Comparative Analysis of NASA Cost Estimation Methods

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Abstract

NASA policy and customer expectations dictate use of various cost estimating tools depending on milestone and program maturity, regardless of level of effort or accuracy of results. This paper presents a case study of the tradeoffs of modeling the cost of an unmanned space mission using different NASA-approved parametric tools. The comparison addresses subsystem and component-level cost estimates, providing invaluable insight into the granularity of cost modeling for complex space missions and differences in results associated with more or less granular estimates. The study provides discussion on the challenges and opportunities associated with parametric cost modeling methodologies due to the varying levels of input detail, and of effort, needed to complete an estimate. It also aims to provide practical insights on the number and types of subjective decisions made when modeling costs using different approaches, and the impacts that these choices have on cost results.

Keywords: *subsystem, component-level, cost modeling, parametric tools, case study, NASA, cost estimates*

Biography

Camille Holly is an ICEAA Certified Cost Estimator/Analyst (CCEA) and Employee-Owner at Technomics, Inc. She has 6 years' experience as an engineering cost analyst, four of which supporting the Cost Estimating Modeling and Analysis Office at NASA Goddard Space Flight Center in Greenbelt, MD. She currently serves as lead cost analyst supporting NASA's Instrument Design Lab focusing on modeling costs for various space systems and developing/presenting cost estimates. She routinely uses various cost estimating tools in her daily work and draws from her practical experience for this paper. She holds a B.S. in Chemical Engineering from Howard University.

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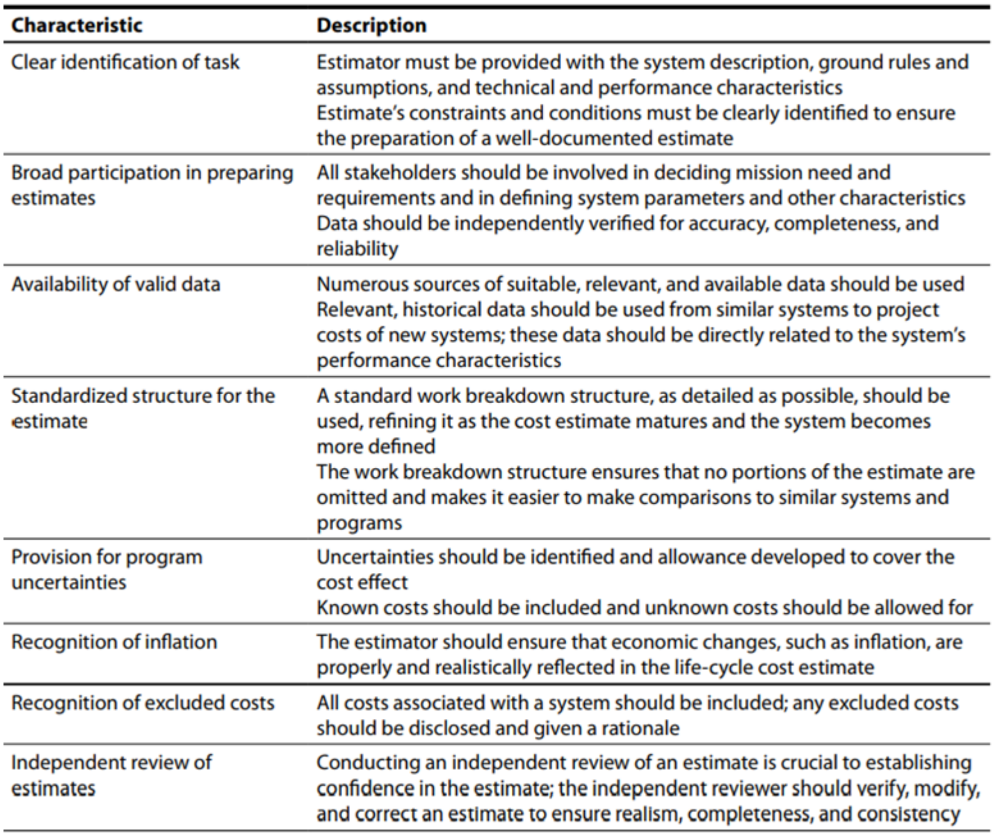
1. Introduction

1.1. The Importance of Quality Cost Estimation in Space Missions

Quality cost estimation enables critical decision-making and ensures efficient resource allocation. As space exploration continues to evolve, the ability to predict and manage costs effectively becomes key to mission success. The large financial investments required for these missions demand credible, reliable cost estimates. Andy Braukhane's 2020 ICEAA presentation highlighted the challenges cost estimators face early in the spacecraft design phase and underscored the importance of robust estimating methodologies to mitigate financial risks [1]. Braukhane identifies two significant challenges: (1) lack of data and (2) data changes, and (3) low heritage and high complexity. With $7.6 billion in cost overruns reported in 2023 [2], the large financial investments required for these missions demand credible and reliable cost estimates. These difficulties are the result of the highly iterative nature of design early in the project and the technical data required to deliver an accurate estimate. This is evident in past NASA missions and highlighted in a U.S. Government Accountability Office (GAO) report that cites a 31% increase in costs on average due to overly optimistic initial estimates. [3]

Cost analysts support the development of NASA missions by formulating independent estimates at various milestones to establish cost resource requirements for contracts and budgets. They implement specific processes, guidelines, and tools to achieve more dependable and consistent cost estimates and analysis. The GAO Cost Estimating and Assessment Guide [4] documents reliable practices to establish a consistent methodology. Estimators can use these guidelines to manage and develop quality cost estimates. This guide references the 1972 GAO report on “Theory and Practice of Cost Estimating for Major Acquisitions” [4]. Table 1 outlines and defines the basic characteristics for reliable cost estimating, which remain widely recognized and referenced in the field



