COST ANALYSIS

Decreasing budgets and increasing international competition are among the pressures that have focused increased attention on system cost. As such, cost analysis is a critical component of systems analysis, the complementary activity to system engineering that considers programmatic issues along with technical performance. A cost analysis consists of an estimate of resources required to realize, sustain, and/or retire a system; an assessment of the uncertainty inherent in the estimate; a study of the impact on the estimate of excursions from a baseline system design; and documentation of the assumptions and methodologies which underpin the estimate.

Cost estimation and analysis are undertaken to address the paramount economic considerations of affordability and cost-effectiveness of a system. Affordability answers the key question: can the system be procured with the funds available? Cost-effectiveness answers a related but crucial question: does the system being specified represent the best use of available funds? *Life cycle cost* (LCC) is estimated to reveal the economic consequence of technical and programmatic choices, and to guide the engineering process toward a system definition that is deemed affordable and cost-effective.

A cost analysis should be performed both prospectively to support decisions and retrospectively as part of project control throughout a system's life cycle. During concept exploration, a cost estimate can be used to discriminate between alternatives. Collecting information for a cost analysis can also result in the clarification of technical, contractual, programmatic, and risk issues that might not have been settled. As the options are narrowed, a cost estimate can serve as a basis for building a budget.

Cost analysis gives insight into the resource requirements and risks to both a contractor and a client. Any procurement organization should have an independent assessment of cost and schedule before seeking bids. On the other hand, the bidders should do an analysis to ensure adequate resources to execute the contract. When the procuring organization is a government agency, a defensible cost estimate is generally required as part of the bidder's proposal.

This article is intended to leave the reader an educated consumer of cost analysis rather than an expert practitioner. The next section introduces the work breakdown structure, which serves as the framework for any cost analysis. The section entitled *Cost Estimating and Analysis* covers the content of an analysis, the methodologies used, the adjustments made to an estimate, and the presentation of an analysis. Related topics and a bibliography conclude this article.

WORK BREAKDOWN STRUCTURE

Careful development of a work breakdown structure (WBS) is the most important part of the cost estimating process. The WBS is a framework for organizing a cost estimate, identifying all elements of cost that relate to the tasks and activities of developing, producing, deploying, sustaining, and disposing a system. They are developed according to the specific requirements and functions the system has to perform. Standardized WBSs, commonly used in government and industry, are defined for classes of systems that, at a high level, identify the typical cost elements comprising the system. These classes include electronic systems, aircraft systems, surface vehicles, ship systems, and spacecraft systems.

Work breakdown structures are tailored to the program or project under which the activities are organized. Program/project tailoring captures unique requirements for system testing, training, installation/deployment, data, and support activities. As the framework for estimating a system's cost, WBS completeness and accuracy is most critical to a cost analyst to ensure that all program items are included. Careful documentation of the cost element definitions in a *WBS dictionary* is indispensable for delineating the scope of the element, ensuring traceability of costs to specific system/program definition, and eliminating duplication or omission of activities.

Work breakdown structures are tiered by a hierarchy of cost elements. A typical electronics system WBS is illustrated in Fig. 1 (1). Shown are four indentation levels. The first level represents the entire system (e.g., the air traffic control radar system). The second level reflects the major cost elements of the system. In Fig. 1, these elements are prime mission product (PMP), system engineering, program management, and system test and evaluation.

The following defines these level-two cost elements.

Prime Mission Product. The PMP element refers to the hardware and software used to accomplish the primary mission of the system. It includes the engineering effort and management activities associated with the system's individual hardware components and software functions. In the system development phase, PMP includes the efforts to design, develop, integrate, assemble, test, and check out the system's hardware and software. In the production phase, PMP includes the materials, direct labor, and indirect labor to fabricate, assemble, test, and check out individual hardware components, and assemble or integrate them as a system.

System Engineering. This element encompasses the overall engineering effort to define the system. This effort includes translating an operational need into a description of system requirements and a preferred system configuration. It also encompasses the effort to plan, control, and integrate the technical efforts of design (hardware and software) engineering, specialty engineering (e.g., reliability, maintainability, human factors, logistics, security engineering, configuration management), production engineering, and integrated test planning to produce an operational system.

Program Management. This element includes all effort associated with the business and administrative management of the system. This effort includes cost, schedule, and performance measurement, as well as contract administration, data management, and customer/user liaison activities.

System Test and Evaluation. This element includes all test engineering, test planning, and implementation and related efforts (test mockups, prototypes) to ensure that the deployed system has been tested against its requirements. It includes

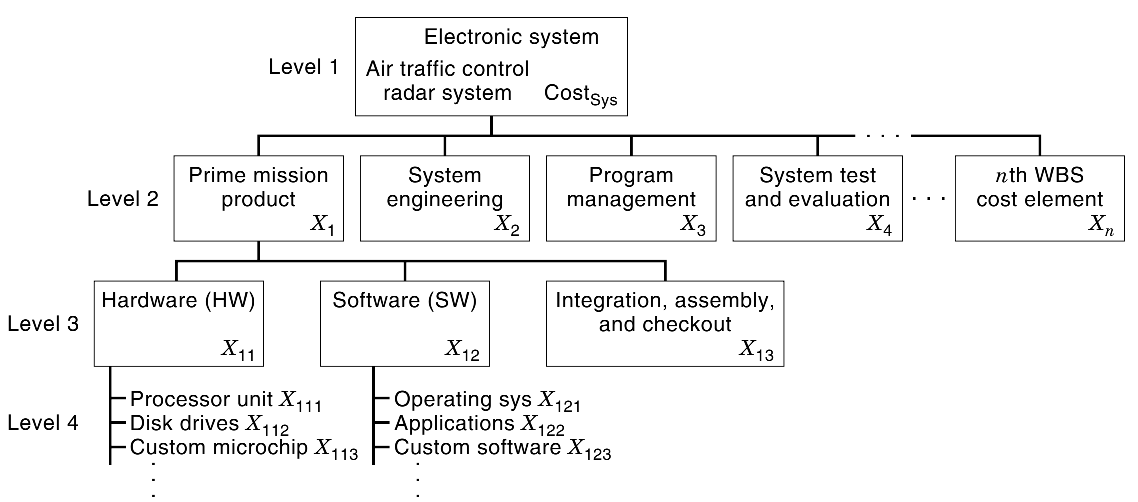


Figure 1. An electronic system WBS.

efforts to obtain and validate engineering data on the performance of the system such as data reduction and reporting.

In Fig. 1, PMP is further delineated into its subordinate level-three cost elements of hardware, software, and integration. Further levels of indentation can be defined to identify individual cost elements of a system's hardware and software, as illustrated by level four of the hierarchy. Level-four cost elements are often the *configuration items* of the system. A configuration item is an aggregation of hardware (e.g., a single electronics box, circuit card, or custom microchip) or software (e.g., a custom-developed software program) that satisfies a particular end-use function of the system.

While Fig. 1 presents a basic framework, a WBS is tailored to the system under consideration. If constructed properly, with consistent definition of the efforts represented at each level, it is infinitely expandable to represent a complex system, and moldable as its definition evolves. For example, level two may be used to further identify major system components or subsystems. In the example of the air traffic control radar system, these may include an antenna subsystem, signal processing subsystem, and radar data correlator subsystem. Levels three and beyond then address the cost elements specific to the individual subsystems and are repeated for each subsystem. The hierarchy of cost elements should unambiguously represent the system configuration to be estimated and must reflect the intended integration at component, subsystem, and system levels. Such a subsystem breakout (or any further indenture breakout of system components or activities) is useful to examine cost impacts of alternative architectures or to segregate and track costs that are the responsibility of different contractors or organizations.

