# Cost Estimating and Analysis in Systems Engineering

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Cost estimating is a multidisciplinary practice that combines analytical rigor, quantitative analysis, experience, and expert judgment to develop realistic forecasts of future costs. As highlighted in ISO/IEC/IEEE-15288:2023, cost estimating serves diverse purposes across the system life cycle, and is an essential tool for providing stakeholders with insights into resource requirements for system development, acquisition, operations and sustainment. Cost estimating is thus integral to all technical and management processes in systems engineering and project management, and is central to project planning, budgeting, and control, where it is frequently utilized in evaluating trade-offs for analyzing alternative products or services. Cost estimating also plays a pivotal role in the decision-making process for investments and contracting, especially when governmental and/or commercial organizations are involved.

The practice of cost estimating is often considered as a blend of art and science and requires a diverse set of skills and domain expertise, particularly in mathematics, to create a realistic cost forecast for proposed products or services. Historically, cost estimating has been the responsibility of a specialized group of professionals known as cost analysts. However, in recent times, it has increasingly required the involvements and participation of systems engineers to meet the growing demands for deeper product knowledge and system design expertise.

There are established industry best practices and de facto standards. Leading professional associations, including the International Cost Estimating and Analysis Association (ICEAA), with its predecessor, the Society of Cost Estimating and Analysis (SCEA), along with the International Society of Parametric Analysts (ISPA), offer a rich set of references (ICEAA 2024; ISPA 2008; PMI 2021), as well as training courses (ICEAA n.d.; DAU n.d.). Furthermore, different government agencies provide policies and guidelines to communicate requirements and promote best practices (GAO 2020; DoD 2020, 2022; NASA 2015).

This article covers fundamental concepts and key methodologies and processes used in cost estimating and analysis. The goal is to provide a foundational understanding of best practices and to support the seamless integration of these methodologies into systems engineering processes.

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# Relationship to Systems Engineering and Project

## Management

Systems engineering is defined as "a transdisciplinary and integrative approach to enable the successful realization, use, and retirement of engineered systems using systems principles and concepts, and scientific, technological, and management methods," according to INCOSE (2021). Integration is the core to systems engineering. It materializes at two different levels.

Firstly, systems engineering integrates the system of interest (SoI) or the prime mission product (PMP) throughout its life cycle, serving as the system design authority from concept definition and design, through development, production, operations, and support. Secondly, systems engineering integrates the project that builds the product, serving as the engineering authority for the project from planning to execution, monitoring, assessment, and control.

Project management involves planning, executing, monitoring and controlling, and closing projects. It encompasses scheduling, resource allocation, risk management, and performance tracking to ensure that the project is completed on time, within budget, and to the specified quality standards.

Cost estimating and analysis is generally considered a practice within the scope of project management, which is a distinctive discipline from systems engineering. However, project management and systems engineering share considerable overlap in scope, especially in the areas of project scope and cost management (INCOSE 2023). The two practices are interdependent and synergistic, particularly in large-scale, complex engineering projects such as those in infrastructure, transportation and mobility, and aerospace and defense systems. In this context, cost estimating plays a crucial role within the project cost management process, underpinning the successful execution and delivery of complex projects.

Furthermore, in practice, engineering cost estimates are generally developed based on the technical scope defined by systems engineers. Cost estimates are heavily influenced by the technical requirements, design complexity, and tasks specified by systems engineering. In other words, systems engineering defines it, cost estimating quantifies it, and project management manages it.

In this context, systems engineers collaborate closely with program or project managers, drawing upon multidisciplinary skills from various fields such as configuration management, information management, risk management, and decision support. Cost estimating and analysis provides a quantitative basis for scope definition, risk management, resource allocation, change management, performance monitoring, tradeoff analysis, and informed decision making. As an integral part of both systems engineering and project management, it ultimately ensures the on-time and on-budget completion of complex projects, ultimately leading to the successful delivery of projects and services.