Characteristic	Description
Clear identification of task	Estimator must be provided with the system description, ground rules and assumptions, and technical and performance characteristics Estimate's constraints and conditions must be clearly identified to ensure the preparation of a well-documented estimate
Broad participation in preparing estimates	All stakeholders should be involved in deciding mission need and requirements and in defining system parameters and other characteristics Data should be independently verified for accuracy, completeness, and reliability
Availability of valid data	Numerous sources of suitable, relevant, and available data should be used Relevant, historical data should be used from similar systems to project costs of new systems; these data should be directly related to the system's performance characteristics
Standardized structure for the estimate	A standard work breakdown structure, as detailed as possible, should be used, refining it as the cost estimate matures and the system becomes more defined The work breakdown structure ensures that no portions of the estimate are omitted and makes it easier to make comparisons to similar systems and programs
Provision for program uncertainties	Uncertainties should be identified and allowance developed to cover the cost effect Known costs should be included and unknown costs should be allowed for
Recognition of inflation	The estimator should ensure that economic changes, such as inflation, are properly and realistically reflected in the life-cycle cost estimate
Recognition of excluded costs	All costs associated with a system should be included; any excluded costs should be disclosed and given a rationale
Independent review of estimates	Conducting an independent review of an estimate is crucial to establishing confidence in the estimate; the independent reviewer should verify, modify, and correct an estimate to ensure realism, completeness, and consistency

Table 1: GAO's 1972 Version of the Basic Characteristics of Credible Cost Estimates

The NASA Cost Estimating Handbook is another extensive resource that provides guidance on the principles and processes of cost estimation across various project phases. It outlines methodologies, best practices, and considerations for developing credible estimates. However, neither of these guidance documents provide clear direction on how to navigate defining the appropriate level of technical detail to inform space mission cost estimates.

A fundamental challenge within the cost community is the lack of specificity regarding the level of detail expected or required for cost estimation and analysis in project support. Often, analysts or customers make this decision based on familiarity rather than the data or resources required to complete the estimate. Andy Prince described in "The Psychology of Cost Estimating" [5], that early in the design process, requirements are often poorly defined or understood. If analysts develop poor cost estimates because of bad models, inadequate data, or lack of training, then those estimates could mislead management into believing that they have sufficient resources.

This, combined with the incorporation of new technologies, creates estimating uncertainties resulting in a lack of clarity that must be acknowledged when deciding on the appropriate level of fidelity for a cost estimate and what tools are most appropriate.

Developing a very detailed technical baseline early in a project's lifecycle can result in a proliferation of unsubstantiated assumptions and uncertainties. A cost estimator may need to make detailed assumptions about a system even before engineers have! This approach often leads to risks that compromise estimate accuracy and give leadership a false sense of confidence in the estimate. This scenario is particularly evident when dealing with complex space missions, where early-stage data is limited, and system details are constantly evolving.

Conversely, solely relying on one high-level parametric or analogy method can oversimplify the estimation process, potentially overlooking crucial nuances associated with specific subsystems or components. The Selection of Methods framework (Figure 1) [11] serves as a widely accepted guiding principle and encourages a balanced approach to cost estimation. It acknowledges the significance of tailoring estimation methods to the maturity level of the project.

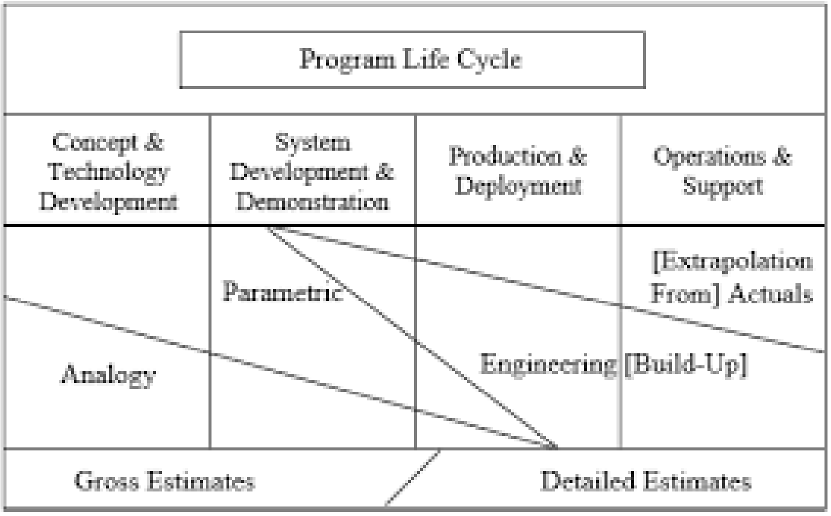


Figure 1: DAU [9] Use of Cost Estimating Methodologies by Phase

The Cost Estimating, Modeling, and Analysis (CEMA) office at the NASA Goddard Space Flight Center (GSFC) continuously wrestles with this challenge when performing estimates for customers. The office is responsible for conducting independent cost assessments as well as developing and maintaining cost estimation tools to validate project estimates. CEMA's cost work relates to projects that GSFC vice a contractor proposes (known as proposal submissions), wins, and is awarded funding to perform. It collaborates closely with project managers, engineers, and other stakeholders to develop reliable and credible cost estimates across NASA projects. Due to the gap in guidance documents and frameworks within the NASA cost community, the CEMA office is embarking on reevaluating their standards through internal validation studies and refining practices to deliver the most accurate analyses possible.

This paper explores the challenges and opportunities of estimating costs at various levels of detail with a case study informed by the author's personal experience estimating a portfolio of missions for NASA. The study offers practical insights into the estimating impacts and level of effort needed for two common levels of space system cost estimation.

2. Background

2.1. Space System Terminology

This section offers key definitions to provide context for the following sections. To understand how these terms relate to the broader scope of NASA missions, it is helpful to examine NASA's standard space flight project Work Breakdown Structure (WBS) [6], depicted in Figure 2.