Depending on the analysis, a WBS may encompass one or more phases of the life cycle—system development, production, deployment, operations and support, and disposal. A generic WBS for the full life cycle of an electronic system is shown in Fig. 2. Here, level one identifies the system as before, but level two aggregates costs by life cycle phase. Level three is then used to identify the major cost elements of the phase.

The level that identifies the configuration items (typically an electronics box for an electronics system) can be expanded to show the detailed hierarchy of subcomponents, reflect the required levels of integration to the next higher assembly, identify nonrecurring versus recurring costs, and provide insight to materials versus labor costs. This expansion is typically used to provide insight into design and manufacturing costs and for examination of trades of technology, design approach, and manufacturing method. Figure 3 presents possible expansions of the cost element "configuration item 1" from Fig. 2, first for the development phase and then for the production phase, where costs are recurring with production quantity.

The extent of WBS tailoring and expansion of levels to represent the details of a system design depends on the purpose of the cost analysis. The detail of the WBS should also be consistent with the planned estimating methods, level of technical and activity definition, and data availability to support the cost analysis. Developed as part of the system engineering process and used to organize the cost analysis, a highly detailed structure can provide insight into the system requirements allocation into hardware configuration items, computer software configuration items, test requirements, and system engineering requirements as well as into their associated costs. The WBS can facilitate comparison of alternative architectures, allocation of system functions to specific components, and design tradeoffs of configuration items by providing the cost consequences of these choices.

Most important to a cost analyst, a detailed WBS can help identify and isolate the system cost drivers, and items of substantial technical risk and cost uncertainty, for the attention of the system designers. Simple aggregations or additional detailed elements can be built into the WBS to highlight costs of system components that, for example,

- Will require significant development or production resources to meet a driving performance requirement
- Will have high materials or labor costs due to immaturity of the manufacturing technology, or
- Will simply require large procurement quantities

A properly tailored WBS is used most effectively by a cost analyst working with engineers to feed back information about high-cost or high-risk components to the design process, and to explore tradeoffs of design or performance.

COST ESTIMATING AND ANALYSIS

Cost estimating and analysis is the synthesis of information, methods, and skills into a process for forecasting the cost of a product or activity. The process generally entails the following steps:

- Developing and outlining a definition of the product or activity to be estimated
- Defining the technical, program, and schedule assumptions for which the estimated cost will be valid
- Defining the scope of the analysis
- Collecting, studying, and organizing data
- Selecting and applying analysis tools or methods
- Examining the sensitivity of the results to the environment
- Adjusting the results for specific economic or technical factors
- Assessing the uncertainty of the results
- Presenting the analysis in ways that can be used effectively
- Documenting the results of the analysis

Contents of an Analysis

System and Program Description. A system and program description provides the "why, what, when, where, and how" that become the basis for the cost analysis. A system description, noting its purpose and relation to other systems, provides the "why" and "what," and guides the creation and review of the cost analysis. A *functional block diagram* is often created by system engineers as the first depiction of the required system functionality and its interrelationships, both internally and with external systems. From this, a *strawman design* is developed to allocate and translate the functional requirements to the specific hardware and software configuration items whose cost is to be estimated. The system de-

Level 1 1 **SYSTEM**

Level 2 **1.1 Research and Development**
Level 3 1.1.1 Prime Mission Product
Level 4 1.1.1.1 Hardware Development
1.1.1.1a Configuration Item 1
1.1.1.1b Configuration Item 2
⋮
1.1.1.2 Software Development
1.1.1.2a Computer Software Configuration Item 1
1.1.1.2b Computer Software Configuration Item 2
⋮
1.1.1.3 Integration, Assembly and Checkout
Level 3 1.1.2 Platform Integration
1.1.3 Support Equipment
1.1.4 System Engineering
1.1.5 Program Management
1.1.6 System Test and Evaluation
1.1.7 Data
1.1.8 Training
1.1.9 Installation/Activation
1.1.10 Facilities Design

Level 2 **1.2 Production**
Level 3 1.2.1 Prime Mission Product
Level 4 1.2.1.1 Recurring Hardware
1.2.1.1.a Configuration Item 1
⋮
1.2.1.2 Software
1.2.1.3 Integration and Test
Level 3 1.2.2 Platform Integration
1.2.3 Support Equipment
1.2.4 System Engineering
1.2.5 Program Management
1.2.6 System Test and Evaluation
1.2.7 Data
1.2.8 Training
1.2.9 Packaging/Transportation
1.2.10 Installation/Activation
1.2.11 Facilities Construction/Modification
1.2.12 Initial Spares and Repair Parts

Level 2 **1.3 Operations and Support**
Level 3 1.3.1 Operations
1.3.1.1 Operator Personnel (pay allowances, replacement training)
1.3.1.2 Consumable Materials (oil, fuel, etc.)
1.3.1.3 Electrical Power
1.3.1.4 Operational Facilities Maintenance
1.3.1.5 Leaseholds (e.g., land, equipment, communications circuits)
1.3.1.6 Software Maintenance
1.3.1.7 Transportation
1.3.8 Support
1.3.2.9 Maintenance
1.3.2.1.10 Personnel
1.3.2.1.11 Maintenance Facilities
1.3.2.1.12 Support Equipment Maintenance
1.3.2.1.13 Contractor Maintenance Services
1.3.2.14 Supply
1.3.2.1.15 Personnel
1.3.2.1.16 Supply Facilities
1.3.2.1.17 Spares, Spare Parts
1.3.2.1.18 Repair Material, Replacement Tooling
1.3.2.1.19 Inventory Administration
1.3.2.1.20 Packaging and Transportation

Level 2 **1.4 Disposal**
Level 3 1.4.1 Dismantling/Decommissioning
1.4.2 Hazardous Waste Disposal
1.4.3 Site Restoration

Figure 2. An illustrative electronic system life cycle WBS. *(Continued)*

scription should also note key physical (size, weight), operational (24-hour operation) and performance (power output, range, system availability) characteristics as well as requirements of the operating environment (ground, airborne, space, and/or stressed vibration, temperature, humidity, electromagnetic interference). Technologies [very large scale integration (VLSI), monolithic microwave integrated circuit (MMIC), object-oriented software] known to be implemented for specific parts of the system can also be designated. These product

Level 3 1.1.1 Prime Mission Product
Level 4 1.1.1.1 Hardware Development
1.1.1.1a Configuration Item 1
Circuit Card 1
Nonrecurring Design
Prototype Materials
Prototype Fabrication
Prototype Test
Circuit Card 2
Nonrecurring Design
Prototype Materials
Prototype Fabrication
Prototype Test
⋮
Configuration Item 1 Prototype Integration Assembly
Configuration Item 1 Prototype Test

Level 3 1.2.1 Prime Mission Product
Level 4 1.2.1.1 Recurring Hardware
1.2.1.1a Configuration Item 1
Circuit Card 1
Materials
Direct Manufacturing Labor
Indirect (support) Labor
Circuit Card 2
Materials
Direct Manufacturing Labor
Indirect (support) Labor
⋮
Configuration Item 1 Integration and Assembly

Figure 3. Electronics system configuration item WBS expansion.

characteristics will impact the cost and also may impact the selection of cost methodology for the analysis.

A program description provides the "when, where, and how" of the activities. A detailed *program schedule* lays out all the milestones covered by the analysis and shows the critical path for identifying schedule risks. For the design/development phase, the schedule notes key design reviews, assembly of prototypes or engineering models, integration and test dates, and dates for key deliverables. For production, the schedule shows the establishment of the manufacturing line, purchase of long-lead materials, first and subsequent product deliveries, achievement of target rate production, system installation, and attainment of initial and final operational capability. A program description provides other programmatic information that may include quantities (prototypes, test units, production units, spares), contractor identification, contractor relationships (e.g., prime/subcontractor), the acquisition strategy (competition, sole-source), contract type, and the geographic location where the activities will be performed.