## Definitions

- *Cost estimating*: an exercise to *predict* the future cost of an item, product, program or task, through collecting and analyzing historical data and applying quantitative models, techniques, tools, and databases. The purpose of cost estimating is to translate system and functional requirements associated with programs, projects, proposals or processes into reliable budget requirements. The term *cost estimation* is also used, sometime interchangeably with cost estimating. It typically refers to the act or action of developing a cost estimate, while cost estimating refers to the practice applied to estimation.
- *Cost estimate*: is the *product* of a cost estimating process, which specifies the expected labor effort or dollar cost required to perform a stipulated task, or to acquire a specific item. A cost estimate may constitute a single value or a range of values. A cost estimate can normally be broken down to cost elements.
- *Cost element*: an identifiable function, or a common group of functions, which have been established as a separate entity for the purpose of estimating, collecting, controlling, and reporting costs.
- *Cost driver*: typically a physical or performance attribute of a system, or programmatic parameter of a project or contract, that has the most influence on total estimated cost. A cost driver can be another cost quantity.
- *Cost model*: an analytical tool or framework used to systematically to characterize the behavior of the system or program and produce a credible cost estimate. It implements cost estimating methods (see

below).

- *Basis of estimate* (BOE): a document outlining the assumptions, methods, and data used to develop a cost estimate. The BOE explains how the cost estimate is generated and typically includes a detailed description of the work to be performed, the planned approach, the required resources, and the expected schedule or timeline. It is a mandatory component in competitive proposals and formal quotes from potential suppliers to clients.
- *Cost analysis*: a range of activities to review and analyze the estimated or actual costs of a system, a program or a project. It is a comprehensive review of proposed cost estimates or pricing data and includes activities such as sensitivity and what-if analysis that assesses uncertainty or risks associated with the estimates. Relying on the same estimating practice and methodologies, cost analysis can be either retrospective or predictive. Retrospective analysis evaluates the actual costs that have been incurred, while predictive analysis assesses the accuracy and validity of cost estimates before they are finalized. In the United States Department of Defense (DoD) procurement organizations, cost analysis is the evaluation of a contractor's cost and pricing data in order to form an opinion on the degree to which the contractor's proposed costs represent what the performance of the contract should cost, assuming reasonable economy and efficiency.
- *Life Cycle Cost* (LCC): sometimes called Total Cost of Ownership (TCO) or Total Ownership Cost (TOC), LCC is the total cost of acquisition and ownership of a system or capability over its entire life cycle. LCC generally includes the cost of research, development, testing and evaluation (RDT&E), manufacturing and production, operation and support (O&S), and where applicable, dismantle and disposal.

## Types of Cost Estimates

Cost estimates are generally categorized based on the purposes they serve. The following are the most common types of cost estimates.

- *Budget estimate*: an estimate developed for the budgeting and funding purposes associated with a program, project, activity, initiative, or operations of an organization, in order to support its objectives consistent with the defined scope, schedule, and resource requirements.

- *Rough order of magnitude (ROM) estimate*: an estimate intended to grossly approximate the expected costs or effort involved in a project, task, or activity. It is often developed in the very early stage of something and with very little specific available information. It is also known as “quick look,” initial, or “ballpark” estimate.
- *Firm cost estimate*: an estimate commonly used in cost proposals and intended to be a binding obligation from an offering organization. It relies on well-defined plans and data, usually in response to a customer’s firm request for proposal. Firm estimates demand the highest level of substantiating detail, requiring the preparation of an extensive backup package to facilitate contractual fact-finding and negotiations.
- *Life cycle cost (LCC) estimate*: a comprehensive, “cradle to grave” estimate to cover all anticipated expenses from inception to disposal that includes research, development, testing and evaluation (RDT&E), production, operations and support (O&S) and disposal costs. It is typically created to aid the planning and analysis of alternatives for capability acquisition. It is created regardless of funding source and should be done as early in the life cycle as possible. As described above, it may also be referred to as Total Cost of Ownership (TCO) or Total Ownership Cost (TOC) estimate.
- *Should cost (SC) estimate*: an assessment of what it should reasonably cost to produce a product, deliver a service, or execute a project under ideal conditions, assuming efficiency in execution, optimal resource utilization, continuous improvement and cost optimization. It is a management tool typically associated with the acquirer to actively seek cost reduction, drive efficiency, and promote collaboration between buyers and suppliers to achieve mutual benefits.
- *Estimate at completion (EAC)*: an assessment of the cost to complete the authorized scope of a project based on the historical performance and progress up to a certain point of that project. Often developed at the onset or during the course of the project, it

provides an estimate of the total cost expected by the time the project is completed. It is an important *earned value management* (EVM) metric, central to project management.

