-based software cost estimating. They are chosen based on their high frequency of occurrence during software projects and are assumed to be the base list for the ABC model. They are: requirements, prototyping, design and specifications, design inspections, coding, code inspections, change management and configuration control, testing, user documentation and project documentation, project management, and maintenance and enhancement. An activity is defined as the sum of the effort needed to complete a key milestone or a key deliverable item. The equation for effort required to complete each activity takes one of two forms (refs. 5 and 6):

$$\text{Effort}_{\text{nominal}} = \text{Size} / \text{P rate} \quad (1)$$

$$\text{Effort}_{\text{nominal}} = (\text{Size}^{\text{Power}}) \times (\text{Size} / \text{A Scope}) \quad (2)$$

The subscript “nominal” is used here because the effort is subjected to the effect of reuse and learning. “Size” is the measure of the software project in Lines Of Code (LOC) or Function Points (FP). “Power” is a positive real number determined empirically through historical data. “A Scope” (Assignment scope) is the amount of work for which one person will be responsible on a software project. “P rate” (Production rate) is the amount of work that one person can perform in a standard time period, such as a work hour, work week, work month, or work year. Jones recommends a set of nominal A Scope, P rate, and Power values by analyzing historical data (ref. 5).

It has been established that software development costs are influenced by reuse and learning. Analysis by Selby (ref. 7) of reuse costs across 3000 reused modules in the NASA Software Engineering Laboratory indicates that the reuse cost function is nonlinear (actually, piece-wise linear), as seen in figure 3.

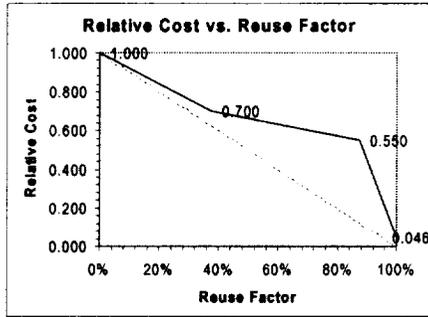


Figure 3. Nonlinear reuse effects.

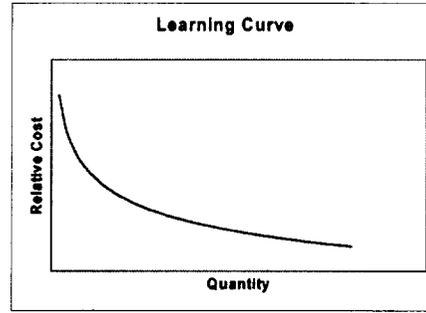


Figure 4. Learning curve.

For the Wright learning curve (a schematic plot is shown in fig. 4), the underlying hypothesis is that the direct labor man-hours necessary to complete a unit of production will decrease by a constant percentage each time the production quantity is doubled (ref. 8).

Combining the effects from reuse and learning, we have:

$$\text{Effort} = \text{Effort}_{\text{nominal}} \times F(\text{Reuse, Learning}) \quad (3)$$

where

$F(\text{Reuse, Learning})$ = Function of Reuse and Learning as described in figures 3 and 4.

The total effort in person-months is the sum of effort of all activities.

COCOMO II

COCOMO II is a rather complicated and well-documented model. Interested readers are referred to Barry Boehm's book, "Software Engineering Economics" (ref. 9), or COCOMO II handbooks (refs. 10 and 11) for further information.

The fundamental equation in COCOMO for the development effort estimate is:

$$\text{PM}_{\text{nominal}} = A \times (\text{Size})^B \quad (4)$$

where

$\text{PM}_{\text{nominal}}$ = Effort expressed in person-months before adjustment.

Size = Size of the software product.

A = A constant (2.94 for the model).

B = A scale factor that is a function of the project scale drivers (SF_i).

The scale drivers are chosen because they are a significant source of exponential variation of the effort or productivity variation of a project. Meanwhile, cost drivers are used to capture characteristics of the software development that affect the effort to complete the project. Cost drivers that have a multiplicative effect on predicting effort are called Effort Multipliers (EM_i).

$$PM_{\text{adjusted}} = PM_{\text{nominal}} \times (\prod_i EM_i) \tag{5}$$

The basic input “Size” in COCOMO is adjusted by a number of factors to account for changes in software requirements, reengineering and conversion of code using automated translation, and codes from existing software that can be reused. The effort equation does not account for the development of software requirements; COCOMO II suggests adding an additional 7 percent to reflect it.

Calibration of the Models

A decision, based on an initial study of the software-cost estimating model requirements, was made not to use the learning and reuse factors for the ABC model and the three size-adjustment factors in the COCOMO II model for this assessment. It is believed that the stringent requirements for using these parameters cannot be satisfied. For example, the reuse factor can be used only when there is prior similar software. Similarly, use of learning factor assumes that the same personnel were working on the same project within a limited period of time.