Ground Rules and Assumptions. Often the elements of the system or program description are uncertain, yet they need to be specified to provide a basis for the cost estimate. Ground rules and assumptions are established to highlight and document those aspects of the analysis framework that will have significant impact if they are changed. *Ground rules* are statements about the form and content of the estimate (e.g., costs include a competitive development by two contractors up through system test, and are stated in 1998 dollars). Ground rules also establish the *scope* of the estimate, distinguishing specifically between costs that are included and those excluded from the analysis. For example, an estimate may not address support costs after delivery to a customer, or it may not include the costs of establishing new production facilities.

Assumptions are suppositions about what will happen at some future time. Assumptions can be established globally for the system or program (e.g., laser technology that meets the requirement will be available before the start of system development, contractor A will be the system designer, all software will be written in C^{++}) or they can be established for the specific cost elements (e.g., a VLSI chip will be used to implement the function, five test units will be needed for performance evaluation, a software development lab will be established). Assumptions change throughout the estimating process; thus, careful recording and tracing of assumptions and their changes to cost estimate versions is necessary. Assumptions may represent significant cost drivers for a system.

Methodology. Once the system and the program description and the WBS are established, techniques for the analysis are selected. Basic cost estimating methods include parametric, analogy, bottom-up, engineering assessment, and vendor quote. A *primary methodology* (for estimate generation) and *secondary methodology* (for estimate verification) are chosen. Further discussion of the selection and application of specific estimating methodologies appear later in this section.

What-If Analysis. Once a baseline estimate is created for a given system description and set of assumptions, *what-if analyses* are employed to determine the sensitivity of the resulting cost to changes in the technical definition or the assumptions. This process entails changing one or more of the baseline parameters and applying the same methodologies to calculate the cost change. At a high level, these are instrumental in quantifying the overall uncertainty of the system cost estimate so that one can plan for adequate funds to cover contingencies. At a detailed level, what-if analyses can show the cost consequence of alternatives, (e.g., changes in requirements, design approach, use of different technologies or alternate contract strategies). One caution is that what-if analyses should be conducted on an LCC basis. Changes may only shift the burden of cost to a different phase, (e.g., reducing the required reliability may save manufacturing cost but increase support costs).

Cost Uncertainty Analysis. An estimate of the cost of a future system is affected by uncertainty. Uncertainty is prevalent in many areas of a system, particularly in its early development phase. These areas include the system's requirements, as well as its technical definition and cost estimation approach. Identifying the uncertainties present in the system and measuring their impacts on its predicted cost and schedule is known as *cost uncertainty analysis.* Its prime purpose is to bring a system's cost-risk drivers into clear view. This enables decision-makers to identify, execute, and monitor risk reduction actions from an informed understanding of potential cost consequences and benefits.

In this discussion, we distinguish between the terms risk and uncertainty. *Risk* is the chance of loss or injury. In a situation that includes favorable and unfavorable events, risk is the probability an unfavorable event will occur. *Uncertainty* is the indefiniteness about the outcome of a situation. We analyze uncertainty *for the purpose of measuring risk.* In engineering applications, the analysis might focus on measuring the risk of failing to achieve the performance objectives of an electronic device, overrunning the budgeted design cost, or delivering the device too late to meet user needs.

Uncertainties are present (to varying degrees) across the life cycle of a system. In the early phases, a system's requirements (e.g., its performance specifications) may be ambiguous. Furthermore, aspects of the system's technical definition (e.g., the number of microchips to manufacture, or the amount of software to develop) may not be well understood. In addition, there is uncertainty in the models, methods, and factors (e.g., prices, labor rates, productivities) used to predict the system's cost. For these reasons, a system's predicted cost should be accompanied by a range of possible costs. One way to develop this range is through the use of statistical methods. How this is done is discussed later in this section.

Methodologies

Cost methodologies are selected depending on the required level of estimate detail, the level of technical definition of what is estimated, the availability of data, and the analysis resources (time and labor). A high-level system cost estimate can be derived by *analogy,* based on a simple evaluation that the system under consideration is like another completed system in certain performance respects or for certain significant cost elements. Adjustments for technology, design, or complexity differences may be based on *engineering assessment.* Where detailed insight into the costs of configuration items is required (to determine where alternative designs or technolo-

Table 1. Cost Estimating Methodology Matrix

Contract WBS Item[a]	Parametric Model[b]	Factor Estimate	Catalog Price	Vendor Quote or Proposal	Tailored Analogy	CER	Staff Loading Estimate	Engineering Assessment
PME					x			
COTS Hardware			x	x	x			
Developed Hardware	x			x	x	x	x	x
COTS Software			x	x	x			
Developed Software	x			x	x	x	x	x
System Test	x	x		x	x	x	x	x
Peculiar Support Equipment		x		x	x	x		x
Training		x		x	x	x	x	x
Initial Spares		x		x	x	x		
System Engineering	x	x		x	x	x	x	x
Program Management	x	x		x	x	x	x	x
Data	x	x		x	x	x	x	x
Common Support Equipment		x	x	x	x	x		
Operational Site Activation		x		x	x	x	x	x

[a] The first level WBS elements shown correspond to typical level two elements identified for electronic systems.
[b] Some parametric models estimate a total development cost that includes most WBS elements.

gies may prove less costly) *parametric models* or detailed *bottom up* or *grassroots* estimates are more appropriate.

Estimating methods are generally selected and applied uniquely for individual cost elements of the WBS, or groupings of cost elements. In any estimate, a variety of methods will be used to cost the elements. Certain methodologies are often better suited and more easily applied to specific cost elements. Table 1 provides a matrix of cost methodologies typically applied to specific cost elements.

Selecting an estimating methodology requires analysis of each cost element to determine the depth of its technical definition, its relationship to the technology state of the art, and the availability of technical and actual cost data for analogous items. A program early in development that has not been defined in detail may employ *parametric* methods or analogy to estimate the majority of its content. A higher level of technical specification permits the application of *parametric models,* the development of tailored *analogies,* or the buildup of detailed *engineering assessments.* To-be-developed items that are at or close to the present state of the art may be estimated by parametric model, analogy, or *cost estimating relationship* (*CER*). With significant data on analogous systems, tailored CERs can be developed using statistical regression techniques. This ties the cost estimate to a set of specific supporting cost and technical data, establishing a higher level of confidence in the overall estimate.

A program entering production may rely on actual *recurring costs* incurred in the manufacture of development articles to estimate production costs. For items that are available currently, *catalog prices* or *vendor quotes* are used mostly. *Grassroots estimates* of manufacturing materials and labor based on parts lists and detailed assembly drawings are employed most often in the electronics industry.

Historical Cost Data. Historical cost data are collected to develop a cost database to derive cost (or schedule) estimating relationships, study trends in the cost of technology, or evaluate the cost-effectiveness of business processes. Regardless of its purpose, the research and use of historical cost data requires special attention.

Developing a cost estimate of a future system is benefited by an understanding of historical costs of similar systems. Historical costs are not guaranteed to be the best predictors of future costs; rather, they provide points of departure from which to judge the reasonableness of a future system's estimated cost. Historical cost data provide analogies to the past and a rationale to argue for adjustments that reflect the present or future state of knowledge.

Historical work units (e.g., staff-hours) are the best form of data to acquire. These data are not perturbed by the kinds of economic influences (e.g., inflation) that affect dollars. With historical work units, the consideration is what set of tasks (or activities) are accounted for in the work units. This is sometimes referred to as work content. For instance, contractor *A* may define software development staff-hours as equal to the total effort from preliminary design to system integration testing. Contractor *B* might define the same effort to include all the staff-hours expended in requirements analysis, which precedes preliminary design. Thus, the work content captured in the historical data must be well understood so the data can be adjusted for consistency.