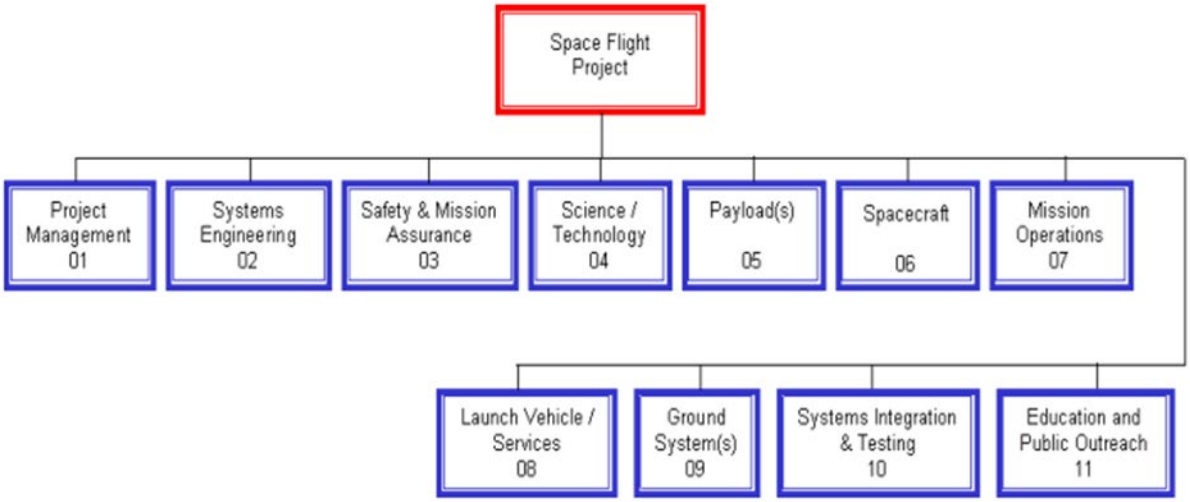


Figure 2: NASA Standard Space Flight Project WBS

The Space Flight Project is considered WBS Level 1, while the major activities supporting the Project are considered in WBS Level 2. The case study focuses on the following WBS elements for comparison of estimating tools and levels of detail:

- **WBS 1.0: Project Management (PM)** – Includes project management, business management, scheduling, procurement management, etc.
- **WBS 2.0: Systems Engineering (SE)** – Includes management of the technical program efforts such as design engineering, software engineering, system architecture development, integrated test planning, technical oversight, etc.
- **WBS 3.0: Safety & Mission Assurance (SM&A)** [1] – Includes design, development, review, and verification of procedures to assure that the delivered spacecraft, ground systems, mission operations, and payloads meet performance requirements and function as intended.
- **WBS 5.0: Payload(s)** – The hardware and software serving as the primary purpose or mission-specific equipment, instruments, or experiments carried by a satellite, spacecraft, or launch vehicle. Payloads are mounted on the spacecraft bus and designed to collect data, transmit signals, or perform other relevant mission functions. There are various types of NASA payloads dependent on the mission, including but not limited to: optical telescopes, active/passive microwave instrumentation, and communication instrumentation. This element includes managing and implementing the hardware and software payloads.
- **WBS 6.0: Spacecraft** – The central structure housing various essential subsystems and components. Also referred to as a Bus, these typically include a standard set of subsystems to provide supporting services such as power supply, thermal control, command and data handling, propulsion, and structural support. This element includes all design,

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[1] When estimating the costs of space missions, WBS elements 1.0, 2.0, and 3.0 are typically lumped together to cover general oversight and management tasks.

development, production, assembly, test, and ground support equipment (GSE) of the spacecraft. Figure 3 is an example of a NASA spacecraft.

- **WBS 10.0: Systems Integration & Testing (I&T)** – Includes the hardware, software, procedures, and project-owned facilities required to perform the integration and testing of the project's systems, payloads, spacecraft, launch vehicle/services, and mission operations.

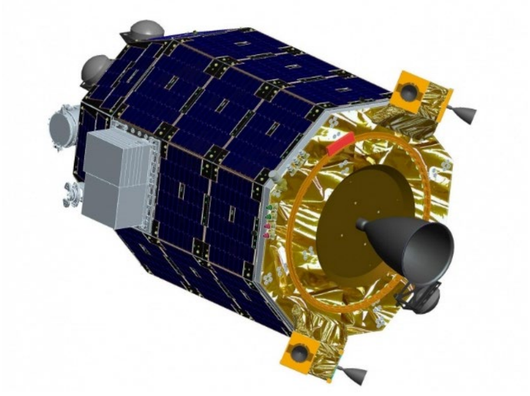

Figure 3: NASA Ames Spacecraft

In addition to the definitions of WBS elements, below are several other important terms worth familiarizing yourself with:

- **Subsystem** – A functional unit of a larger spacecraft or payload designed to perform a specific set of functions such as communication, propulsion, power generation, thermal control, etc. Each subsystem typically consists of a combination or hardware and software that work together to contribute to the mission objectives of the space system.
- **Component** – An individual, discrete element or part within the overall spacecraft, space subsystem, or payload. These components may be physical hardware, such as sensors, antennas, batteries, or electronic devices, or comprise of software or firmware contributing to the functionality of the space system. Several components make up a subsystem.
- **Ground Support Equipment (GSE)** – The specialized tools, systems, and infrastructure used on the ground to support the preparation, testing,

and launch of space vehicles. This includes items such as test facilities, transport systems, and communication interfaces for the successful deployment and maintenance of space missions.

- **Engineering Test Unit (ETU)** – A prototype or model designed for testing and validating engineering concepts, components, or systems related to space missions. ETUs serve as a central tool in assessing the functionality, reliability, and performance of space technologies before their deployment.
- **Flight Spare** – An additional component, subsystem, or device carried on a spacecraft to mitigate risk of system failures during the mission. These spares are pre-packaged, tested, and ready for deployment in case of malfunctions.

2.2. Cost Estimation Terminology

In addition to providing an overview of these technical space systems terms, it is equally important to address fundamental terms for how cost estimating is applied to space systems. These key terms are provided below.