- *Independent cost evaluation* (ICE): a cost analysis performed by an independent group of experts to assess the reasonableness, accuracy, and completeness of a cost estimate submitted by an offeror. ICE uses the same data provided by the original estimate and involves analyzing and verifying supporting information, such as cost drivers, assumptions, and uncertainties. It typically develops an independent estimate or view, in comparison to the original estimate, and identifies risks and opportunities associated with the program or project.
- *Not-to-exceed (NTE)* and *not-less-than (NLT) estimates*: estimates commonly used in contracting and project management to define the maximum allowable and minimum acceptable costs for the project or contract. These estimates provide basic parameters for managing stakeholder expectations, preparing budgets or proposals, and making informed decisions.

## Cost Estimating Process

A cost estimating process generally consists of a seven-step process, as depicted in **Figure 1**. In practice, however, the process may be customized based on factors such as the type of estimate being developed, data availability, and the maturity of developmental stage.

Cost estimating is an iterative process characterized by multiple feedback loops. For instance, data analysis may lead to further questions, necessitating additional data collection. Similarly, validating estimates might involve applying different estimating methods, which could require gathering new data.

Estimates evolve continuously as design matures, development progresses, and more data becomes available. Existing estimate must be refreshed based on updated technical and program management baselines to support major program and project milestones.

**Step 1:** Develop the Work Breakdown Structure (WBS). The WBS establishes a common frame of reference for relating job tasks to each other and aggregating cost elements at the summary level of detail. It is used to capture the scope of work intended for the estimate. A WBS consists of two parts: a tree-like hierarchical structure defining work elements, and a WBS dictionary, which defines the terms used in the structure. The U.S. DoD developed MIL-STD-881 (DoD 2022) to provide the standard framework and instructions for developing a WBS.

**Step 2:** Establish a technical baseline. A technical baseline includes all the information required for an estimate, captured at a specific point in time. It includes the technical scope approved for the system under development such as the configuration items, the programmatic scope for the project such as schedule and milestones, as well as the ground rules and assumptions made as the basis for the estimate. While the development continues, the baseline must be frozen for the purpose of estimation.

**Step 3**: *Collect data*. Data collection involves two kinds of data: the data for the system and program under estimation, and the historical data or database from the like systems and historical projects. They may be collected at the same or different times. The data for estimation is collected from the ongoing system design, necessary in identifying required cost drivers. Collecting historical data is required to apply methodologies and develop or update CERs. As emphasized previously in the methodology section, it is critical to interview key stakeholders, including those from the current and historical programs, which is necessary for understanding of the data collected.

**Step 4**: *Analyze data*. Collected data must be analyzed to derive useful metrics and enable the application of a cost estimating methodology. Data analysis involves examining collected data to identify useful patterns and gain insights into the appropriate estimating methods to apply to different parts of the estimate. There are commonly deployed tools for data analysis, including scatter plotting, deriving descriptive statistics (e.g., mean, variance, standard deviation), identifying outliers, updating historical database, and calibrating parametric models.

**Step 5**: *Apply estimating methodology and develop cost estimating relationships*. Select the best estimating method (see Cost Estimating Methodologies section below) based on available data. Establish the *ground rules* and *assumptions* for estimating, as they will dictate how data is used and influence the final outcome of the estimate. Once patterns are identified from data analysis, CERs can be established for different cost elements. This may involve recalibrating or fine-tuning existing CERs to align with the newly collected data or specific project requirements or characteristics. Commercial off-the-shelf estimating models must be calibrated with collected data before being used to generate estimates.

**Step 6**: *Roll up and validate estimates*. Once the CERs are created, estimated cost or effort can be generated based on the cost driver inputs. When appropriate calibrations, commercial off-the-shelf estimating models may be used produce and summarize the estimate. After the estimates are generated, they must be validated to ensure reasonableness and completeness. Sensitivity analysis and cross-technique validation can be applied to key cost elements. Risk assessment should also be conducted.

**Step 7**: *Generate cost reports*. Cost report provides a written justification for the cost estimate. This is a formal documentation that captures all aspects of the estimating process and provides sufficient information for a third-party analyst to fully understand how the estimate is developed and to replicate the estimate at a later time, if necessary. In the contracting process, this document is called the *Basis of Estimate* (BOE), which is required to support the bidder's cost proposal.