The situation is trickier with historical dollars. In this case, the consideration is not only the work content of the dollars but also the economic and cost accounting influences that affect dollars. Given this, historical cost data must be normalized for both considerations before any inferences can be drawn from the information. Normalization, in this sense, typically includes the removal of inflation to bring the dollars into a common base year. It might also include removing or adjusting cost accounting effects such as a company's overhead structure or profit margins.

Normalization is an essential aspect of researching, collecting, and preparing historical cost data for any type of analysis or inference. When historical cost is suitably normalized, the result is data that have an understood and near-common economic basis.

Parametric Models. A parametric estimate derives costs as a function of the parameters that characterize the system being estimated. In theory, any WBS element can be estimated using a parametric approach. For example, hardware costs can be estimated as a function of weight or by using a factor for dollars per effective isotropic radiated power (EIRP), software costs as dollars per line of code, or data costs as a function of the total estimated pages of data required (dollars per page). Parametric estimates are frequently used to estimate hardware costs. Most software cost models are parametric; they generally estimate effort as a function of lines of code and cost-driver attributes that adjust the effort estimate for specific development and maintenance characteristics.

Parametric models can be calibrated, or modified, to more closely fit actual data. Some of the automated models have a calibration routine; the analyst enters not only system parameters, but also actual costs, and the model will compute complexity factors to be used for estimating the cost of similar systems.

Selection and use of a parametric model requires an awareness of its limitations, the nature of the data in the database, and the validity ranges of the input parameters, determined from the database.

Hardware Models. Several models have broad use in government and industry. These include Lockheed Martin's Parametric Review of Information for Costing and Evaluation-Hardware (PRICE-H), Galorath Associates' System Evaluation and Estimation of Resources-Hardware (SEER-H), and the US Air Force's Unmanned Space Vehicle Cost Model, Seventh Edition (USCM7). The PRICE-H model estimates prime mission hardware costs, as well as total system development and production costs. For an electronics item, the primary input is the weight of active electronics, which is then adjusted by complexity factors. The model is proprietary with limited visibility into its equations and databases. SEER-H is similar to PRICE-H but employs knowledge bases to build up estimates. USCM7 also estimates satellite hardware nonrecurring and recurring costs parametrically. The equations for the model and database information are provided in the model's documentation.

Software Models. The software cost element usually includes software design, programming, informal and formal testing, documentation, software development management, quality assurance, independent validation and verification, and configuration management of individual computer software configuration items (CSCI). Firmware may or may not be included in this WBS element. However, firmware is always either part of hardware (hardware-intensive firmware) or software (software-intensive firmware) PMP.

There are several commercially available models that provide a general framework for estimating effort, cost, and schedule for new developments or enhancements to existing software. All require estimates of lines of code or function points. Product attributes and development environment attributes, such as personnel skill and experience and number of development sites, are also generally required. Some of these tools also estimate size and life cycle cost. Versions of the PRICE and SEER models have the capability to estimate software cost.

Microcircuitry Cost Analysis. Microcircuits are becoming the pervasive building blocks of electronic functionality in electronic systems. It is essential for cost analysts to understand the major cost issues of application-specific integrated circuits (ASIC) and off-the-shelf microchips. Also, serious schedule problems can arise if a significant amount of microchip development is needed during system development.

The initial development costs for nonrecurring design engineering and chip prototype fabrication should be estimated as part of nonrecurring PMP development. ASIC chip unit production costs are estimated based on lot quantity, wafer size, and yield. These are estimated separately from other electronics and added to the recurring hardware cost. Several methods are available for estimating ASIC chip design nonrecurring engineering, prototype fabrication, and production unit costs. These include parametric models, lookup tables based on cost experience or contractor data, analogy to similar chips, and general industry cost planning factors. PRICE-M, a parametric microelectronics cost model, can be used for chip costing, but should be calibrated for the type of chips being considered. These costing techniques are applicable to VLSI and MMIC chips. Questions often arise over the cost savings achievable through the use of monolithic integrated circuits versus packaged discrete components. Breakeven analysis is useful for determining the minimum production quantity for such a comparison.

Analogy. The use of analogy as a cost-estimating methodology, sometimes referred to as comparative cost estimating, is based on the premise that if two systems are alike in some respects, their costs should be similar. Cost estimating by analogy combines available system, program, or product descriptions, and applicable historical cost data in a logical manner to highlight similarities and differences. Analogies can be used in preparing development, production, and operations and support cost estimates, and can be applied at many different levels of the WBS. A gross analogy of total system or program cost to that of some comparable program is often made for sensibility checks. More detailed analogies for individual hardware items or engineering tasks are often developed as the primary cost methodology.

Analogies can take many forms. They can compare cost to cost, labor hours to labor hours, dollars per line of code (LOC) to dollars per LOC, labor hours per month to labor hours per month. The analogy process consists of estimating a new item cost as a function of a known item cost and of relative differences between them. The comparison and extrapolation processes are critical. This method requires that the analyst obtain a description of the new system, program, or product and assess the relative differences of the known item as compared to the item to be estimated. Technical specialists familiar with both systems make necessary comparisons and develop quantitative factors and adjustments that characterize the systems' differences in technology, complexity performance, function, and physical attributes. This process requires collection of both technical and cost data at consistent levels. An analogy should only be made at the level dictated by the level of system/product definition (both new and old), the available analog data, and the understanding of differences between the old and new systems by the technical experts.

Analogy as a cost-estimating methodology is best used when the new system/product consists of modified or improved versions of existing components. However, it is also used successfully in other estimating tasks, provided the analyst uses the most recent and applicable historical data and follows sound logic in extrapolating from historical cost data to future activities. In general, the smaller the extrapolation gap in terms of time, technology, and scope of activity, the higher the confidence in the analogy estimate.

Bottom-Up. *Bottom-up estimating* is the process of estimating system or item costs from basic material and labor estimates. Bottom-up estimating is sometimes called *grassroots estimating,* or *detailed estimating* (engineering or manufacturing). Compared to other estimating methodologies, bottom-up estimating methods generally require more detailed definition of the item during the estimating process, and there are more data on which to base the estimate. For engineering and some indirect manufacturing labor, activities are defined in a detailed task statement of work, and the hours of labor required for each task are assessed by specific labor category and skill level. The assessment is made using historical data collected from real experience (e.g., design hours per circuit or hours per drawing) or by a quantitative analysis of the required time for an activity (e.g., hours per cycle of an environmental test). Labor rates specific to those labor categories (e.g., $*X* per hour for a level 5 electrical engineer), are applied to the labor estimates to determine the direct labor cost. Overhead and *burden* rates (percentages of the direct labor cost) specific to the contractor or business/cost center are multiplied by the direct labor cost and added to derive a *fully burdened* or *wrapped* labor cost. Burden includes certain overhead, material, or product handling, business, and administrative costs and allocation of capital resources that are determined by a contractor's accounting structure, current business base, facility requirements, and current indirect costs. Burden also includes a contractor's fee or profit.

Bottom-up estimates are most often and easily prepared for items in production, where future production costs are based on detailed and recent cost history. They are used extensively in electronics manufacturing to estimate new jobs and monitor manufacturing performance, as well as to prepare labor forecasts, profit and loss statements, and budgets. A detailed materials list enumerating the quantity of components needed, by part number, for each assembly becomes the basis for generating both the material and labor cost estimates. Such a materials list can be developed from a schematic, or (less accurately) by analogy to a similar item. Unit prices of the components (e.g., integrated circuits, resistors, wire assembly, chassis) are obtained from vendor catalogs or historical data. These unit prices are adjusted for quantity discount (i.e., the stated unit price is based on a specific quantity that is different from the actual quantity to be purchased) and then extended by the quantity to derive a total materials cost for the unit. The total materials cost is adjusted for losses (assembly allowance, inferior part quality, and obsolescence/material substitution) normally involved in the manufacturing process.