- **Mission-Level Estimation** – The comprehensive financial estimate that encompasses all WBS levels. This includes all activities associated with the planning, development, launch, and operation of an entire space mission.
- **Subsystem-Level Cost Estimation** – The process of estimating the financial resources required for designing, developing, manufacturing, testing, and integrating a system at the level of the subsystems, or summations of components, involved. This level of estimation requires subsystem technical information which integrate to form the overall system.
- **Component-Level Estimation** – The process of estimating the financial resources required for designing, developing, manufacturing, testing, and integrating a system at the individual component-level of a system or subsystem. This type of detailed cost estimate requires technical

information of the components within the subsystems that form the overall system.

- **Wrap Factor** – A multiplier applied to portions of the cost estimate to estimate additional costs beyond those directly estimated (e.g., flight software development, ground support equipment, etc.). This factor is used to “wrap” indirect costs not discretely estimated into the cost estimate.
- **Confidence Level (CL)** – The degree of certainty associated with the estimated costs of a project or system. It represents the estimator’s level of confidence that the actual costs will align closely to the estimated value. A higher confidence level implies a greater certainty that the estimated costs will closely align with the actual costs, while lower confidence level implies a higher degree of uncertainty associated with the estimate.

3. Cost Estimation Process

3.1 Scope of Analysis

The analysis described in this paper encompasses multiple WBS elements to provide a complete picture of cost impacts at different levels of a space mission, including:

- spacecraft bus (WBS 6.0)
- instrument payload (WBS 5.0)
- mission level (WBS 1.0, 2.0, 3.0, 5.0, 6.0, and 10.0).

(Note: The mission-level analysis excludes WBS 4.0, 7.0, 8.0, 9.0, and 11.0, as these elements are not provided by the component-level estimating tool employed for this paper.)

Table 2 shows the intersection of WBS elements analyzed and levels of technical fidelity.

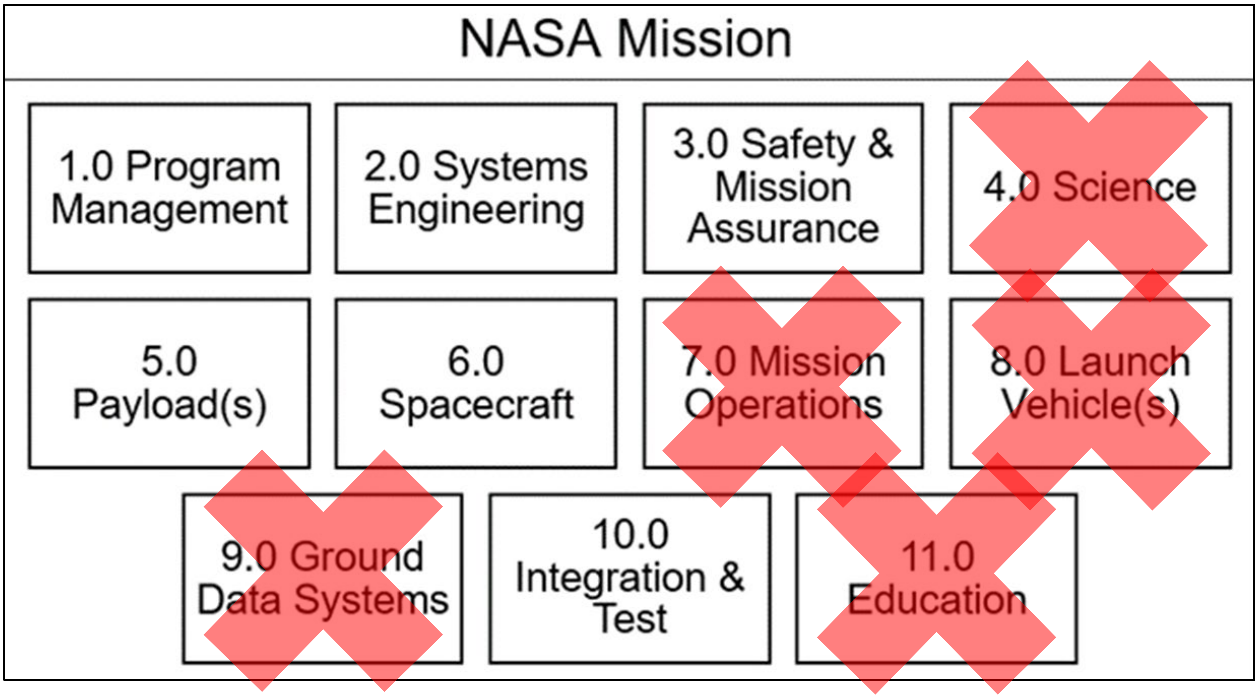

Table 2 WBS Level Categorization of Modeling Methodology

This case study and paper were created to introduce the topic of modeling historical missions using tools that require technical details at different levels (subsystem-level versus component-level) of detail. It is meant to serve as a framework for other cost groups that may grapple with the use of cost models of varying levels of fidelity and the associated time investment to define technical baselines to accommodate these levels.

This case study demonstrates the results of parametrically modeling the costs of a historic interplanetary mission containing one spacecraft bus and four instruments (A through D) using different parametric tools. It is important to note that comparisons to actuals were not conducted during this case study. Further data collection and normalization of historical costs is required to validate the estimates.

3.2 Technical Baseline Definition

The primary parameter inputs for this study came from Concept Study Reports (CSRs) and Master Equipment Lists (MELs) for the spacecraft bus and instruments. MELs provide details of space systems' individual hardware components. The MEL defines heritage, mass, composition and materials, quantities (for flight units, engineering design units, and flight spares), contingency design status, planned level of modification, and new developments.

Heritage and maturity are expanded upon within the CSRs for greater insight into the level of modification required for each component. The CSRs are included in the proposal submission, providing comprehensive scope of a space mission. The report describes the mission's scientific goals, mission design, hardware, management plan, etc. Technical data, available in CSR documents, served useful in areas where the MEL lacked sufficient detail for cost modeling.