As indicated previously, cost estimating is always an iterative process. It should be revisited and updated for each major milestone of the development project. There are intermediate feedback loops that may be necessary to complete the process, as shown in **Figure 1**. For example, analysis of data may need additional interviews to fully understand the historical behavior; applying methods and developing CERs may uncover gaps in data, which triggers additional collection efforts.

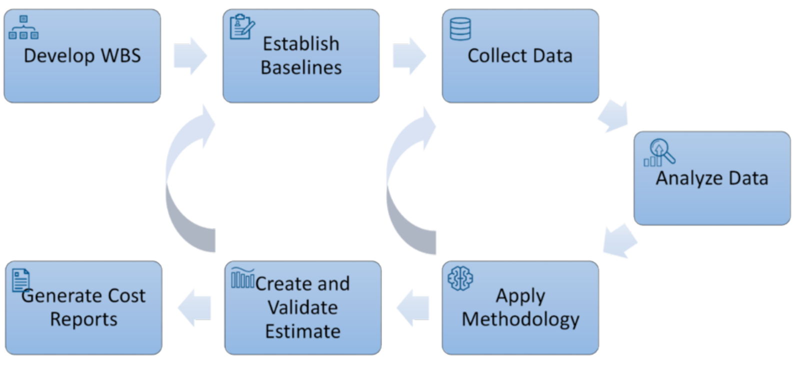



**Figure 1. The general cost estimating process.** (SEBoK Original)

# Cost Estimating Methodologies

Cost estimating methods, also referred to as costing techniques, are the building blocks in developing of a cost estimate. They establish the basic approach to use the historical data and provide the basic structure for statistical relationships. These methods are the basic “algorithms” that relates the historical data to future cost.

Three primary methods are commonly applied when developing a cost estimate (you may hear some other names; but they are mostly synonymous with one of the three methods). These three techniques are *analogy*, *parametric* and *build-up*.

## Analogy Method

The *analogy*, also known as *comparative*, method is just what it sounds like – an attempt to estimate costs by comparing the new system with a similar (or analogous) system or by drawing parallels between the current project and a similar past project to estimate costs. It is based on the idea “it’s like one of these.” An analogy can be done at the system, subsystem, component, project, or task level.

The analogy method is not simply a matter of asserting that an item cost an amount, X, and therefore will cost X in the future. Generally, some adjustments must be made to one or more attributes of the old item to estimate the new item. These quantities for adjustment, known as *cost* or *size drivers*, are typically physical (such as size and weight) and performance (like speed and power) characteristics of a system or service that are the primary drivers for cost or effort. They may also include programmatic metrics such as quantity or schedule, as well as supplier performance or economic adjustments for inflation. For example, suppose the current version of an engine generates 10,000 lbs of thrust and costs $20M dollars to build and that the next-generation version of the same engine is designed to generate 15,000 lbs of thrust. Applying the analogy method, the estimated cost of building the new engine, assuming the use of the same manufacturing technology, would amount to $30M dollars (= 15,000 / 10,000 * $20M). As a second example, if assembly of the current-generation engine initially took 320 person-hours to assemble and unit test 10 equipment racks. Assuming the same process, it is estimated to require 1,600 person-hours (= 50 / 10 * 320 hours) to assemble and unit test 50 racks.

Analogies are generally used in the early stages of the program life cycle, especially when detailed data is lacking but estimates are necessary for decision-making. Many development programs have heritage or legacy systems that can serve as a basis for comparison when estimating costs or efforts for new systems. Additionally, the analogy method can also be used as a validation or crosscheck for estimates created through other methods.

## Parametric Method

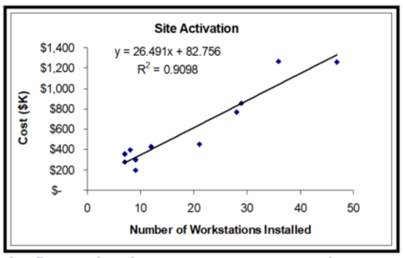
The *parametric*, also known as *algorithmic*, costing technique is based on mathematical relationships between specific system attributes or parameters (such as weight, thrust, power, lines of code) as one or more independent variables, and the estimated cost or effort of the system as a dependent or derived variable. “This pattern holds” is the fundamental concept underlying this methodology. These parametric relationships are typically expressed as mathematical equations, commonly known as *cost estimating relationships* (CERs), in a general form

The CERs are developed with a statistical framework using historical data collected on similar programs or systems. The independent variables (x, y, …) are known as *cost drivers*. They can be physical characteristics, performance or operational parameters, programmatic variables, or even other costs.