Direct manufacturing labor is estimated by specific labor category and manufacturing function (e.g., component preparation, placement, soldering, inspection and test for an electronic circuit board). Direct manufacturing labor is often estimated using *labor time standards and allowances,* developed from time/motion studies specific to the component being acted upon. The standards may be industry standards or standards developed for a particular manufacturing facility, technology and experience. Standard hours per component for assembly, inspection, and test functions are applied to the numbers of components to estimate standard time. Standard time is then adjusted by allowances for personal, fatigue, and delay time, performance (e.g., variance from standard, rework, engineering change), and realization (i.e., adjustment for a quantity that is different from that on which the standard is based). Labor, overhead and burden rates are applied to the resulting time estimates for each labor category.

Engineering Assessment. Engineering assessments are used when there are insufficient data or technical definition to use other methodologies such as analogy, bottom-up, or catalog pricing. Here, experts knowledgeable in the technology or functional specialty and often having experience with similar systems provide their judgment as to the effort required to complete a task. The more detailed the task description, the better the understanding of the effort required and the ability to modify the estimate if the task changes. This estimating technique is frequently used when the technology is at state-of-the-art limits and other sources of hardware estimates are not available.

Staff-loading estimates, based on engineering assessments of staffing needs over an activity's schedule, are a specific application. For example, it may be assessed that the design of a set of circuit cards may require four engineers full-time for a period of three months. (Separate estimates of materials or other direct charges needed for the activity must be made.) A detailed description of the task and estimate of its duration forms the basis for the judgment as to the number and level of staff required. A staff-loading projection can also follow a distribution (e.g., uniform, beta) depending on how the work is expected to be distributed within the schedule. Efforts for system engineering or project management often follow a distribution related to the project milestones, and these distributions are replicated and thus predictable for similar projects. A staff-loading estimate can also be a refinement of an analogy estimate.

Catalog Pricing and Vendor Quotes. Catalog prices are preferred for determining the cost of equipment that can be clearly specified by manufacturer, type, model, or nomenclature. The costs are traceable and there is little ambiguity about product requirements. Such equipment is commercially available and requires no additional engineering or manufacturing effort to deliver its specified performance. Equipment and software catalogs often provide extensive breakdown of pricing to facilitate selection of performance options, accessories, warranties, maintenance agreements, or vendor support. Unit pricing as well as pricing at quantity discount break points is provided.

Vendor quotes can be obtained for nonrecurring or recurring efforts (design, product modification, fabrication, test) or for procurement of quantities of specified items. Vendor estimates are subject to the uncertainty of the vendor's interpretation of the work for which the quote is requested, and also the vendor's motivation for providing the quote.

Operations and Support Cost Analysis. Operations and support (O&S) costs include all costs related to the operation and upkeep of the system. They include the cost of operating and maintenance personnel, the cost of power to operate the system, the recurring facilities cost, transportation, repair materials, support equipment, recurring maintenance training, and spares. A work breakdown structure for O&S costs is gen-

Table 2. Illustrative Operations and Support Work Breakdown Structure

Operations

1 Electrical Power (e.g., battery, generator, commercial)
2 Materials (e.g., fuel, paper, computer supplies)
3 Operator Personnel (e.g., pay, allowances, replacement training)
4 Operational Facilities Maintenance
5 Leaseholds (e.g., land, equipment, communications circuits)
6 Software Maintenance (e.g., enhancements and corrections to operational software)
7 Other Costs (e.g., utilities for ops facilities, transportation of equipment)

Support

1 Maintenance
  a. Personnel (e.g., organizational, intermediate, depot maintenance)
  b. Maintenance Facilities
  c. Support Equipment Maintenance
  d. Contractor Maintenance Services
2
  a. Personnel
  b. Supply Facilities
  c. Spare Parts
  d. Repair Material, Replacement Tooling
  e. Inventory Administration
  f. Packaging and Transportation

erally tailored to the program to reflect a system's deployment, operations, and logistics support structure. The work breakdown structure should include all elements of personnel, materials, facilities, and other direct and indirect costs required to operate, maintain, and support the system during the operational phase. A sample O&S WBS is given in Table 2. Besides the costs of personnel and parts consumed in maintenance of the equipment, O&S includes the costs of maintaining the necessary supply system for parts, equipment, and maintenance information.

Operations and support costs are not typically included in a development and production cost estimate, unless that estimate includes interim contractor support, the operation of a development facility, or O&S of early development models in the field. However, O&S is frequently a major consideration in design decisions. In addition, most programs require a life cycle cost (LCC) estimate to pass major review points. Programs also make maintenance supportability decisions during the acquisition phase, and those decisions should be based on O&S cost criteria.

Life Cycle Cost Models. Historically, the operations and support costs of electronic systems have often been significantly higher than their development and production costs. A system that is affordable relative to its development and production may have onerous O&S costs. This situation typically occurs in evaluating the use of new versus older technology. New technology may require higher initial acquisition costs, but then provide much higher reliability and reduced operations costs. Older technology often is cheaper to acquire, since it has benefited from an extended production learning curve, but may impose frequent maintenance and high staffing costs. Thus to better understand the relative affordability of alternative system solutions, it is necessary to capture their full LCC.

The LCC model is a mathematical representation of the system's design, operation, and logistics support structure. Life cycle cost models serve many purposes. These include support to choosing among design alternatives and developing cost-effective logistics support strategies. Typical tradeoffs that require an LCC model to properly evaluate are:

- New versus older technology
- COTS equipment versus military standard developments
- Contractor versus organic government maintenance
- Lease versus buy
- Site repair versus factory repair
- System modernization versus replacement

A system's LCC is affected by many parameters including the equipment's design, reliability, and maintainability characteristics; the specific maintenance concept; and the deployment environment. These parameters are captured in the LCC model's cost elements, as illustrated in Table 3. In a detailed LCC model, operations and support costs are generally computed in a bottom-up fashion based on individual equipment characteristics at either the line replaceable unit (LRU) or shop replaceable unit (SRU) level. For instance, the condemnation spares cost, denoted by CSC, is the total cost to replace failed LRUs (and component SRUs) that will be con-

Table 3. LCC Model Cost Elements

Development

1 Hardware Design Engineering
2 Software Design Engineering
3 Hardware Prototyping
4 Development Support (e.g., Systems Engineering, Program Management)

Production

1 Prime Mission Product
2 Production Setup and Installation
3 Production Support (e.g., Systems Engineering, Program Management)

Initial Logistics Support

1 Base Initial Spares
2 Depot Initial Spares
3 Initial Technical Documentation
4 Test Program Set Software
5 Initial Training
6 Initial Depot Support Equipment
7 Initial Base Support Equipment

Recurring Logistics Support

1 Condemnation Spares
2 Repair Labor
3 Repair Materials
4 Technical Documentation Update
5 Recurring Training
6 Support Equipment Maintenance
7 Stock Fund Surcharges
8 Software Maintenance

demned at the site or factory-level over the life of the system. This cost can be computed for each LRU of type I by (2)

$$\text{CSC}(I) = \text{FAIL}(I)^*\text{PIUP}^* \begin{bmatrix} \text{UC}(I)^*\text{LCOND}(I)+ \\ \text{UCSRU}(I)^*(1-\text{LCOND}(I))^*\text{SCOND}(I) \end{bmatrix} \quad (1)$$