The technical data provided feeds into the cost methods at different scales. At the component-level, the analysis necessitates a detailed breakdown of the system into dozens of individual components, each associated with numerous technical variables. These variables encompass a wide range of parameters capturing everything from mass, material composition, and beyond. Due to the required input granularity, extensive research is performed to source data identifying each component's unique characteristics and cost drivers. In contrast, subsystem-level methods operate at a more aggregated level, typically focusing on the major subsystems with significantly fewer technical parameters. Careful consideration of inputs is also essential in subsystem-level methods, as they rely on a smaller set of parameters that drive most of the cost.

3.3 Cost Analysis Methodology

Parametric tools use cost estimating relationships (CERs) to estimate the cost of an item (component, subsystem, etc.) based on a combination of technical parameters. Credible CERs are crucial to the reliability of a cost estimate. Certain NASA-approved commercial parametric cost modeling tools require definition of space systems at the component-level or even lower levels to produce a point estimate. The case study uses parametric tools to perform both component-level and subsystem-level estimates.

For the former, the estimates of individual components are summed into assembly-level estimates at the subsystem level, which then sum again to full instrument level. Additional costs for Flight Software (FSW) development, Ground Support Equipment (GSE), Environmental Testing (ET), and other non-hardware costs are included, in addition to System Level Costs (SLCs) for Program Management (PM), Systems Engineering (SE), and Safety and Mission Assurance (SMA), Integration & Testing (I&T) and other oversight. After completing all component-level modeling, a Monte Carlo risk analysis was performed for each instrument, the instrument suite, the flight system, and the mission-level.

For the subsystem-level estimates, the process mimics what’s described above except the estimates are derived at a higher level. CERs in subsystem-level model apply parameters to estimate costs through the description of design using characteristics proven to drive costs.

A mission-level cost template was used to estimate the cost of PM, SE, MA, and I&T at the highest level of the project and then added to the results of the component-level and subsystem-level estimates.

4. Case Study Comparative Analysis

4.1 WBS 5.0 and WBS 6.0 Comparative Results

For WBS 5.0, total cost of four instruments comprising the payload along with their associated PM, SE, MA, and I&T was estimated. The component-level cost estimate at 50% confidence level (CL) was approximately double that of subsystem-level cost estimate, as shown in Figure 4.

The difference in cost may be due to the component-level modeling considering more information regarding heritage and complexity, key cost drivers, than the possible with the subsystem method. As noted earlier, the subsystem-level model only accommodates higher level, but easier to estimate, technical parameters such as mass, power, and programmatic details as inputs. Cost estimates for each instrument are shown in Figure 5 and Figure 6. Each graph displays a cost difference of a factor of two for component-level to subsystem-level estimates. The magnitude and consistency of differences in component-level versus subsystem-level estimates indicate that some uniqueness in the payloads may not be captured by the underling main drivers of a subsystem-level parametric method (e.g., mass, power, etc.).

