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The Space Between Us: A Novel Collaborative Spacecraft Estimating Framework

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Abstract

Government space acquisitions are renowned for their complexity and can suffer from notable cost and schedule overruns. The space cost community is composed of disparate organizations employing different cost estimating methods, even when the same industry partners are building the spacecraft. This paper leverages a Technomics internally-developed space estimating framework, industry-released Cost Estimating Relationships from multiple agencies, and NRO CAAG external collaboration experience to examine and contrast previously incompatible methods, and improve synchronization.

Biographies

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Benjamin Truskin is a project manager and Employee Owner at Technomics. He has 10 years of experience as an ICEAA Certified Cost Estimator/Analyst (CCEA) supporting the DoD, IC, and other federal agencies providing data-driven decisions to leaders. Ben’s experience includes: cost estimation and phasing, data policy and normalization, methods development, source selection support, industry interface, database requirements development. He received his Master’s and Bachelor’s in Aerospace Engineering from The Pennsylvania State University.

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1. Introduction

1.1. Who is the Space Cost Community?

The Space Industry is a rapidly growing sector of the global economy. Check the news and you will see press releases and news reports of new commercial investments, defense initiatives, and scientific innovations pushing the vanguard of today's technology. This expansion is fueled by several macroeconomic factors, including: more automated manufacturing and integration, microelectronics, increased adoption of digital engineering, and massive economic shakeups in the launch market. In the United States alone, the space sector is projected to grow from $469B in 2021 [1] to over $1T by 2040 [2], and the count of active satellites in orbit is expected to increase by an order of magnitude, from 5,500 today to approximately 58,000 by 2030 [3].

Orbital space provides a unique environment and vantage point supporting the mission and access needed by numerous entities and industries. The community spans commercial, governmental, scientific, education, and defense customer bases. Within those bases there are numerous groups with responsibilities for the acquisition or spacecraft, estimating of spacecraft, and management of space system acquisition and administration of budget. As depicted in Figure 1 below, these groups can be categorized into the major missions of Defense/Intelligence, Civilian/Scientific, and commercial.

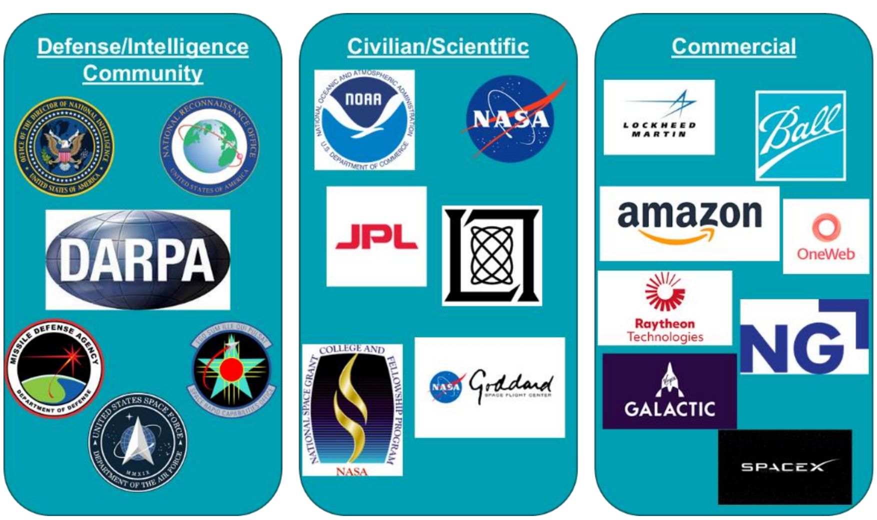

Figure 1: The Space Cost Community

The above figure is not intended to be an exhaustive census, but rather an overview of who is active in the space cost community (including the ICEAA community) or well known. These groups all have stakeholders reliant on their capability to execute space system development and acquisition.

Spacecraft development is typically on the leading edge of industry research and development. Satellites are incredibly expensive to build and operate, and oftentimes have immovable schedule milestones (e.g. launch). Therefore, credible cost estimating and effective management is of paramount importance. Many groups exist to estimate cost, each with their own sets of methods, data, approaches, scope and resources. The Technomics development team identified major differences in these enablers that opened the door for an incredible opportunity to synthesize them in a manner that will benefit the space cost community at-large and encourage future collaboration.

1.2. What is the Impetus for SPACEFRAME?

To set the stage for our discussion of the Space Parametric Cost Estimating Framework (known as SPACEFRAME) that follows, it is important to give some background information about the developers' support to the space cost estimating community and how this has shaped their professional perspective. In 2021, the initial year of SPACEFRAME's development, Technomics had been steadily supporting two fundamental clients in the space cost estimating community: 1) NASA Goddard Cost Estimating, Modeling, and Analysis (CEMA) Office and 2) National Reconnaissance Office (NRO) Cost and Acquisition Assessment Group (CAAG). This support, combined with past experience supporting and collaborating with other space cost groups such as the Office of the Director of National Intelligence (ODNI) Requirement, Cost & Effectiveness (RC&E) and U.S. Space Force's (USSF) Space Systems Command (formerly known as Space and Missile Command) led to a shared, multi-organizational situational awareness of the landscape of government space system cost estimating practices.

Initial discussions amongst the development team led to the identification of an important capability gap across the known space community. Namely, each government office was relatively open about collaborating and sharing models and methods, but this sharing was being done in an ad-hoc fashion. There was a lack of standardization in application and/or documentation that often led to multiple groups developing unique, but fundamentally similar methods for the same scope. This uniqueness of estimate applications extended to the actual cost modeling as well, wherein each group leveraged either commercial tools or their own homegrown models, thereby furthering the state of non-commonality due to varying levels of insight.

1.3. What is the Objective of SPACEFRAME?

In light of the identified capability gap and inefficiencies, the initial goals of SPACEFRAME included:

a. Collect, organize, align, and apply disparate agency methods for common application in a single framework.
b. Demonstrate that, with relatively small investment, the space cost community could benefit from efficiencies gained by leveraging resources developed across the various groups. The development team’s vision was that a tangible investment in making disparate methods available will result in a further desire amongst cost groups to collaborate, share data, and better understand how they could work together.
c. Provide a singular scalable framework allowing for the development of individual estimates and numerous scenarios. The goal was to have a framework that supported the estimate tasking trade space from a single independent cost estimate, through risk analysis, all the way to Analysis of Alternatives and business case type analysis.
d. Remain as open-source as possible to allow for users to plug their own methods and data or develop native capabilities on their own.

Technomics was able to demonstrate and operationalize all of these capabilities with the completion of SPACEFRAME 1.0. This is not to say that development of SPACEFRAME is done! As discussed in Section 7, efforts to improve this capability as it is applied in customer settings and is leveraged by a larger user base are ongoing.

2. Problem Statement

Space acquisition is challenging! As recently publicized with the completion of the James Webb Space Telescope, or the buildout of industrial mega-constellations for real-time space-based communications consistently do not meet schedule objectives. As documented in numerous GAO reports, spacecraft acquisition involves some of the most complicated and highly-tested machinery produced by humans, a reality that understandably translates to chronic cost and schedule growth.

This technical complexity is reflected in the acquisition processes of spacecraft. Compared to most commodities, spacecraft have long acquisition cycles, with significant lead time needed for technology development and parts procurement. Spacecraft routinely experience cost and schedule growth from conceptual phases to completion. Recent GAO reports on space acquisitions identified average growth ranging from 30% to 44%[4,5] . Similarly, other specific space acquisitions can find their cost growth once increased budget needs are realized [7].

Many governmental and commercial organizations have identified cost growth as a significant challenge, and invested in development of improved cost (and schedule) estimating capabilities to further their ability to understand and mitigate potential uncertainty/risk. Some of these cost estimating groups have been plying their craft for 40 years, but the complexity of space acquisitions poses persistent challenges that require continuous, critical evaluation of potential improvements to data and methods.