Therefore, the two models were then calibrated using information provided by NASA on the development of another NASA-developed air traffic control DST. Using the size and cost information of the NASA DST, the parameters in the ABC as well as in the COCOMO II models were adjusted. The calibrated models then show great agreement over a wide range of software sizes, as seen in figure 5 (the error bars in figure 5 represent the range of COCOMO estimates from optimistic to pessimistic).

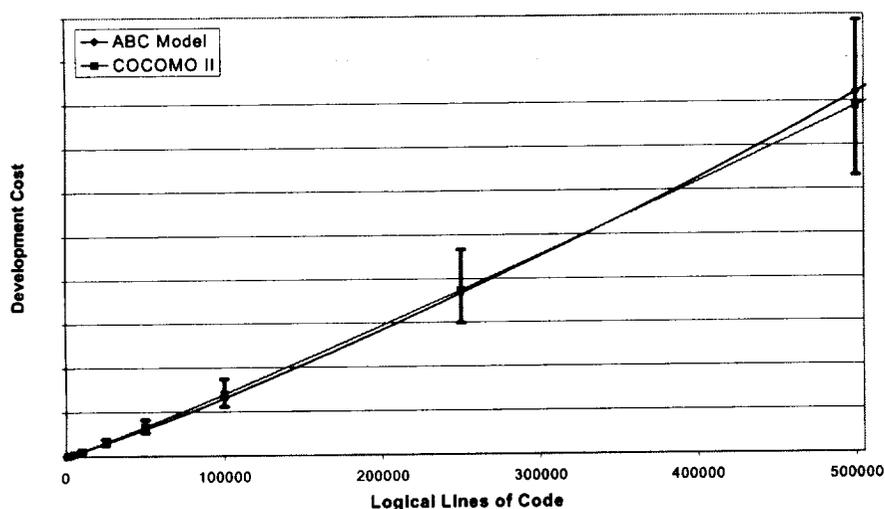


Figure 5. Comparison of the calibrated ABC and COCOMO II cost estimates.

Some of the conceptual DSTs are at a preliminary stage, so even the software requirements are not completely specified. So, the software size of the conceptual DSTs was estimated based on NASA expert opinion and analogy with previously developed NASA DSTs. The software costs were then estimated using these software sizes in the ABC and COCOMO II models.

Hardware-Related Cost Estimation

As seen in table 1, only three of the cost factors were estimated using a hardware cost estimating model. However, the costs could be substantial and should not be overlooked. In this section, the cost model for one of the cost factors, initial hardware acquisition, is described.

In discussion with NASA, it was determined that the conceptual DSTs would have hardware requirements that are very similar to other, previously developed, NASA DSTs (analogy). A detailed list of hardware (including backups) needed at each site for a previously developed NASA DST was obtained. Three types of hardware were needed for normal operation, namely, network equipment, computer processing equipment, and support equipment.

Using analogy, this list was adjusted to reflect the requirements of the conceptual DST. Because all equipment is a COTS-based product, the unit price for all major hardware components was obtained from their vendors. The total hardware cost at a conceptual DST site was then calculated.

$$C_{DST} = \sum_{\text{all hardware}} (\text{Units} \times \text{Price}) \tag{6}$$

where

$$C_{DST} = \text{Initial hardware cost for DST at a site.}$$

The initial hardware acquisition cost is a one-time cost at each site for a conceptual DST.

Other Cost Estimations

Most of the cost factors in table 1 needed to be assessed by other, ad hoc methods. For these costs (e.g., FAA's program management, technology transfer, telecommunication, power, as well as hardware, telecommunication disposition costs, etc.), specialized cost estimating methodologies were developed using either parametric, analogy, or expert judgement methods. In this section, the Cost Estimating Relationship (CER) for one of the cost factors, FAA's Program Management, is described below.

FAA's personnel costs can be a major component of the ongoing costs of the DST program and of complying with government regulations. These are estimated as the product of the quantity of labor required and the total compensation paid per unit of labor. Labor requirements are estimated in full-time equivalent (FTE) work years, and total compensation as a function of the labor category and its corresponding burdened salary rate per FTE per year.

$$Cap_{DST} = (52 \times 40) \times \sum_k Nfte_k \times Ffed \times Salary(Lc_k) \tag{7}$$

where

Cap_{DST} = Annual program cost for DST in year t.

$Nfte_k$ = Number of full-time equivalents (FTEs) required for each position k.

Lc_k = Labor category for each position k.

$Salary(Lc_k)$ = Burdened hourly salary rate for Lc_k .

$Ffed$ = Federal employee burdened salary rate fraction.

t = All years that the DST program is active.

$52 \times 40 = 2080$ = Number of working hours per year.

The cost Cap_{DST} applies every year from the start year to the end year of the FAA's DST program.

CONCLUSIONS

A structured life-cycle cost estimating methodology was developed for air traffic control DSTs under development by NASA. The following three areas were found to be crucial to the methodology: coverage of all cost factors, developing/selecting appropriate cost estimating methods for different cost factors, and correct timing of all costs. The use of the methodology was illustrated with some examples. A key issue is data collection. The parameters in parametric models and cost estimating relationships must reflect the attributes of the organizations involved.

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