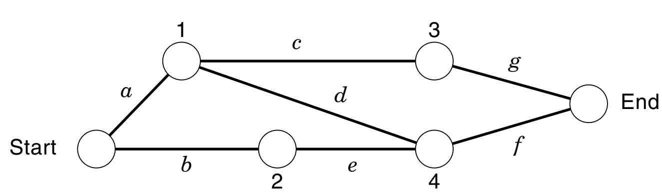
where

FAIL(I)	is the estimated number of yearly failures of LRUs of type I for the total system, computed by FAIL(I) = NLRUS(I)*YOH/MTBF(I)
NLRUS(I)	is the number of LRUs of type I deployed in the total system
YOH	is the yearly operating hours for all system equipment
MTBF(I)	is the mean time between failure for LRUs of type I
PIUP	is the operational system lifetime in years
UC(I)	is the average cost for LRUs of type I
LCOND(I)	is the proportion of failures of LRUs of type I that are condemned on failure
UCSRU(I)	is the average cost of an SRU within an LRU of type I
SCOND(I)	is the proportion of failed SRUs within an LRU of type I that are condemned on failure

Schedule Estimating. In a general sense, cost *is* a function of schedule. The cost of a labor-driven activity may be estimated by assessing the number of staff required over the scheduled duration of the activity; also, the cost of an electronic component (or device) will vary according to the time it's developed (or procured). Program schedule is the usual departure point for estimating program cost. Cost analysts need to understand a program's schedule and its implications from a cost risk perspective. Cost risks are often linked directly to a program's planned (or mandated) duration.

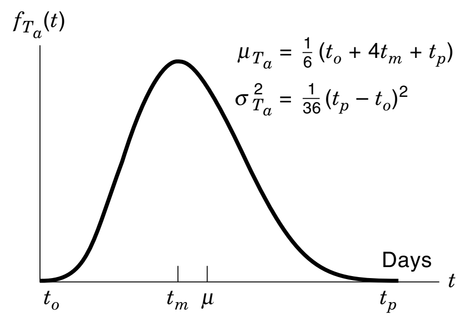
At the planning stage of a program, schedule may be derived using analogy-based approaches, engineering judgment, or a combination of the two. If a detailed schedule is required, analogy-based approaches may be augmented by the use of a schedule model. Schedule models typically require developing a network of activities, determining their precedence relationships, and estimating the time required for each activity. An example of a schedule network is shown in Fig. 4.

In Fig. 4, the activities are shown by the lettered lines (also referred to as arcs). An activity is a task, or a set of tasks that consumes resources and requires time to complete. The lines are also used to indicate a precedence ordering of activities. For example, in Fig. 4, task f has immediate predecessor activities d and e. The nodes (shown by the circles) represent discrete events (e.g., interim milestones) that result when one or more activities are completed. The sequence of activities that yields the longest path through the network is called the *critical path.* Any increase (or delay) in starting these activities lengthens the overall project schedule. All other paths through the network have durations less than the duration of the critical path. Thus, activities along the critical path have *no slack* associated with their start times.



Assume the lines connecting the nodes reflect a left-to-right precedence ordering of activities a, b, c, d, e, f, and g.

Figure 4. Example schedule network topology.



T_a = Overall time duration of activity a
$T_a = \{t{:}t_o < t_m < t_p\}$

Figure 5. Beta distribution of an activity duration.

Classical approaches for constructing a network-based schedule are the Program Evaluation and Review Technique (PERT) (3) and the Critical Path Method (CPM) (4). Modern methods have origins to both approaches. CPM uses deterministic estimates of activity durations. Each activity proceeds to its successor activity with certainty (i.e., with probability equal to unity). Under CPM, each activity duration is estimated by a fixed value.

The United States Navy developed PERT nearly coincident to the development of CPM. Although PERT is very similar to CPM, its primary distinction is representing each activity duration by a range of values instead of by a fixed value. The range is defined by three points. These reflect an optimistic time t_o required for the activity, a most probable time t_m required for the activity, and a pessimistic time t_p required for the activity. PERT uses these values to specify a beta probability distribution (1) of the activity's overall time duration. This is illustrated in Fig. 5, where T_a is the overall time duration of activity a in a network.

For each activity in the network, PERT computes the mean μ and variance σ^2 of its duration. Formulas for approximating μ and σ^2 are shown in Fig. 5. The mean duration of the project is the sum of all the mean durations of all activities on the critical path. The variance of the project is the sum of the variances of the durations of all the activities on the critical path, assuming the activity durations are *independent.* Given this, the probability distribution of the project's overall duration will be approximately normal, in accordance with the central limit theorem (1).

PERT/CPM networks were developed in the late 1950s. Since then, techniques for using networks as a tool for schedule estimating have advanced considerably. Advanced network techniques such as Graphical Evaluation and Review Technique (GERT) (5) and SLAM II (6) provide enormous modeling flexibility. This includes the ability to build stochastic networks where activity branching between nodes is probabilistic instead of deterministic, where feedback looping to an earlier event (e.g., because of rework) is permitted, and where the entire network can be simulated to reflect alternative scenarios.

One of the drawbacks to network-based schedule estimation is its reliance on a well-understood and well-described set of activities. For many programs, particularly in their early conceptual phases, this information is not well known or not available. In this case, a network-based schedule model is not possible. An alternative to network-based schedule models is the parametric model, which is discussed briefly in the following section.

Parametric Models for Schedule Estimating. In many instances, program schedule is estimated from a parametric model. Parametric models are usually regression equations developed from a statistical analysis of historical data. Equation (2) illustrates a parametric model for a software development schedule (7).

$$\text{Sched} = 5.9(91 + 0.66I^{1.52})^{0.25}\epsilon \tag{2}$$

In the expression above, the independent variable is the number of delivered source instructions I (expressed in thousands); the regression error of the model is given by ϵ. The output variable is *Sched,* which is the number of development months.

In Eq. (2), a development schedule for software can be estimated from just an assessment of its size I. Parametric models are conducive to uncertainty analyses. An analysis could be conducted where, in Eq. (2), the variable I takes on a range of possible values instead of just a single value. From this, a probability distribution of schedule could be developed. This would provide insight into the chance of not exceeding a particular schedule in the set of possible schedules for the activity or program.

Although parametric models for schedule estimating require less information than network-based approaches, they can have large errors associated with their predictions. These errors reflect how well the model fits the data upon which it was built. Lastly, analysts must pay close attention to the scope of activities captured by a particular model. A schedule model must be sufficiently well documented to distinguish between the activities that are in scope from those that are out of scope.

Cost Uncertainty Analysis. Mentioned earlier, the estimate of a system's cost can be significantly affected by uncertainty. Recognizing this, any predicted cost should be accompanied by a range of other possible costs. Statistical methods are recommended for determining this range. Statistical methods provide several advantages. First, a range of possible system costs can be produced that is a function of the cost ranges of the components (or elements) that comprise the system; second, statistical methods support determining the probability that a particular cost in the range of possible costs will not be exceeded; third, probability information can be directly associated to the amount of reserve dollars needed to remain within budget, or within a required threshold.

A traditional way to express a range of possible costs is by a probability distribution. Simply stated, a *probability distribution* is a mathematical rule associating a probability α to each possible event. There are two ways to present a probability distribution. It can be shown as a probability density or as a cumulative probability distribution. Figure 6 illustrates this from a cost perspective. The range of possible values for *Cost,* in Fig. 6, is given by the interval $a \le x \le b$. The probability that *Cost* will not exceed a value $x = c$ is given by α_c. In Fig. 6(a), this probability is the area under $f(x)$ between $x = a$ and $x = c$. In Fig. 6(b), this probability is $F(c)$.