2.1. Limitations of Spacecraft Historical Data

Space systems are not consumer commodities, have traditionally been highly customized, and are not acquired as regularly as some other types of systems. That makes historical cost data challenging to come by and necessitates use of less ideal sources (e.g. proposals, ROMs, industry trends). Short timelines to complete estimates and meet acquisition milestones amplify the problem, leading to the current paradigm of siloed data and methods built from them, even when actual historical data is collected. As anyone with a statistics background will tell you, the more data you have as a foundation to make projections, the more confident in your projection you can be.

It is uncontroversial statement that a best practice to utilize methods based on relevant historical data for estimating cost [6]. This is not to say there is no value in non-historical data, but all those sources come with significant caveats about usability and implicit and/or explicit biases in their derivation. While those less authoritative sources are oftentimes easier to find, the focus of SPACEFRAME is to facilitate easier use of actual data and methods built from them and, in turn, disincentivize the use of biased sources.

Technomics is a firm believer that if acquisition groups could collect, normalize, and measure execution against historical data beyond solely their own data, they could develop methods make better decisions faster than ever. While not every group has invested the time, has the analytical support needed, or recognized the need to develop methods internally, that does not mean they have to live without any open-source data-driven estimating capability. The first step groups can take into this world is leveraging methods other groups have published based on their collected data and measuring how those perform for them. From there groups can iterate by calibrating to their own data as they collect, before amassing enough data to consider their own methods development.

2.2. Limitations of Current Methods

The government groups in Figure 1 have a core set of responsibilities to decision-makers to provide data collection, data normalization, estimating methods, and cost estimating support at various stages of program lifecycle.. The data collection responsibility, and the policies that enable groups to collect data, is fundamental to how and what methods are derived.

Because these groups are generally good practitioners of cost estimating, they tend to go about their work with similar, policies and procedures…but of course because this is government acquisition there's always idiosyncrasies and tangible differences between the groups which affect what data is collected, when it is collected, and why. These differences tend to fall into a few major areas:

Varying Data Collection Requirements/Policies – Acquisition groups have data collection requirements with varying levels of data detail requirements, government oversight, technical/cost fields collected, etc. Also, some acquisition groups have drastically different capabilities for implementing data collection policies to meet their needs.

Mission – Cost groups support a plethora of missions, which forms the basis of how groups value certain types of information. For example, a group which builds one-off experimental spacecraft may not be as concerned about non-recurring/recurring cost splits as an agency building a constellation of spacecraft supporting some other mission, which necessarily requires estimation of numerous quantities of spacecraft.

Proprietary Data– Some groups get involved at various phases of program acquisition, some engaging with industry very early on. The earlier in concept development a group is involved, the greater the likelihood that data collected from industry is sensitive in a commercial context and may be delivered to the government with additional stipulations on its protection.

Classification – It's the mandate of some of the government organizations, particularly those residing in the Department of Defense and Intelligence Community, to necessarily protect information about their mission due to national security considerations. The missions themselves are classified to protect threats to national security, and by extension this will impact the technical and cost information that can be shared.

Underpinning the above discrepancies is the fact that investment in methodology sharing comes with indirect benefits to the sponsoring organization. Organizations justify developing methods focused on their stakeholder needs, and do not always invest time translating those methods for a wider audience.

Finally, there's a challenge of how methods are documented in the physical sense. This includes challenges of accessing where methods are stored, and the disparate formats organizations choose for documenting the methods. Even after the authors, with a combined 40+ years supporting the space cost community, brainstormed the known methods, it took several months to research and navigate the downright labyrinthine location of some repositories. This is before encountering the discrepancies in formats groups may choose to document or release their methods including: Excel Cost Models, Excel Databases, PDFs, Word documents, PowerPoint.

2.3. Overview of Curated Methods

Despite all the challenges highlighted earlier in this section, there are several government groups that make efforts to share released methods with the space cost community. These groups include NASA (i.e., methods such as Project Cost Estimating Capability (PCEC) and NASA Instrument Cost Model (NICM)), NRO (i.e., Box-Level CERs, Subsystem Level CERs, SEITPM CERs, Demo Satellite Cost Model (DSCM)), and Space System Command (i.e., Unmanned Space Cost Model (USCM)).

In total, our team reviewed and aligned over 225 individual methods from the above sources as well as other smaller sources. These methods are primarily CERs with varying degrees of accompanying documentation and details. Not surprisingly, these methods required extensive normalization to ensure consistency across all methods included in the library., The challenges encountered in this all-important normalization effort are discussed in the following sections.

It is also important to note that our library standardization and structure accommodates inclusion of other types of parametric relationships where cost is not the dependent variable, such as Schedule Estimating Relationships.

3. Differences in Published Methods

As discussed in Section 2, there are challenges to overcome if analysts in the community want to pool as much work together to leverage methodologies (and ultimately the underlying data) to inform their analysis. In this section the authors will discuss some of the more tangible challenges encountered when actually developing a standardized library of methods for SPACEFRAME.

3.1. Dependent/Independent Variables

To an outsider, one CER might look more or less the same as another. “They all solve for cost, right?”. An experienced analyst should be wary of this oversimplification!

For example, one government organization may normalize all recurring cost methods to solve for Theoretical First Unit (T1), another might solve for Average Unit Cost (AUC), and a third might not have clear non-recurring/recurring splits at the methods level and instead provide a separate rule of thumb to allocate costs. Or, as we encountered, some groups chose to solve for cost per month as their dependent variable rather than total cost. Even if the cost scope was the same, the authors had to take care to normalize for the published base year of methods. For some organizations that included variables on both the dependent and independent sides of the equation.

On the technical front, there were some common examples of varying inputs for the same underlying parameter. The simplest of these is mass, with scientific organizations such as NASA preferring inputs in kilograms, while other groups such as NRO CAAG and USSF SSC utilizing pounds. A less measurable parameter, yet technical in nature, is that there is no consensus on how to capture the effects of heritage on estimating costs (particularly non-recurring), with groups using a combination of Technology Readiness Level, a 0.01-10 ‘heritage scale’, % New Design, or categorizations (e.g. ‘Minor Modification’, ‘Major Modification’, ‘New Design’) with stratifications. While accounting for the change in mass units is more straightforward in the mathematical sense, the author’s found themselves having to develop novel approaches to translate between these varying measures of heritage.

Another challenge to overcome in standardizing methods application is that scope and level of insight derived from methods may vary. The challenge of varying scope is not as simple as tackling a mathematical transformation, and required the SPACEFRAME developers to consider inclusion of contextual fields in SPACEFRAME that future users could leverage to avoid future mistakes. A relatively simple example of this is one group’s subsystem model may exclude a certain irregularly bought component (e.g. exquisite bus flight computers from a bus subsystem), while another group may include those costs because it’s more common for their programs to purchase the component. The captured definitions may not explore those distinctions or there may be gray area for SPACEFRAME users to ensure the total scope of an estimate is captured.

3.2. Functional Forms

Challenges can also arise from the disparate ways groups organize their functional forms. One example of this was CERs with a stratifier, where traditionally the authors would expect a functional form of $\$ = a * Mass^b * c^{Stratifier}$ but find some CERs with a form flipping the final term so instead $\$ = a * Mass^b * Stratifier^c$. The second form necessitates that the stratifier no longer take on simple Yes/1, No/0 values and instead use something more exotic such as Yes/e^1, No/1 values.

Even within an organization's published methods, changes in application can cause challenges in a standardized methods library. For example, groups that use % New Design as a driver for NR costs have vacillated back and forth between using the input as an actual percentage (0-1 scale) or as a whole number (0-100 scale), which requires careful consideration to ensure estimates are not incorrectly calculated by an order of magnitude or more!

3.3. SEITPM

One basic challenge with comparing Systems Engineering/Integration & Test/Program Management (SEITPM) methodologies is that unlike hardware, there's less agreement in how to normalize and organize these scopes of activity. While 90%+ of the MIL-STD 881 Work Breakdown Structure (WBS) is common amongst the space cost community, SEITPM continues to be an area that reflects inconsistent treatment. For example, NASA has a prominent focus on Mission Assurance as a separate analytical activity from SEITPM, and thus has methods dedicated to that scope. In contrast, other cost groups capture mission assurance as part of their Systems Engineering activities and cost.