As a hypothetical example, the estimated cost of site activation (C) in $K is a function of the number of workstations ($N_{WS}$) installed. One identifies a group of similar site activation projects and collects the historical project data. Analysis of the data results in a scatter plot, as shown in **Figure 2**. A CER is derived using linear regression of the scatter data, expressed as a simple equation.

| | X (Cost Driver) Number of Workstations | Y Cost ($K) |
|---|---|---|
| Site 1 | 8 | $ 398 |
| Site 2 | 28 | $ 769 |
| Site 3 | 12 | $ 430 |
| Site 4 | 9 | $ 199 |
| Site 5 | 21 | $ 447 |
| Site 6 | 29 | $ 851 |
| Site 7 | 47 | $ 1,258 |
| Site 8 | 7 | $ 359 |
| Site 9 | 36 | $ 1,267 |
| Site 10 | 9 | $ 300 |
| Site 11 | 7 | $ 275 |

a. *Table of num. workstations vs. activation cost*




b. *Scatter plot of activation cost vs. num. workstation, and a linear regression of the data points*

**Figure 2. Historical site activation data, in tabulated form and scatter plot, and a linear regression of the scatter data points.** (SEBoK Original)

The parametric technique is applicable across a wide range of estimates and throughout all phases of the system life cycle. It is often the preferred method for cost proposals, and is frequently favored by source selection authorities. In addition, it is particularly effective in sensitivity analyses, what-if scenarios, and cost-based trade studies, as it allows for the adjustment of system attribute values acting as cost drivers to directly influence the estimated cost or effort.

Most commercial off-the-shelf (COTS) cost estimating tools rely on parametric-based cost models at their core. These algorithms constitute a significant portion of the commercial market value of these tools and are often considered the "secret sauce" provided by the tool vendors.

## Build-up Method

The *build-up* method, also known as *detailed* or *bottom-up* estimating, constructs estimates for higher level cost elements by aggregating or “rolling up” detailed estimates from lower level cost elements. It involves estimating costs at the lowest definable level where data exists and summing it up along a hierarchical structure. A *work breakdown structure* (WBS) is generally used to define this hierarchical structure. It provides a standard framework for organizing cost estimates and, therefore, is the cornerstone of this technique.

Based on the idea “it’s made up of these,” the build-up method requires breaking down the project into smaller components or work packages and estimating the costs of each individual element. These individual cost estimates are then aggregated to produce the total project cost involves estimating at the lowest definable level where data exists and summing it up along the hierarchical structure. The build-up method works best when low-level detailed cost actuals or estimates are available. It is most effective in operational settings where processes are well-established, and standards and performance factors are clearly defined, enabling effective management of work and measurement of performance.

## Other Methods

Two other methods are less rigorous and prevalent, but can be very useful sometimes.

The *expert opinion method*, also known as the *engineering judgment method*, uses an expert or group of experts to estimate the cost of a system. It is often done through one-on-one interviews, round-table discussions with multiple experts, and the Delphi technique, where a group of experts anonymously provides their responses and the results are aggregated.

While expert opinion can offer valuable insights, it is generally considered to be too subjective and prone to biases. Therefore, it should only be utilized as a last resort when other methods are unavailable or to obtain high-level, low-fidelity estimates for “quick looks.” Additionally, it may serve as a cross-check, corroborate objective data, or adjust estimation based on expert insights.

*Extrapolation from actual* involves using actual costs from past or current items and historic trends to predict future costs for the same item. It is best applied in production settings to estimate the follow-on production units or lots based on the cost of completed units. There are several variants of this method, including *averages*, *learning curves*, and *estimate-at-completion* (EAC). “Extrapolation from actual” is generally not considered a separate method itself, but a subset of other methods, such as *earned value management* (EVM).

## Comparison of Techniques

When developing a cost estimate, it is essential to select the most suitable methods for the given task. While it is possible to use multiple techniques within a single estimate, it is crucial to determine how and when each technique should be applied. Just like any other aspect of project management, each technique comes with its own set of strengths and weaknesses and varying degree of applicability for different stages of a program's life cycle. A comparison of the three techniques is provided in **Table 1**.