In real-world engineering projects, it is often necessary to define and work with subjective probabilities. Subjective probabilities are those assigned to events on the basis of personal judgment. They are measures of a person's degree of belief that an event will occur. Subjective probabilities are usually associated with one-time, nonrepeatable, events—those whose probabilities cannot be objectively determined from a population of outcomes developed by repeated trials or experimentation. Subjective probabilities must be consistent with the axioms of probability (1). For instance, if a microelectronics engineer assigns a probability of 0.70 to the event "the number of gates for the new processor chip will not exceed 12,000," then it must follow that the chip *will exceed* 12,000 gates with probability 0.30. Subjective probabilities are conditional on the state of the person's knowledge, which changes with time.

Instead of assigning a single subjective probability to an event, subject experts often find it easier to describe a distribution of probabilities by a mathematical function. Such a function is called a *subjective probability distribution.* They are common in cost uncertainty analysis and often look like the function in Fig. 6(a). Because of their nature, subjective probability distributions can be thought of as "belief functions." Subjective probability distributions are governed by the same set of mathematical properties associated with probability distributions (1).

Probability distributions result when variables (e.g., weight, power output, staff level) used to derive cost are allowed to assume values randomly within ranges of feasible values. For instance, the cost of a satellite might be derived on the basis of a range of possible weights, with each weight allowed to occur randomly. This approach allows cost to be *treated* as a random variable. It is recognized that values for these variables (such as weight) are not typically known with sufficient precision perfectly to predict cost, at a time in a program when such predictions are needed.

The Process. An overview of the cost uncertainty analysis process is shown in Fig. 7. The variables $X_1, X_2, X_3, \ldots, X_n$ represent the costs of n WBS elements that comprise the system. For instance, X_1 might represent the cost of the system's prime mission hardware and software; X_2 might represent the cost of the system's systems engineering and program management; X_3 might represent the cost of the system's test and evaluation. Discussed above, the values of these variables typically cannot be predicted with certainty. Therefore, probability distributions are developed for $X_1, X_2, X_3, \ldots, X_n$ that associate probabilities with their possible values. Such distributions are illustrated on the left side of Fig. 7. These distributions are then summed to produce an overall probability distribution of the system's total cost. Such a distribution is shown on the right side of Fig. 7.

The input part of this process has many subjective aspects. Probability distributions for $X_1, X_2, X_3, \ldots, X_n$ are either specified directly (subjective) or they are generated from a

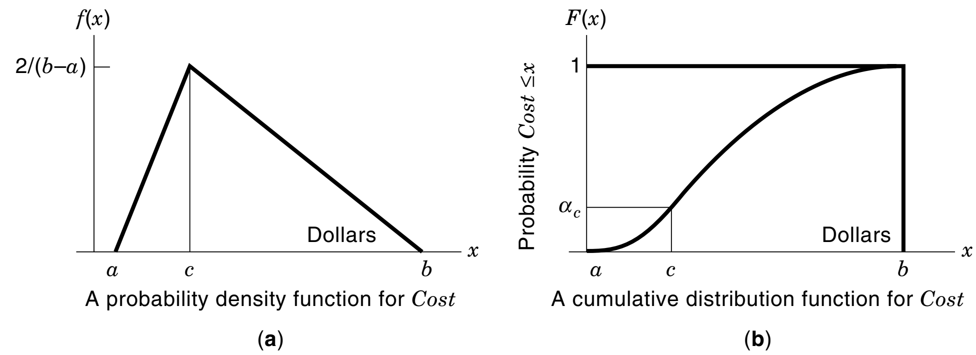


Figure 6. Types of probability distributions.

mathematical process. Direct specification relies on expert judgment to characterize a distribution's shape. The probability density is the usual way to make this characterization. The specification of probability distributions for X_1, X_2, X_3, . . ., X_n is usually done around their point estimates. The *point estimate* of a variable whose value is uncertain is a single value for the variable in its range of possible values. From a mathematical perspective, the point estimate is simply one value among those that are feasible. In practice, a point estimate is developed by an analyst before an assessment of other possible values. It provides an anchor about which other possible values are either directly assessed or directly generated.

Analysis Methods and Tools. Techniques for cost uncertainty analysis fall into two categories. These are analytical approaches and the Monte Carlo method. In practice, a combination of these approaches is used. Analytical methods rely on the axioms and theorems of probability theory to combine the probability distributions of X_1, X_2, X_3, . . ., X_n into a distribution of total cost, illustrated in Fig. 7. However, at times there are practical limitations with a purely analytical approach. A system's work breakdown structure can contain cost-estimating relationships too complex for strict analytical study. In such circumstances, the Monte Carlo method is frequently used. This is an empirical method based on the concepts of statistical sampling. The Monte Carlo method can be described, in this context, as follows:

- For each random variable defined in the system's WBS, randomly select (sample) a value from its probability distribution function.
- Once a set of feasible values for each random variable has been established, combine these values according to the cost estimation relationships specified across the WBS. This process produces a single value for total system cost.
- Repeat the above two steps k times (k = 10,000 random samples are usually sufficient to meet the precision requirements of most simulations, particularly for cost uncertainty analysis). This produces k values with each representing a possible (i.e., feasible) value for total system cost.
- Develop a frequency distribution from these k values. This distribution is the simulated (i.e., empirical) distribution of total system cost.

With the development of powerful personal computers, a number of software products are available for conducting Monte Carlo simulations. Such products include @Risk (8), Crystal Ball (9), and Analytica (9). The first two products operate in conjunction with electronic spreadsheets. This is a popular environment for conducting cost uncertainty analyses, particularly since cost models are often developed in spreadsheets. Analytica is not a spreadsheet application. It uses influence diagramming techniques, a highly visual environment, to define the cost model and its associated interrelationships.

Uses of Cost Uncertainty Analysis in Program Planning. The cumulative distribution function of a system's total cost, shown on the right in Fig. 7, is used to support budget recommendations. The budgeted cost for the system should include contingency (reserve) dollars. *How much reserve is needed?* If the budget was chosen as the cost at the 50th percentile, then chances are good this cost will be exceeded. Choosing a reserve level around the 70th to 85th percentile is equivalent to budgeting a cost that has only a 30% to 15% chance of being

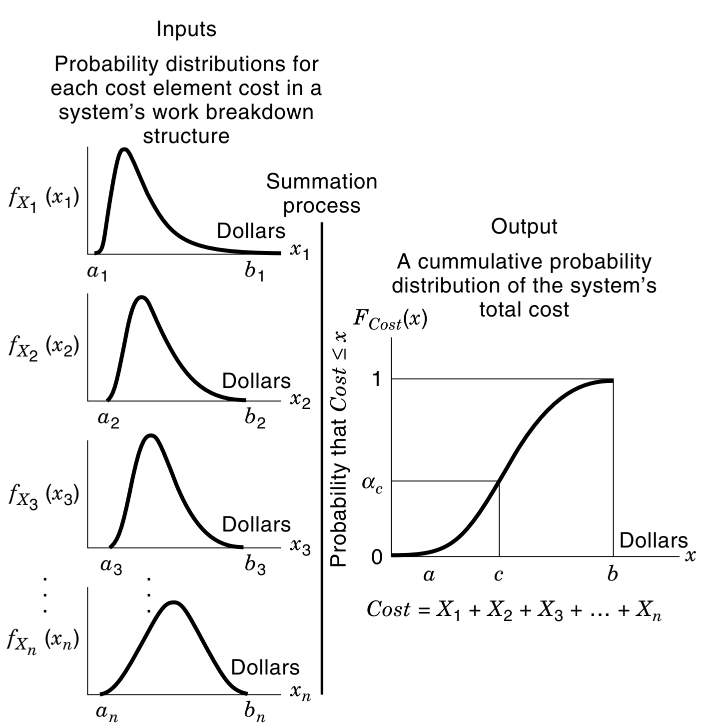


Figure 7. Cost uncertainty analysis process.

exceeded. A useful analysis exercise is showing the cost of increasing confidence. For example, it might be shown that increasing the confidence from the 70th percentile to the 85th percentile costs 2.5 times as much as increasing the confidence from the 50th percentile to the 70th percentile. This provides the decision maker with a quick sense of the "up side" cost risk in the system.