Even when there is agreement on the WBS, groups may take varying approaches to generating an estimate. While all groups whose methods were collected for SPACEFRAME capture data on Systems Engineering (SE) and Program Management (PM) as separate activities, some groups estimate these costs combined in one parametric while others have separate SE and PM parametrics and may even have parametrics to estimate each by phase.

The team gathered nearly thirty different SEITPM methods covering estimates for payload subsystems, communication subsystems, flat percentages, mission assurance, space vehicle SEPM, I&T, Launch System Integration (LSI), Special Test Equipment (STE), and many others. The functional forms of these methods vary widely, and rely upon independent variables such as mass, vehicle quantity, cost basis of the subsystem or system being estimated, and integration difficulty. This lack of standardization makes using multiple organization methods incredibly difficult.

4. SPACEFRAME

In short, SPACEFRAME is an Excel-based parametric space system cost estimating model which leverages a broad base of community-developed methods in order to produce estimates and excursions supporting numerous applications. The idea behind SPACEFRAME was to provide a base capability of best in breed published methods and the extensibility to customize and incorporate further adapted, customized, or un-released methods and data.

4.1. Framework Overview

As part of the initial development team’s requirement analysis process, something that stood out as a major requirement was portability to numerous customers and their disparate computer networks. This led to the initial requirement that the model be based in Excel, given Microsoft Office’s ubiquitous nature in potential customers’ IT systems. Building the model in Excel also brings benefits of familiarity to much of the core customer base, traceability given Excel’s inherent functionality, and modularity given the ability to remove/modify sheets as needed for various clients or estimating needs. The general structure of SPACFRAME is depicted in Figure 2.

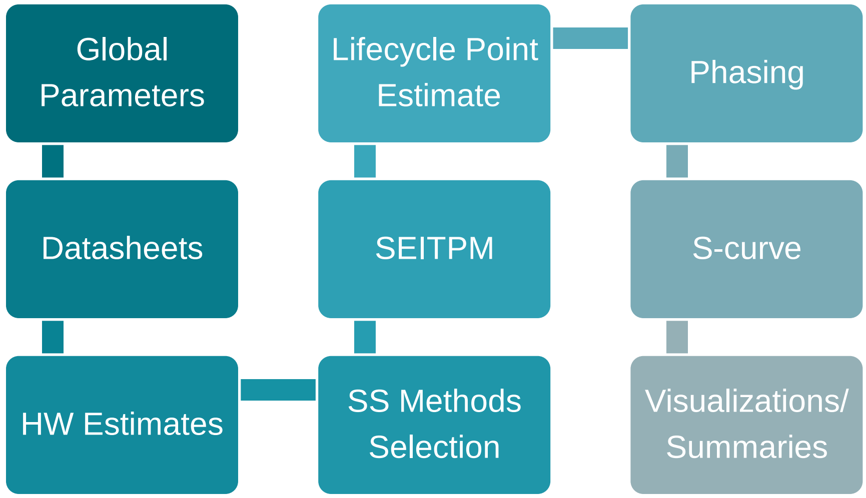

Figure 2: SPACEFRAME Structure

This structure, which should be familiar to analysts experienced with Excel-based models, is designed to flow from inputs and technical baseline definition to estimate generation for HW and then SEITPM estimating to Phasing to uncertainty/risk analysis and finally summarization. The remainder of this section is dedicated to walking through these at a summary level.

4.2. Inputs

In general, SPACEFRAME focuses on two primary subsets of inputs to derive estimates from. First are the Global inputs which define an estimate. These types of inputs include:

- Programmatic – Schedule inputs, Mass Units, Heritage Units, Fees/Burdens
- Estimating – Inflation Index, Mission Class/Type,
- Scope – Enterprise scope to capture beyond the space system (e.g. Launch, Ground System, Operations, etc.)
- Client Specific – There is a sandbox section where users can set up global inputs not captured in the buckets above. One example of this might be foreign exchange rates for organizations dealing with foreign suppliers.

Second are the inputs that constitute the technical baseline. These are the key parameters which define the hardware within a system. They are utilized based on the intersection between estimating method input requirements and input availability. More specifically, the level of detail required by a given estimating method drives the level of technical baseline inputs required. A best practice is to develop a datasheet that can be passed from engineers to the estimating team and back, which can also feed SPACEFRAME directly. Key parameters SPACEFRAME relies upon for technical baseline definition are:

a. Mass (lbs. or kg)
b. Heritage (e.g. Technology Readiness Level, Percent New Design)
c. Quantities (Production Units and Development Units)
d. Method/Commodity Specific Inputs (e.g. Transmitter Power, Mission Class, Thrust, Bandwidth Frequency)

SPACEFRAME is designed to be extensible, with the ability to run numerous excursions of the technical baseline. This allows analysts to modify key technical inputs (e.g. What if more batteries are needed?, What if the structures subsystem must be redesigned?), or add/remove entire units (e.g. What if Control Moment Gyros are needed instead of Reaction Wheels?).

4.3. Methods Applications

Once a user has set up their inputs and various technical baselines for estimating, then the user can select methods to estimate the hardware of their systems and the numerous excursions. SPACEFRAME provides users the ability to apply up to five types of methods to estimate the space hardware:

- Box-Level CERs
- Subsystem-Level CERs
- Box-level Analogies
- Subsystem-Level Analogies
- Box Combination – Summation of selected box-level analogies and box-level CERs based on user choices

For CERs, SPACEFRAME provides users an interface for selecting available methods based upon the published methods available to that customer (including custom methods they've input themselves) and the scope of what is being estimated. Analogies can be input manually or linked to an existing database.

Unlike most models that force a user to select a singular method for a specific element of hardware, SPACEFRAME encourages the user to estimate using as many of the above methods as practical and compare and contrast the results as appropriate. Users can also set up entirely separate excursions with the same technical baseline and different methods in a single SPACEFRAME file if an analyst wants to do that comparison. This capability enables estimate crosschecking earlier in the process, thereby resulting in a stronger estimate earlier.

4.4. Outputs

Once a user has a completed programmatic and technical inputs and assigned estimating methods, then the user can begin summarizing results and presenting them in formats relevant to their stakeholders' needs.

First, users can take the results of their selected methods and present base year estimates by WBS element that include non-recurring/recurring breakouts. SPACEFRAME produces one of these tables for every excursion an analyst runs.

Once the noted base year estimates by WBS element are complete, SPACEFRAME provides analysts the ability to phase and inflate the estimate at one or more levels. Currently SPACEFRAME incorporates a Weibull Curve phasing library, but can accommodate numerous other curve shapes based on available data and organizational preferences. SPACEFRAME also can automatically constrain curves to known budgetary conditions or for other needs, a very useful feature in today's fiscally challenging environment.

SPACEFRAME is capable of performing risk analysis and interfacing with homegrown and commercial solutions for risk analysis. Current capabilities include closed-form, scenario-based S-curve visualization, and the ability to export key parameters needed to interface with Commercial off the Shelf (COTS) products such as Crystal Ball or Argo, or with home-grown Monte Carlo simulation tools.

Finally, SPACEFRAME provides a standard set of graphics depicting selected base-year scenarios or risk-adjusted results utilizing Excel's standard graphics as desired. These could easily be replaced with organizational standards for graphical depiction, or be linked into customer specific visualization tools.

4.5. User Guide & ExampleSat

Aside from the pure technical capability of the Excel-based framework, the authors also recognized the benefits of investment in a User Guide to accompany the Excel-based framework. The current 50+ page User Guide serves two primary functions: assist users with application of the tool for actual estimating and serve as a reference and training aid for analysts new to space estimating.