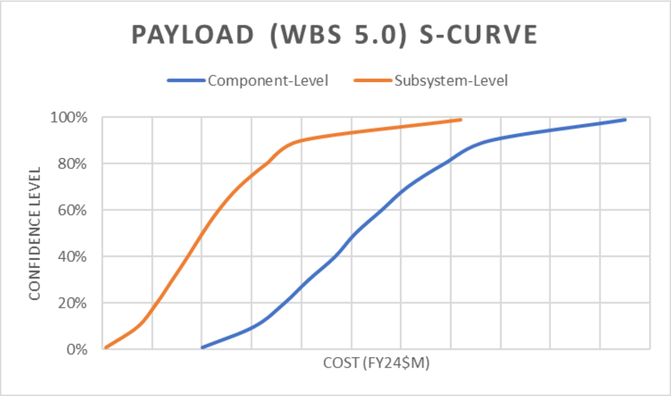

Figure 4 WBS 5.0 Payloads S-Curve

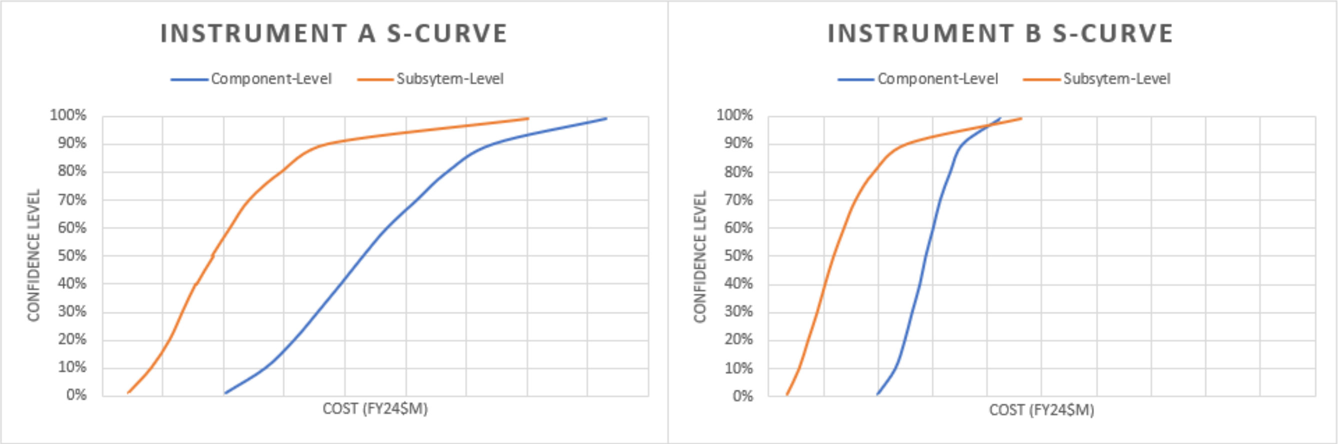

Figure 5 Payload S-Curves for Instrument A and Instrument B

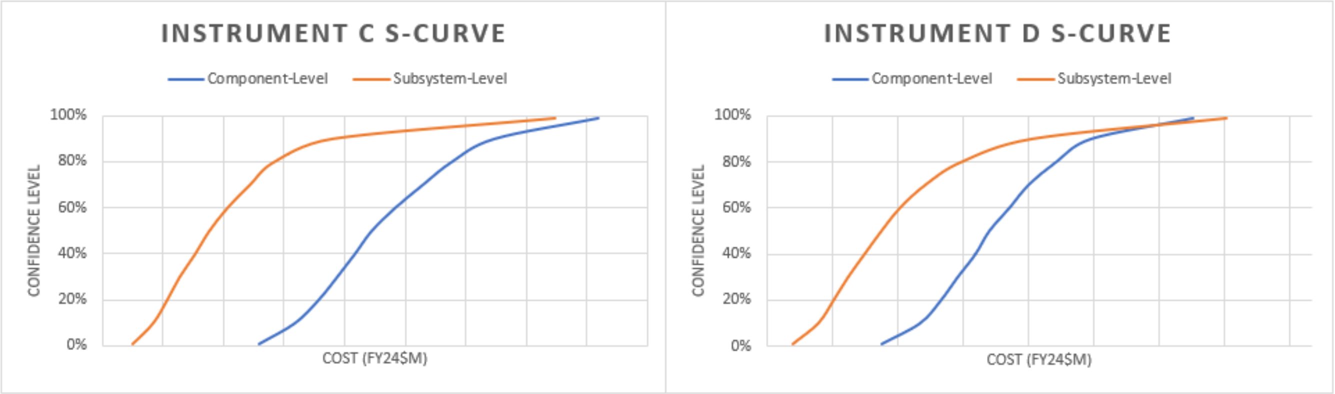

Figure 6 Payload S-Curves for Instrument C and Instrument D

The analysis shifted directions upon comparing estimates for the flight system, WBS 6.0 (Figure 7). The subsystem-level estimate is approximately 2.5 times the component-level estimate. Additionally, the S-Curve for subsystem-level encompasses a broader cost range than the S-Curve for component-level. The wider range of the subsystem-level S-Curve indicates greater uncertainty associated with that estimate. This is plausible given the lower technical detail, though it’s also plausible that the component-level S-curve may be understated because of uncertainty around the lower-level technical inputs that required assumptions.

Several factors contribute to the variance in uncertainty between component-level and subsystem-level estimates. At the component-level, the model estimates system maturity based on the heritage of each component. Since the spacecraft leveraged mostly high-heritage hardware, it was viewed as a high-heritage spacecraft, even though the components had to be configured in a new way and undergo significant testing to operate in an interplanetary environment. Adjustments were made to complexity factors at the System Level to account for complexities associated with interplanetary science goals, but the accuracy of these adjustments were limited.

In contrast, the subsystem-level model incorporates not only high heritage but also considers aspects such as design, development, fabrication, and integration and testing (I&T) schedule. The subsystem-level model incorporates more complexity factors to account for spacecraft orbit, mission risk class, mission type, organizations involved, etc. Identifying these diverse parameters requires a comprehensive understanding of the mission and the hardware. Although heritage contributes to less uncertainty, the combination of the above result in the subsystem-level's wider uncertainty range

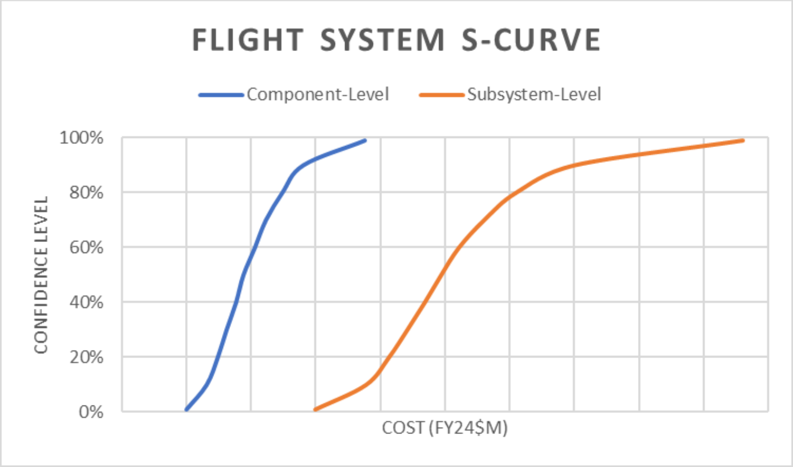

Figure 7 WBS 6.0 Flight System S-Curve

4.2 Mission-Level Comparative Results

For the mission-level estimate comparison, we found that the subsystem-level cost estimate surpassed the component-level even though component-level cost estimates were higher for all four instruments. This is a result of the considerably higher flight system estimate for the subsystem-level estimate. Section 4.3 addresses the challenges encountered during the estimation process that affected the cost estimates for both methods.