A budgeted (or recommended) cost taken as a value from a cumulative distribution function should be compared to the value that is the sum of the individual point estimate costs of each WBS cost element. The difference is the contingency dollars needed for the program. In the early phases of a program, contingency dollars often exceed acceptable levels. Bringing this insight to the decision maker is one of the most important products of cost uncertainty analysis. It is often the catalyst behind a series of technical and managerial actions to reduce risk and keep the program achievable and affordable.

Benefits. Cost uncertainty analysis provides decision makers many benefits and important insights. These include:

- *Baselining Program Cost Risk.* For a given system configuration, acquisition strategy, and cost-schedule estimation approach, baseline probability distributions of a program's cost can be developed. This distribution must be regularly updated as the program's uncertainties change across the life cycle. Generating this distribution supports identifying and planning a program cost that has a specified probability of not being exceeded. This distribution also provides program managers an assessment of the likelihood of achieving a budgeted (or recommended) cost.
- *Estimating Reserves.* A basis for estimating and justifying contingency dollars as a function of the uncertainties specific to a given system can be developed. Sensitivity analyses can be conducted to assess how contingency dollars are affected by changes in specific program risks. In addition, the relationship between the contingency dollars recommended for specified (or desired) levels of confidence can be examined.
- *Conducting Risk Mitigation Tradeoff Analyses.* Cost probability models can be developed to study the payoff of implementing specific risk-mitigation activities (e.g., rapid prototyping) on reducing contingency dollars. Furthermore, families of distributions can be generated that compare the cost and cost-risk impacts of alternative system requirements, schedule uncertainties, and competing system configurations or acquisition strategies.

Adjustments to Estimates

Inflation. Cost estimates are normally prepared in constant dollars to eliminate the effect of price level changes over time. Inflation indices are used to adjust estimate elements to the same constant dollars and are also used to inflate constant dollar estimates to then-year dollars for budgeting purposes. Inflation indices published by the government, (e.g., the consumer and producer price indices), or indices developed for particular labor classifications, materials, manufactured products or industries can be applied. A company may also conduct its own analysis of historical price trends and the sensitivity of its costs to general inflationary trends in the economy to determine a set of company-unique indices.

Cost Improvement (Learning). Cost improvement has two different sources. The first is the lowering of vendor prices with increased quantities. This form of cost improvement is sometimes called material performance and is priced by material break points for material or component purchases. The second is the reduction of costs due to increased manufacturing volume. In the literature, this is called learning.

A learning curve, or cost improvement curve, is a relationship between production cost and production volume. It indicates that the cost to produce each additional unit is decreasing, and the amount of the decrease is less with each successive unit. The relationship between cost and volume can be described by a power equation of the form shown below. This formula is linear on a logarithmic grid. The relationship corresponds to a unit or cumulative average learning curve according to whether y is the cost of the xth unit or the average cost of the first x units.

$$y = ax^b \tag{3}$$

where

a is cost to produce the first unit
x is number of units produced
y is predicted production cost of the xth unit (or average of first x units)

$$b = \frac{\log r}{\log 2} \tag{4}$$

r is learning rate expressed as a decimal.

Each time the total quantity of items produced doubles, the cost per item (either unit cost or cumulative average cost, depending upon the curve selected) is reduced to a constant percentage of the previous cost. For example, on a 90% unit curve, the cost of the fourth unit is 90% of the cost of the second unit. The usual interpretation of learning as employed by electronics manufacturers or by industrial engineers refers to unit cost.

The cost improvement described by learning curves in the electronics industry is typically a result of one or more of the following:

- Workers' increased ease and familiarity with tasks that results from the repetition of manufacturing operations
- Improvements in tool coordination, shop organization, and engineering liaison
- Development of more efficiently produced subassemblies
- Development of a more efficient parts-supply system
- Tooling improvement (e.g., correction of tooling errors, improved design, refined operation sequencing, normal development of new technologies)
- Product engineering improvements (e.g., clarification of drawings, correction of engineering errors, design simplification)
- Industrial engineering improvements (e.g., time and motion study, development of manufacturing aids, methods improvement, machine/factory layout improvement, optimum sequences, systems, and procedures improvement)

Table 4. Outline of Cost Analysis Document

Executive Summary:	A high-level view of analysis summarizing purpose, scope, and estimates of cost and schedule
System Description:	Technical information in sufficient detail to understand and evaluate the cost analysis
Acquisition Strategy:	A description of the plan for how the system will be acquired
Ground Rules and Assumptions:	Aspects of the analysis framework that will have significant impact if they are changed
Estimating Methodologies:	An overview of the primary and secondary methods for deriving the cost estimates
Cost Summary:	More detailed summary of estimates than is contained in Executive Summary
Detailed Cost Derivation:	A complete description of the calculation of the cost estimate in sufficient detail to allow replication
Uncertainty Analysis:	A detailed description and quantification of uncertainties in the system's cost and schedule estimates
Conclusions and Recommendations:	A summary of key insights and important findings

- Production control improvement (e.g., improved dispatching and shop loading, refinement of manufacturing/assembly scheduling, familiarity with routing and usage, correction of erroneous paperwork)
- Improvement in overall management

Technology Advances. A widely recognized issue with using historical databases as a basis for estimating cost is that they do not reflect advances in technology. For example, one would not use systems based on vacuum tube technology to estimate the cost of a system based on microcircuitry. While the problem is clearly acknowledged, there is no single solution. Some models use a factor. Others rely on trend curves that plot cost per some key technical parameter against time. One example would be plotting price per processor speed of a computer over time. Regardless of the method used, a clear understanding of what is changing is essential.

New Ways of Doing Business. A trend toward exploring new ways of doing business such as spiral development of a system has presented the cost analyst with a challenge not unlike assessing the impact of new technology. Once again, one must be certain that the data used to generate the resource estimate for a new system embody the same characteristics, and one must have a clear understanding of how the implementation of the new program will be different.

Presenting a Cost Analysis

A good cost analysis is necessary, but not sufficient in itself, to provide cost insight. The information about the analysis must also be structured and organized to highlight the important cost drivers and to establish the credibility of the analysis. Written cost documents and briefings are the typical means for accomplishing these objectives. Documentation of an estimate will be used by decision makers as well as system engineers and cost analysts. Therefore, such a document must contain a clear system technical and program definition and adequate detail to replicate the analyses and estimates. Table 4 presents a topical outline of a document of a cost analysis.

Cost Estimate Presentations

Presentations should contain the same general information as the documentation; however, briefings are usually initiated to answer specific concerns, and therefore, the format will vary significantly from one briefing to another. Summary information and main conclusions/recommendations should be presented first. Then, details are provided to build confidence in the estimation process and, in turn, in the estimate. Finally, a summary of the material presented should be provided along with any conclusions and recommendations.

If the briefing is describing a large estimate, sample data should be included in detail, rather than presenting all data at a summary level. Graphics and illustrations are encouraged when they will enable the listener to assimilate the information more efficiently. Cost data should be presented in rounded figures.

RELATED TOPICS

Organizations and Certification

The two professional organizations dedicated to cost analysis are the Society of Cost Estimating and Analysis (SCEA), and the International Society of Parametric Analysts (ISPA). Both hold local and national conferences and training sessions. ISPA holds overseas meetings. SCEA sponsors a professional certification program. Upon passing a written examination, an individual becomes a Certified Cost Estimator/Analyst. In addition, the American Institute for Aeronautics and Astronautics includes an Economics Technical Committee that encompasses cost estimating and analysis. Other organizations such as the Military Operations Research Society include sessions on cost analysis at their conferences.

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