The User Guide begins by walking analysts through the context of why SPACEFRAME was developed, what capabilities have been developed to date, and what use cases SPACEFRAME is envisioned to support. This is followed by a discussion on estimating fundamentals and definitions as it pertains to space system estimating. A sheet-by-sheet functionality walkthrough is then provided and a FAQ section based on beta testing and common use cases is provided.

Integrated with the text-focused User Guide is an exemplar estimate for a system dubbed 'ExampleSat'. The data for ExampleSat is totally fictitious, but representative of a low-earth orbiting optical observation astronomy telescope. ExampleSat comes with a set of datasheets and technical/programmatic inputs designed to simulate the experience an analyst might have collecting data in a real-world scenario.

An appendix to the User Guide is dedicated to walking analysts through the estimate of ExampleSat in SPACEFRAME. This appendix offers analysts comprehensive training and refresher opportunities. This powerful enabling capability is the result of having the dynamic model pre-populated, screenshots and explanation contained within the User Guide, and additional artifacts simulating the process of data collection and modeling.

5. Case Studies

A series of estimating case studies were developed for this paper using complete sets of agency-specific methods. The goal was to highlight the disparities that can arise from estimating the same system with different sets of methods. All case studies addressed in this section were based on an estimating scenario representative of a space acquisition that could be undertaken by any space cost community group.

The satellite baseline for these case studies is a notional single communications spacecraft in low earth orbit. This is as common a mission as a spacecraft can have, with common components that should be represented in historical acquisitions of defense, intelligence, and civilian/scientific organizations.

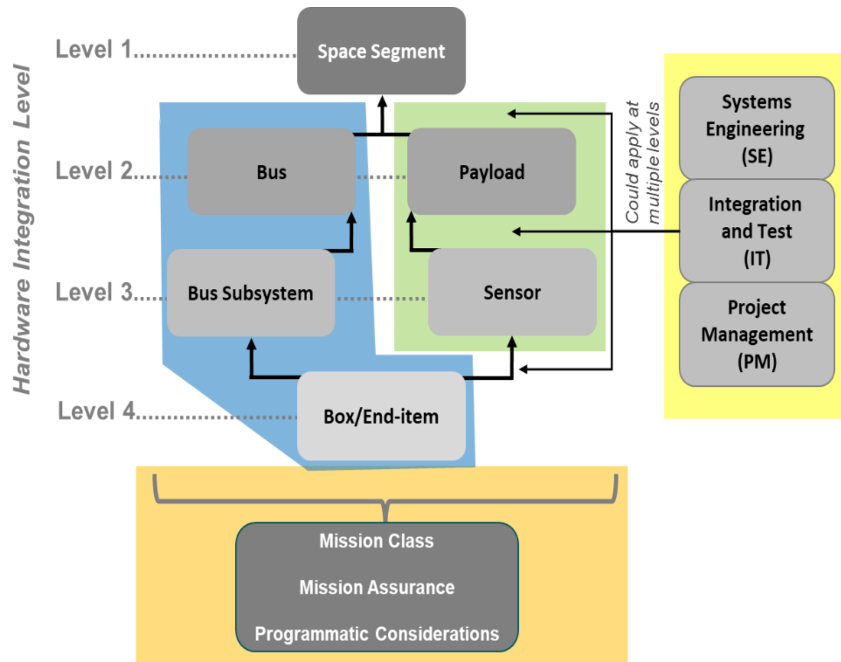

Figure 3: Case Study Alignment to Space System Development. Case Study 1 (Blue), Case Study 2 (Green), Case Study 3 (Yellow), Case Study 4 (Orange)

Remember, the goal of the case studies is to compare methods across organizations for a hypothetical system representative of historical data that comprises the methods assembled (or at least as close to as possible).

For our hypothetical acquisition, we are comparing four actual released sets of estimating methods spanning several space acquisition organizations. As a measure of protection, we will only be referring to these methods as A-D, but these are based on actual released methods that Technomics has curated and conformed to fit within SPACEFRAME. This enhances the realism of the case study and mimics behavior that the authors have seen when developing SPACEFRAME and applying it in a more operational setting.

The case studies are ordered in a logical fashion to more accurately reflect how analysts would estimate these complex systems. Figure 3 depicts the alignment of case studies against a high-level block diagram of space system assembly.

For the reader uninitiated in space systems, a consolidated terminology overview follows:

- Space Segment – The complete integrated system performing the mission on orbit
- Payload – The hardware and software performing the actual mission function while on orbit (e.g. communication suites for a communications spacecraft)
- Bus – The hardware and software that provide supporting functionality to the payload. Typically composed of numerous functionally interconnected sub-assemblies
- Subsystem – Next lowest level of assembly below Bus or Payload. For the bus this would typically capture: structure and thermal management (SMS&TCS) power management (EPS), attitude control (ACS), propulsion (PRS), telemetry tracking & control (TT&C).
- Box/End-Item – The lowest level of assembly typically estimated via parametric methods on space systems. These are functionally distinct and physically segregable units (e.g. batteries, solar arrays, thrusters, etc.). These definitions are expanded upon in Section 0 for readers' reference as well.
- SEITPM - Including the systems engineering, program management, integration, assembly, test, and checkout of complete elements (i.e., the prototype or operationally configured units, which satisfy the requirements of their applicable specification, regardless of end use), financial support, mission assurance, and many other tasks. This work can be done at multiple levels of assembly (e.g. Space Vehicle, Bus, Payload, Subsystem, Box).
- SEITPM Base – The scope of hardware and/or software that is within the purview of SEITPM activities. For example, the SEITPM base at the space vehicle level

includes the bus and all payloads, while at the bus subsystem level would include the boxes and software that comprise that subsystem/

The authors intend for the case studies to build on one another: each represents one aspect of satellite design, and every layer adds cost to previous layers. It's important to note that this does not mean the variances discussed below are independent of one another (e.g. difference in hardware estimates drive differences in estimated SEITPM). This has the effect of exacerbating differences that exist in a single case study to a very large difference when reconciling at higher levels that may be influenced by multiple differences.

5.1. Case Study 1: Bus Boxes and Subsystems

For the first case study, we are comparing the completed estimates at the bus and lower subsystem levels across the four organizations' methods. Figure 4 captures the highest level of analysis, with total bus costs shown and breakouts of non-recurring (NR) and recurring (REC) cost.

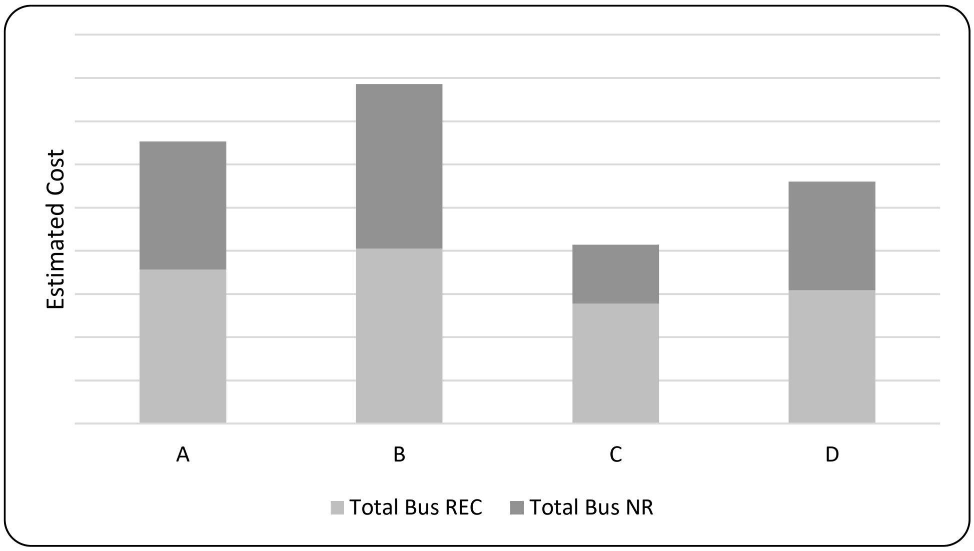

Figure 4. Estimated Bus Cost by Organizational Methods

At the total bus level, there is a spread of almost 100% between the four organizational methods! In a joint acquisition scenario, one group might assess the bus acquisition as achievable, while another group looking at the same technical baseline may have significant concerns about the viability of the acquisition.