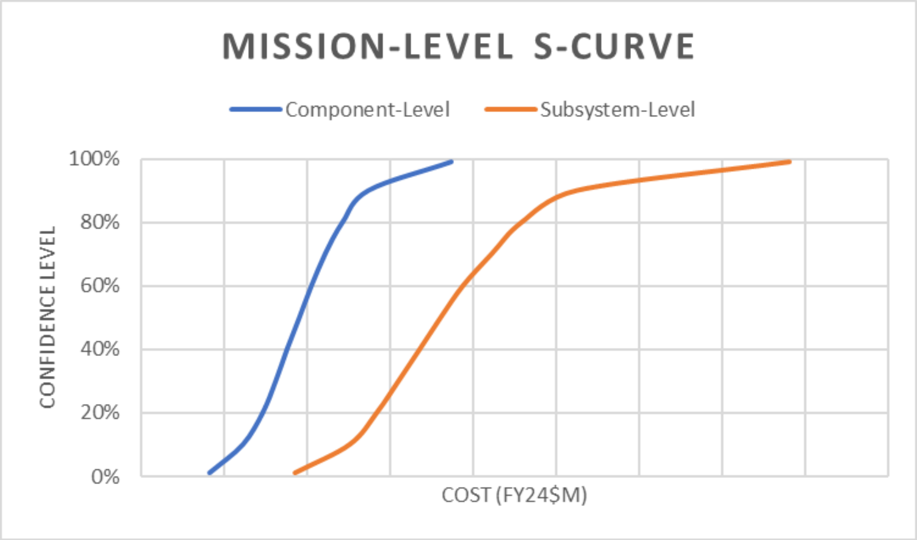

Figure 8 Full Mission-Level S-Curve

A final observation about the mission-level estimate is necessary. There is very little overlap in the S-curves produced between products, for the same mission and technical baseline just at different levels of fidelity. This indicates that either the tools are based on very different datasets, or that possibly the assumptions required to translate a technical baseline between varying tools has a large impact on the resultant estimate. This observation is consistent with previous recent research (Truskin, Wekluk 2023) [10] indicating that the methods used by different space agency produce very different estimates for the same space system.

Figure 9 depicts the distribution of estimated costs by WBS for both the component-level and subsystem-level estimates at the 50% CL. For the component-level estimate, instrument development (WBS 5.0) is largest cost, representing 46% of the total. In contrast, for the subsystem-level estimate flight system (WBS 6.0) is the largest cost (65% of the total) and WBS 5.0’s share of the total (19%) is less than half its share of the component-level estimate.

An explanation for the difference in the distribution of costs between the two estimating methods is not possible at this time and warrants future study.

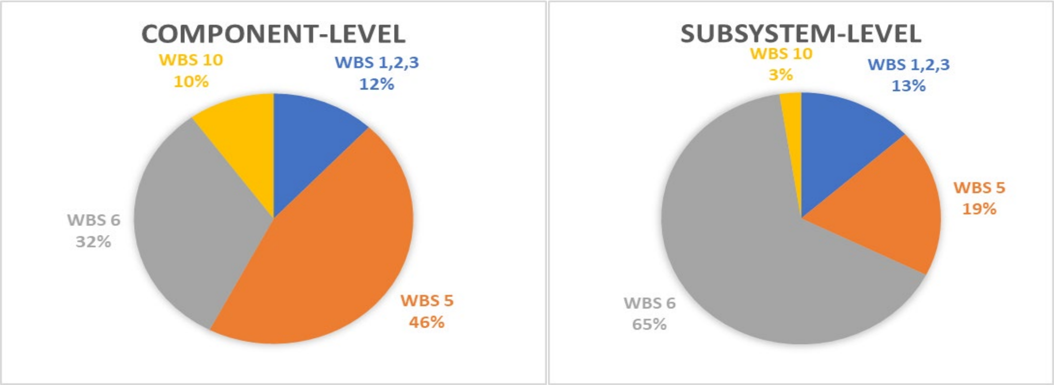

Figure 9 Component-Level vs. Subsystem-Level Distribution of Cost by WBS Element

Figure 10 depicts the percent difference between the component-level and subsystem-level estimates, each at 50% CL, for each instrument and other areas of cost identified earlier. For this figure, the subsystem-level estimates are baselined at 1. The figure indicates that the component-level estimates are, on average, double the subsystem-level estimates for each instrument. Conversely, the figure shows that the component-level estimate for WBS 6.0 is nearly half (62%) that for the subsystem-level estimate.

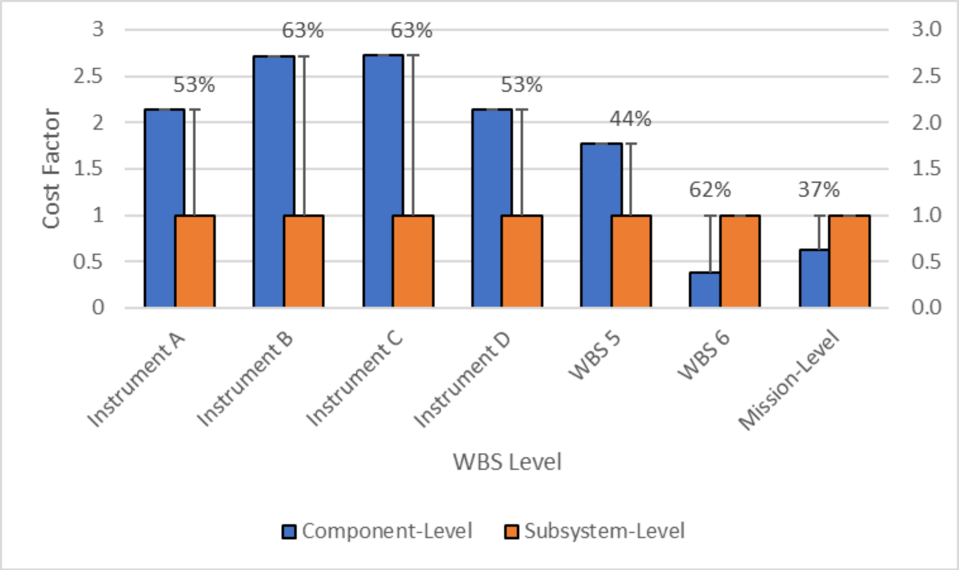

Figure 10: Percent Difference in Component-level vs. Subsystem-level Cost Estimates

The comparison of results between subsystem and component-level cost estimates showcases an emphasis on different mission areas – component-level shows higher cost for WBS 5.0, while subsystem-level shows higher cost for WBS 5.0. Since the component-level estimate is more granular, considering the cost implications of every component, one might expect it to produce a higher cost than the subsystem-level estimate. However, we demonstrated that the subsystem-level method produced a higher cost estimate for WBS 6.0 (Spacecraft). It should be noted that a different subsystem-level tool was used to estimate WBS 6.0 and WBS 5.0 (Payload). This gives some rationale as to why the subsystem-level estimate was roughly 2.5 times higher than the component-level estimate for WBS 6.0. The difference in CERs and parameters considered influence costs for both tools.