**Figure 3** presents a guideline provided by the Department of Defense (DoD 2022) regarding the typical application of various costing techniques relative to the DoD program lifecycle model. It outlines the approximate distribution of the different techniques across different phases of the DoD acquisition cycle.

**Table 1**. Comparison of estimating methodologies.

| Methodology | Advantage | Disadvantage |
|---|---|---|
| Analogy | • Relatively simple, quick, and low cost<br>• Best used early in program before detailed requirements, or as “sanity check”<br>• Difficult to refute if there is strong historical resemblance | • Subjectivity in making adjustments<br>• Difficult to identify common cost drivers between old and new systems for comparison<br>• Lack of objective validity tests<br>• Limited to stable technology and processes |
| Parametric | • Relatively simple, quick, and low cost<br>• Easily adjusted for changes by modifying input parameters<br>• Best for sensitivity and impact analyses<br>• Effective for cost-based trade studies<br>• Objective measures of validity<br>• Preferred by cost analysts | • Highly dependent upon quantity and quality of historical database<br>• Expensive to collect and maintain historical database<br>• Must continue to update relationships to adjust for updates in relevant programs, processes, and technologies applied<br>• “Black box syndrome” with pre-existing CERs and commercial models |
| Build-Up | • Most detailed technique and data, and best inherent accuracy<br>• Easy to see exactly what the estimate includes and contribution of cost elements<br>• Variance factors based on historical data for a given program or a specific manufacturer<br>• Typical required to support organizational cost and pricing proposal | • Expensive and time consuming to develop<br>• Requires large amount of data to be collected, maintained, and analyzed<br>• Detailed specifications and definitions required<br>• May underestimate system integration and other “under the line” system level cost<br>• Small errors can easily magnify<br>• Omissions and duplications are likely |

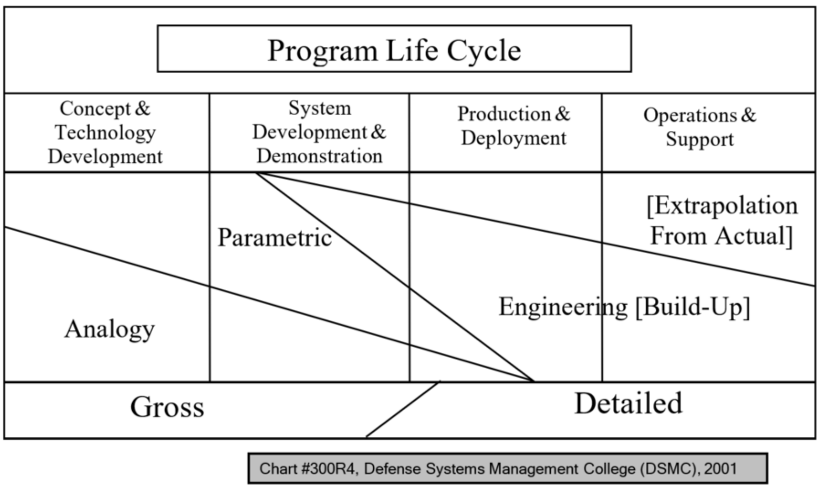



**Figure 3. Application of methodologies relative to DoD program phase lifecycle model.** (Public Domain, Defense Acquisition University. Used with permission.)

## The Role of Historical Data

Data, particularly historical data, is the very foundation for cost estimating. Without it, there is no basis for applying methodologies, and the estimates lack both credibility and defensibility. In essence, without data, there can be no cost estimation, and any estimates made without sufficient data would be nothing more than mere guesses.

Collecting historical data is akin to forensic analysis of the development history, and it is typically done as a separate effort before estimation is required or as part of continuous enterprise knowledge management and process improvement efforts. It can be considered a project in its own right, requiring dedicated resources and tools, as well as access to both technical and financial data. An important aspect of historical data collection is stakeholder interviews, or the ability to speak to the system design and project management authorities of the historical programs, in order to enable understanding of the data collected.

## Conclusion

Cost estimating is a multidisciplinary practice that develops future costs for products and services by analyzing historical data and using quantitative methods. It falls in the intersecting areas of systems engineering and project management and demands a wide range of skills and expertise, particularly in mathematics. Effective cost estimating relies on collaboration between systems engineers and cost analysts. This practice is crucial for decision-making, especially in areas involving resource allocation and investment planning.

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## Additional References

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