This problem is magnified when looking at the splits between NR and REC. NR has a spread of over 150%; though expected to have more uncertainty than REC cost estimating, would still make reconciliation a challenge. Upon summary review of methods, the increased spread in NR may be due to the varying usage of heritage in the parametrics. These differences could be completely transformed if a constellation was being estimated instead of one vehicle or an option for a bus with more heritage was being assessed.

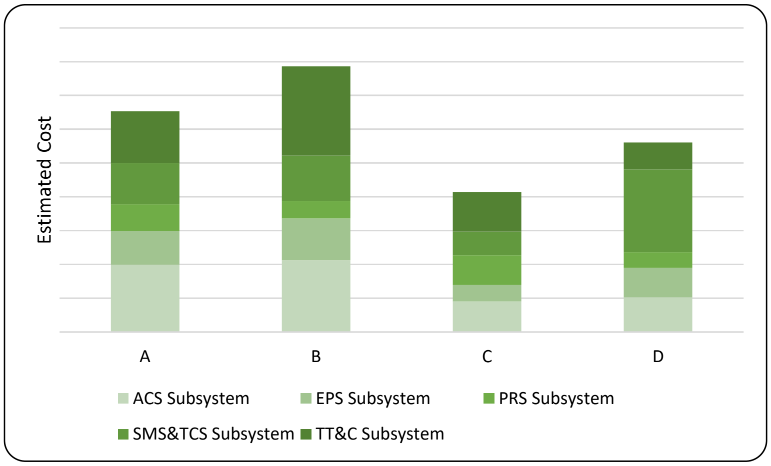

Figure 5. Bus Subsystem Cost Estimates by Organizational Methods

Looking at the bus costs by subsystem (Figure 5), rather than NR/R splits, presents interesting results as well. This is where the differences in technical drivers in CERs and functional forms becomes prominent. For example, Organization B's methods ascribe 54% more costs to the Telemetry, Tracking & Command (TT&C) subsystem than any other group, and Organization D ascribed approximately 30% less to the TT&C subsystem than any other group. This could be studied further by looking at the historical technical complexity and requirements of these organizations' TT&C subsystems, looking for drivers that could be controlled for in parametric space.

Another example of this is that Organization D estimates are roughly double the cost for the Structures & Thermal subsystem than any other group, while the same is true for Organizations A & B ACS Subsystem's estimates when compared to the others. This speaks to the potential for a deeper dive into normalization (e.g., Does Organization D have more stringent structural requirements or include Payload scope in their structures?, Do Organizations A & B have a performance requirement that translates to a need for more complex ACS subsystems?).

To complete our review of Case Study 1, let's take a look at the residuals to the mean for each of the organizations estimates for NR and R scope at the subsystem level.

Figure 6 showcases how the spread in estimating methods increases as the scope narrows both by WBS level and by NR/R split.

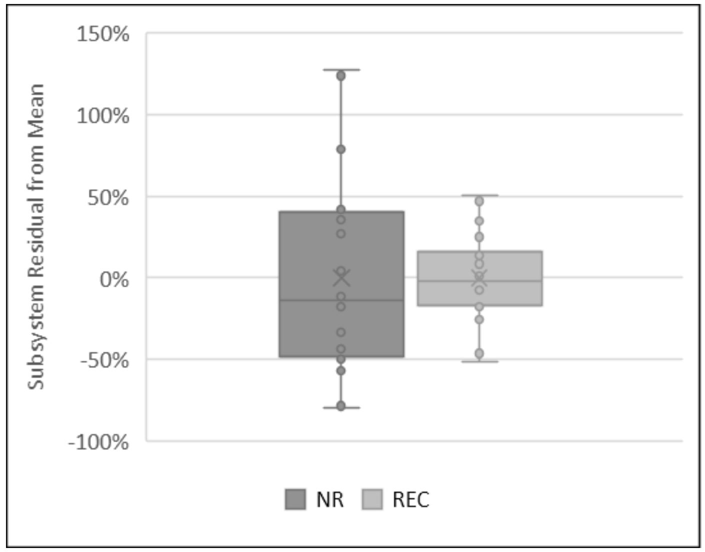

Figure 6: Bus Subsystem Level Residuals against Mean Estimate

By definition the average error from the mean is 0%, however as indicated in the box-whisker plot, the spread is significant. There are subsystems where one organization's method might estimate as much as double or as little as one-fourth the mean. There are not many conceivable scenarios, hypothetical or not, where two government organizations buying essentially the same thing should see such disparate results coming from methods derived from their historical data. This places significant burden on estimators to reconcile in parallel with estimate development in order to convince their respective decision makers and stakeholders that their estimates are credible.

5.2. Case Study 2: Communications Payload (CPL)

For the second case study, let's turn our attention to the payload portion of the exemplar estimate. Payloads are much more customized than the bus to the mission(s) a space system is designed to fulfill, and as such there's less definition of standardized subsystems for that scope. This results in less comparability at lower levels of assembly, so for Case Study 2, we'll only be able to compare NR/REC splits at the payload level and two subsystems composed broadly of electronics and antenna/structure respectively.

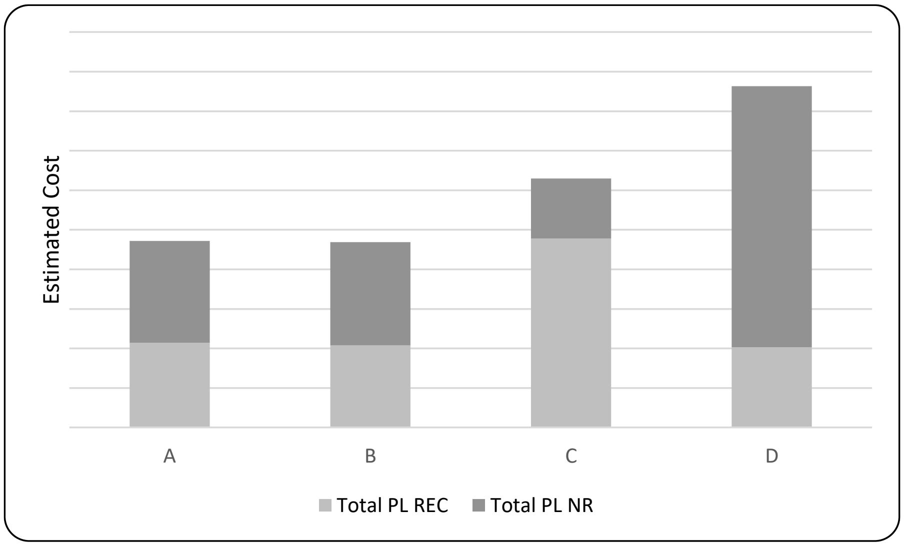

Figure 7. Estimated Payload Cost by Organizational Methods

Given the more customized and complex nature of payloads, even relatively simpler ones such as communication payloads, it's not a surprise to see organizational methods in Figure 7 show further divergence for this scope. At the total level, there is similar spread to Case Study 1. Organizations A & B estimate very similar costs, but Organization C estimates 35% greater cost than their average, and Organization D is again another 37% higher than Organization C.

The disparities of PL estimating are further exacerbated when reviewing NR/R splits. The breakout of costs ascribed to REC vs. NR varies significantly from 24% REC for Organization D to 75% REC for Organization C. This would result in further reconciliation challenges, particularly if these organizations were looking at purchasing additional quantities or authority for design effort only was being studied. Organization D reflects more disparate results; a REC estimate 34% below the average and NR estimate 84% above average.