4.3 Challenges Encountered During the Estimation Process

For component-level cost modeling, complexity and technical characteristics of each component must be assessed. Modeling at this granular level requires comprehensive data, often necessitating exhaustive research and analysis. This level of detail is time-consuming to acquire and can introduce a higher probability of input errors, potentially leading to costly consequences in the form of input-induced estimating error. It took several months to produce the component-level estimate for this case study, whereas the subsystem-level estimate was completed in weeks.

In some cases, assumptions were made for key input parameters not defined in the technical data that could drastically change the cost estimate for a component. One such example is the optical elements within Instrument B. Each optical element was modeled separately in the component-level model, with individual items estimated to cost millions of dollars when parameters remained at their default settings. If these assumed input parameters are not properly adjusted for various characteristics of the component, these types of estimates are prone to significant errors beyond typical variances. As a result, analysts must give serious considerations to whether the default input values of component-level cost estimating tools are sufficient or whether additional data is required to adjust these input values as appropriate.

Subsystem-level cost estimation introduces its own set of challenges. The lack of granularity can be a limitation, as it may not allow analysts to adequately account for special considerations reflected in the component-level model. For example, when modeling a Charge-Coupled Device (CCD) detector (a frequently used imaging detector), the subsystem-level tool simply asks if the component is included in the instrument, to which an estimator answers *YES* or *NO.* No further details are required.

Additionally, subsystem-level estimates are more analog-based in nature, relying more directly on historical data than a build-up or engineering judgment. This creates challenges in adapting to the unique characteristics of evolving technologies and materials, as the limited set of cost drivers considered in subsystem-level estimates may not capture the dynamic nature of technology, resulting in oversight of critical cost drivers.

Returning to the CCD detector example, the estimate implicitly assumes this detector is like past CCD detectors included in the historical dataset used to develop the related CERs. This is not a problem if the assumption is valid; however, it poses a concern if the CCD detector being estimated contains newer technology or other advancements that might not have anything similar to reference.

Assumptions are critical in both subsystem-level and component-level estimation. In some cases, the data or information required for a parameter that drives costs for a particular subsystem or component may not be provided by MELs, CSRs, or engineers.

Any assumptions that a cost analyst is required to make may (or not) be beyond their expertise. For example, the aperture parameter of a simple mirror may default as extremely large in the cost tool when the actual input is much smaller but not known by the estimator. Without the descriptive information, the analyst may be forced to trust the model's default setting.

While analysts use their best judgment to assign a heritage rating or adjust the level of complexity of hardware, this is not something that can be easily taught and requires significant oversight. These subjective choices directly impact the cost estimate. Andy Prince's 2023 NASA Cost and Schedule Symposium (NCSS) presentation, "Complexity the Right Way" [9] highlighted the impact of subjective inputs, most notably the use of complexity factors in parametric models, and the need for guidance "that makes decisions less dependent on the idiosyncrasies of one professional".

A historical mission was used in this case study to avoid conflicts that could arise in using a current mission. This presented unique challenges that impacted the accuracy and reliability of the cost estimates. One primary challenge was the availability and completeness of historical data related to the mission. Since the mission occurred in the past, there were some gaps and inconsistencies in the records, making it difficult to obtain a comprehensive dataset for cost modeling. I relied on archived documents, reports, and project files, which might not capture all cost elements or could be outdated. Another obstacle was that there were no knowledgeable engineers available to provide clarification or answers to questionable aspects of the mission and data. This led to assumptions and possibly important information left out of the cost models.

As designed, the available methods require significant professional judgment that profoundly impacts analytical results. The cost estimation process has its share of challenges. It is important to be aware of the nuanced factors, at component-level and subsystem-level, that can significantly impact the accuracy of estimates generated by parametric cost models.

5. Conclusions & Next Steps

While component-level estimation is criticized for its time-intensive nature and susceptibility to input errors, it provides unparalleled detail and specificity. This level of detail enables a thorough understanding of cost drivers at the individual element level, facilitating targeted cost management strategies and risk mitigation. In contrast, subsystem-level estimation, although less detailed, offers its own advantages. Its more aggregated nature allows for quicker assessment and can serve as a pragmatic, less time-consuming approach for preliminary budgeting. Additionally, the analog methodologies typically employed at this higher level of estimation can provide flexibility, particularly for projects where component-level parametric models may not be applicable for one reason or another.

Effectively navigating these challenges requires a nuanced approach that thoughtfully considers the tradeoffs between granularity and efficiency and precision and pragmatism. One suggested approach for managing uncertainty in each type of estimate is to perform estimates using multiple methodologies. While employing multiple methodologies is recommended, time and data constraints may not always accommodate this approach.

Therefore, future space cost estimation research should prioritize validation studies of existing parametric tools. These studies should evaluate tool performance across a spectrum of space mission types, sizes, and complexities. There is a need for data-driven guidance on utilizing appropriate estimating methods at the proper time. Conduct of a sufficient number of rigorous independent validation efforts will facilitate development of this guidance.

Furthermore, dedicated research is needed to develop tools that enable this independent validation work. This identified capability gap in the space cost estimating community is consistent with prior research leveraging a parametric cost estimating framework (known as SPACEFRAME) to showcase the discrepancies in and lack of understanding of methods used by cost agencies estimating very similar types of space systems [9]. The next step is to compare across two dimensions, looking at methods across agencies and technical detail by level of fidelity.

In closing, the future of space cost estimation tools hinges on their ability to adapt to emerging challenges. The tools of tomorrow should not merely be calculators of costs. Instead, they should serve as intelligent, adaptive resources that assist decision-makers in navigating the complexities of mission planning and execution.

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