Turning our analysis to the subsystem level, further disparities are not clear (Figure 8). All groups ascribe similar ratios of cost to the antenna (26-35%) versus electronics; however, the overall magnitude of difference between organizations results in Organization D's methods estimating a communications payload electronics cost alone that is greater than the entire communications payload of organizations A & B.

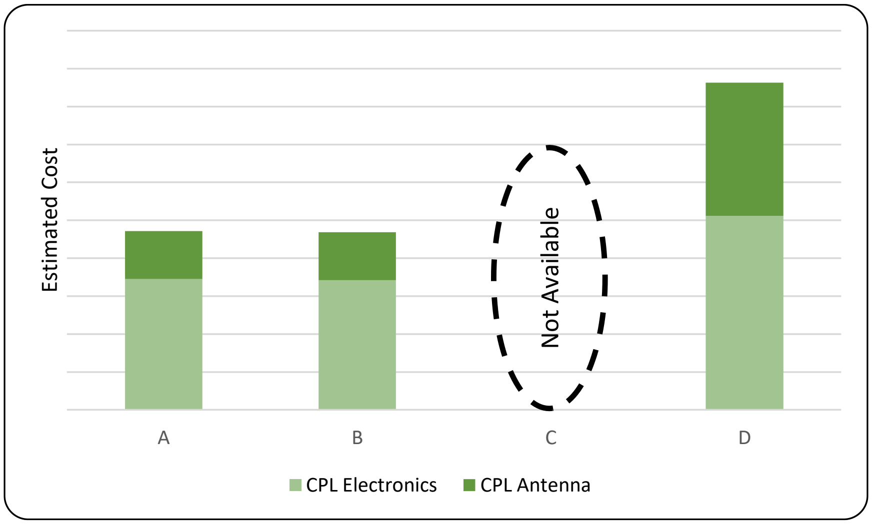

Figure 8. PL Subsystem Cost Estimates by Organizational Methods.

5.3. Case Study 3: SEITPM

For the third case study, the team examined layers of SEITPM for the programs. SEITPM exists at all levels of the WBS: 1) a box needs to be integrated, managed, and tested; 2) the box needs to be assembled with the subsystem; 3) the subsystem needs to be integrated into the bus; 4) the bus and payload need to be integrated to deliver the satellite; and finally, 5) the space-to-ground interfaces must be managed. All four organizations treat SEITPM differently, including where cost is booked in the WBS to how estimation methods are developed.

As stated in Section 3.3, functional forms vary widely and rely upon mass, vehicle quantity, cost basis of the subsystem or system being estimated, and quantification of perceived integration difficulty. The team used SPACEFRAME to build estimates using different methods, but at similar levels, in order to contrast the approaches. Figure 9 below highlights a wide range of outcomes for Systems Engineering/Program Management (SEPM), Integration & Test (I&T), Launch Systems Integration (LSI), Special Test Equipment (STE) and Payload SEITPM.

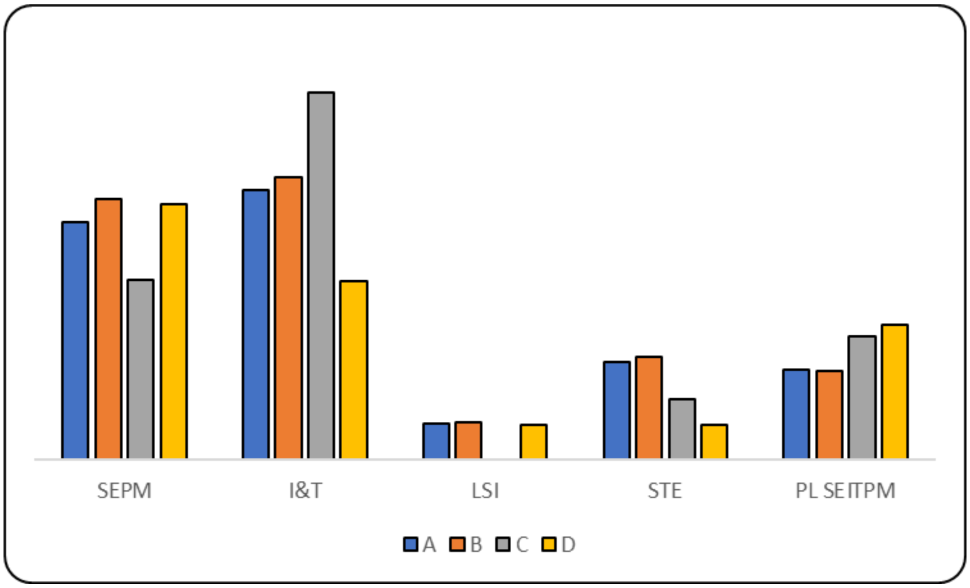

Figure 9. SEITPM Estimate Results by Type.

Many of the SEITPM methods include a cost basis as a primary independent variable. That means SEITPM estimates can amplify already large differences in the underlying hardware/software estimates that are then being integrated, commonly referred to as the SEITPM 'base' for satellite systems. Figure 10 below shows the SEITPM estimates stacked on top of their respective cost bases in a darker shade of the same color. The NR and REC bars highlight two separate phenomena:

1) Many of the cost bases (see orange REC and light-orange SEITPM bars) are roughly similar, though percentage-wise the differences are quite significant. Organization D CERs predict a far lower SEITPM cost than Organization C, with A and B falling somewhere in the middle.

2) The NR cost base varies significantly between all the organizations, but the SEITPM estimates tend to exacerbate differences, especially in Organization C compared to the rest of the organizations.

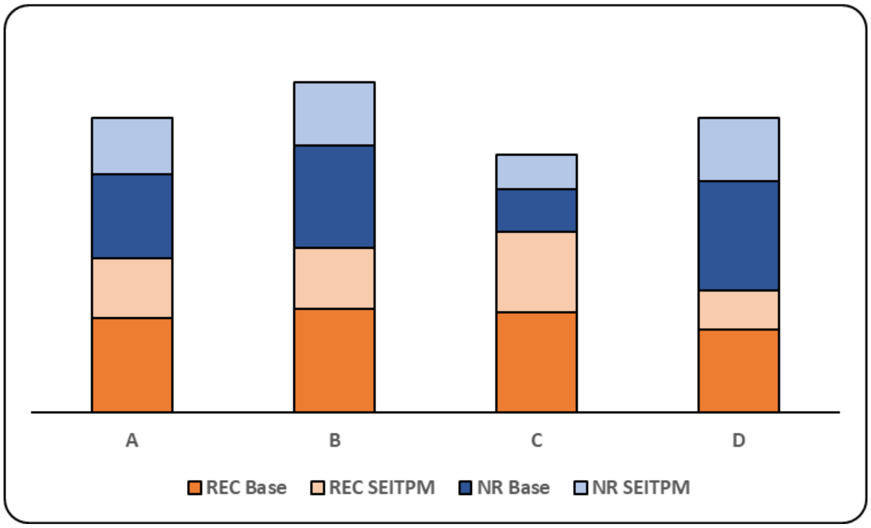

Figure 10: NR and REC SEITPM and Cost Base.

Case Study 3 alerted the team to important structural differences in how SEITPM costs are allocated amongst *all* CERs for all organizations. We are aware that some companies and estimating organizations book SEITPM at varying levels for normalization purposes and approaches differ organization-to-organization (e.g. Bus-level vs. Spacecraft-level SEITPM). This difference in normalization levels underpins what methodologies get published and developed. The team believes this to be an area ripe for collaboration in the future across the space cost community.

5.4. Case Study 4: Mission Assurance, Mission Class and Testing

For the final case study, the authors felt it was worthwhile to discuss a less discrete technical parameter that organizations trade regularly but is not as easily measured as mass, power, or even heritage. This parameter is mission assurance, also known as mission class.

Mission assurance is the level of requirements imposed on a program to perform analysis, testing, and oversight with the goal of reducing risk and ensuring mission success. Different groups characterize mission assurance in different ways. The most well-known is the NASA Mission and Instrument Risk Classification Guide [9], which categorizes missions from A to D with A being the most stringent requirements and D taking on the most risk. This is summarized in Figure 11 below.

Mission and Instrument Risk Classification Considerations		
Priority (Relevance to Agency Strategic Plan, National Significance, Significance to the Agency and Strategic Partners)	Very High:	Class A
	High:	Class B
	Medium:	Class C
	Low:	Class D
Primary Mission Lifetime	Long, > 5 Years:	Class A
	Medium, 5 Years > – > 3 Years:	Class B
	Short, 3 Years > – > 1Years:	Class C
	Brief, < 1 Year:	Class D
Complexity and Challenges (Interfaces, International Partnerships, Uniqueness of Instruments, Mission Profile, Technologies, Ability to Reservice, Sensitivity to Process Variations)	Very High:	Class A
	High:	Class B
	Medium:	Class C
	Medium to Low:	Class D
Life-Cycle Cost	High :	Class A
	Medium to High	Class B
	Medium :	Class C
	Medium to Low	Class D

Figure 11. Risk Classifications. Considerations for Class A - Class D NASA Missions and Instruments.

Most space acquisition agencies leverage these definitions to some extent for their own purposes when estimating. Over time this has affected how groups estimate systems beyond incorporating technical drivers. For example, NASA methods, including PCEC and NICM, capture mission class as an explicit driver in some of their methods. For example, a CER may take on the functional form $\$ = a * Mass^b * C^{Mission\ Class}$, where the mission class stratifier C is regressed based on supporting data. These mission class stratifiers can be very impactful; with some taking as much as two-thirds of the cost out of an estimate when toggled!

Alternatively, other groups account for this effect via other means. For example, the NRO CAAG presented at the 2017 ICEAA Professional Development and Training Workshop on their Mission Assurance and Acquisition Complexity (MAAC) model, which is used to quantify the impacts of mission assurance at a finer fidelity than 4 mission class categories [10]. The results of this model can adjust estimates by a continuous factor of up to 80%!

Finally, some groups segregate datasets and resultant methods entirely depending on the mission class and acquisition approach. This approach has a benefit of ensuring more homogenous datasets, but comes with some challenges as well. Namely there's the challenge of deciding where on the mission assurance continuum to segregate datasets, and the challenges of understanding how the selection of two (or more) disparate methods based on mission class impacts the resultant estimate.

In the context of our case study, hopefully it's clear that not all organizations handle mission class similarly, and that is an added variable when reconciling methods or resultant estimates. For example, if we changed the parameters of Case Studies 1-3 to adjust for a lower-mission class system, some of the organizations' methods would be discretely impacted, some would require input from other models quantifying the relationship to cost (those other models may or may not be released by the way) and some organizations methods may not be adjusted as well. This effect can outweigh the impact of technical driver differences, and adds to the challenges associated with organizations tasked with estimating these complex space systems.

6. Conclusions

6.1. Case Study Results

The team ran all the case studies with the intention of highlighting differences in methods, and potential areas for normalization across cost organizations. Critically, none of the case studies exist in a vacuum, and the principles discussed above tend to compound on one another. Initially, a payload is selected to perform a mission, and a bus is selected to supply the payload everything necessary to perform the mission. SEITPM is needed to make the payloads and the bus work properly and operate together, then work with the ground and other enterprise infrastructure. Fee is paid to incentivize the work.

The culmination of these building blocks is highlighted in Figure 12. The chart shows the additive costs of various cost building blocks, and their percentage contribution to the total cost. We selected one of the organization’s methods to depict, but this graphic looks fundamentally the same for all the organizations. The very reason for the satellite, the built payload, represents only 5% of the system cost! Design work for the payload is over three times the payload build cost. The combined 22% for REC and NR payload is the result of Case Study 2. The sum of NR and REC costs for the Bus and Communications Payload costs represent 36% of the acquisition, the result of Case Study 1. Space vehicle SEITPM is another 31% (12% REC, 19% NR), the result of Case Study 3. As we highlighted in Case Study 4, the adjustment from a commitment to reduced mission assurance, testing standards, and commercial-like acquisition practices can see adjustments of up to 80%! Interestingly, only some estimating organizations make any kind of acquisition complexity adjustments, so that is a huge potential difference in the final satellite cost estimate that is not shown in the first three case studies.

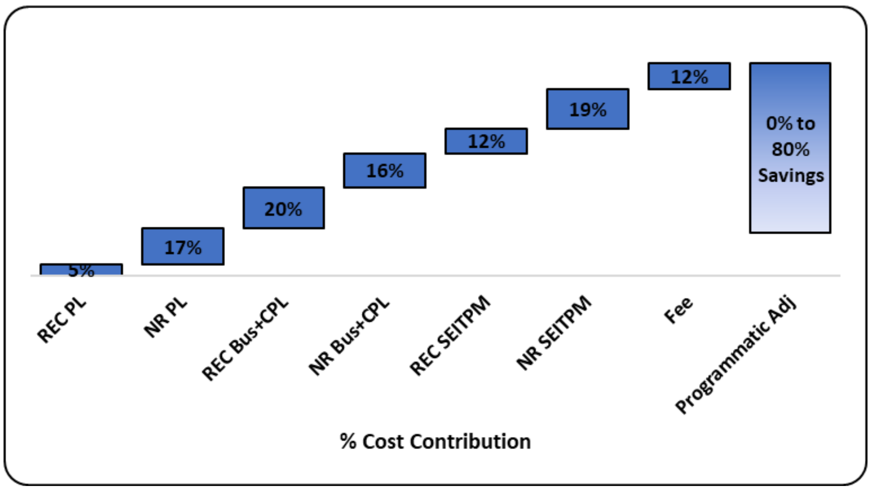

Figure 12. Space Vehicle cost building block waterfall. In this chart, costs build up with to show their affect on total cost, but can come down the bar at the far right based on acquisition approach.

6.2. Differences in Methods

It would be foolhardy to assume one suite of parametric methods could satisfy the breadth of needs of the entire space cost community! There are certainly unique aspects to what different groups do, but the goal of this study and what we are learning by applying SPACEFRAME in actual customer environments is that those differences should be understood, not borne out of a lack of documentation or understanding.

Case Studies 1 and 2 highlights the effects of how organizations buying different types of satellites leads to methods inconsistencies. Those differences manifest as methods with unique independent variables which may result in significant estimate disparities for the same fundamental scope. Scientific agencies buy weather and experimental satellites, while defense agencies buy more navigation and Intelligence, Surveillance and Reconnaissance (ISR) satellites. Commercial entities buy more communications satellites providing services such as radio, television and internet.

Case Study 3 highlights large differences not only in methods, but also in how SEITPM is normalized through the WBS. Some organizations CERs are heavily reliant upon mass, while others are dependent mostly on cost base, and still others use solely technical parameters or estimate monthly cost.

Case Study 4 demonstrates how much acquisition practices can affect estimates, and how estimating organizations could collaborate to better understand acquisition-complexity-like adjustments.

6.3. What Can Be Done?

In the problem statement section, we discussed the challenge of groups producing estimates that are disassociated from their historical data. While this problem can seem insurmountable when first being addressed, the benefits of addressing one fundamental of the cost estimating process support and lower the bar to entry for others. Think of this as a data flywheel, depicted in Figure 13, where investment in one or more areas has synergies with the others. For example, standardizing normalization processes results in standard structures easing the development of storage solutions. Subsequently standard storage solutions allow for the development of methods

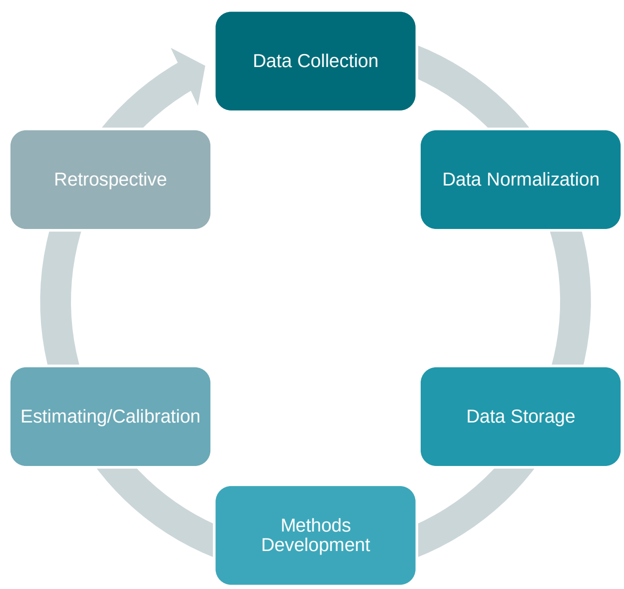

Figure 13: The Transparent Data Flywheel

because datasets are able to be pulled from a strong repository. Those groups responsible for estimating or acquisition support must find ways to impress upon their stakeholders the need to collect data and use said data for developing future estimates.

6.4. Best Practice for Methods Development

For those organizations that are more mature in their cost estimating and methods development capability, do not despair! Our experience building SPACEFRAME highlighted the fact that more can be done to increase the usability of published methods and influence of groups developing and publishing said methods. Those improvements fall into a couple key buckets:

- Accessibility – It's understandable that some groups need to control who inside and outside the organization can access data and how that data is shared. However, our experience indicates that it is not easy in some cases to determine how to get access or what constitutes permissible use cases. Groups should consider providing information on how to access methods for internal and external stakeholders whenever information is publicly briefed.
- Normalization Process Control – If collected data is to be used for methods development, it is critical for analysts creating methods to exercise some level of control over the data collection and normalization process to ensure usability. The programs performing acquisition rarely benefit directly from the collection of good cost/technical data, so left to their own devices they will tend to make decisions to simplify requirements and/or reduce data homogeneity and usability.
- Context/Definitions – What is the context for a particular method that was developed and its intended application? Cost drivers that are not widely understood (e.g. mass) are not always defined and consequently left to analyst interpretation. It is essential to have answers to clarifying questions such as: 1) What is the exact scope of costs covered by the method? and 2) What are the limitations of the dataset (e.g. commercial data only)?
- Ranges/Units – Ensure the clarity of dependent and independent variable definitions (e.g. “Power” vs. “Maximum Transmission Power (W)”).

Simple Variable Definition – When possible, groups should review methods for situations where an input is not user friendly or, worse yet, even impossible for less-familiar analysts to leverage. One example is a method that requires an un-published ‘sub-model’ as an input. Another example could be the one discussed in Section 3.2 where a user had to recognize stratification was not a 0/1 but rather a 1/e decision.

6.5. How can the community better leverage one another?

This is the final section for us to stand on our soapbox and advocate helping the space cost community improve their capabilities via further collaboration. Although we are just beginning to brief external parties about SPACEFRAME, the authors have a couple important preliminary recommendations that warrant discussion here.

a. Invest in cost methods-focused forums! Some groups in the space cost community host relatively well-attended forums known as Cost Integrated Process Teams (CIPT) (e.g. NRO CAAG, USSF SMC, NASA), but the primary focus tends to be on collaboration with the industrial base. In the authors’ experience, government collaboration and methods sharing is typically tend to be an afterthought. There likely is not enough momentum at this point to justify a wholly separate forum, but perhaps a focused side session at each CIPT meeting or once annually could be a starting point. ICEAA’s Annual Professional Development and Training Workshop could also serve as a forum for this sort of collaboration.
b. Combined with the point above, it’s clear that groups could better leverage each other’s methods if there were more consistent formats used to release methods. This paper has already touched on some of the best practices for making methods interpretable, but beyond that organizations can ensure there is one document or source that enables analyst awareness of all developed methods available for estimating space systems.
c. Encourage external feedback via mediums such as CIPT meetings, public facing portals to methods (where possible) and professional organizations (e.g., ICEAA). There will certainly be a need for protection in certain

situations, but the more users of a method, the more battle tested it becomes, and the more refined the method can become for application at the original developing agency!

We hope the above principles resonate and motivate action. While we acknowledge that there are limitations to the benefits that can come from methods and data sharing, we are confident that we are nowhere near the proverbial ‘knee-in-the-curve’ of diminishing returns relative to investment in collaboration and sharing.

7. Next Steps

The work presented here is not done! Space acquisition is a long process, and our attempt to improve community practices through open-source analytical means will necessarily take time. Technomics wants to further the broad use of both historical data in methods development and transparent cost estimating models within the space cost community. Our plan, shown in Figure 14, is to evolve SPACEFRAME via parallel paths, i.e., the capability presented within the framework itself and the ecosystem of supporting infrastructure. This ecosystem development is a recognition that estimating is never done in a vacuum, meaning SPACEFRAME is reliant on skilled analysts applying methods and best practices such as data collection, WBS structuring, etc.

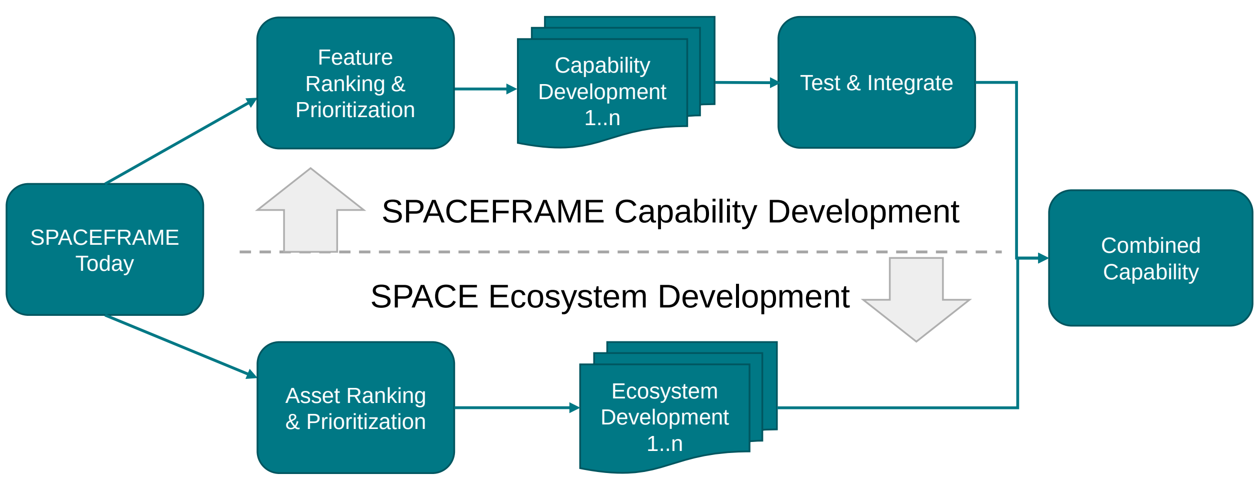

Figure 14: SPACEFRAME Maturation Approach

Technomics is expending effort developing both capabilities and the broader ecosystem linkages. This effort is being informed by customer needs and input that will drive prioritization of the next wave of features. Additionally, this effort is being informed by new analyst training and related lessons-learned about what supporting infrastructure can better leverage the results of SPACEFRAME as a capability now.

While we are not prepared to talk about all the ongoing and future work that will benefit SPACEFRAME down the line, the authors welcome any outreach from community members looking to improve the data collection, data sharing, methods development, or general collaboration environment. The space cost community is small and has significant challenges that can only be improved upon with further collaboration!

8. Appendix A: Resources

8.1. Acronyms, Initialisms & Abbreviations

Acronym	Definition
AUC	Average Unit Cost
CER	Cost Estimating Relationship
CIPT	Cost Integrated Process Team
COTS	Commercial Off the Shelf
IRAD	Internal Research and Development
NASA	National Aeronautics and Space Administration
NICM	NASA Instrument Cost Model
NRO CAAG	National Reconnaissance Office Cost and Acquisition Assessment Group
ODNI	Office of the Director of National Intelligence
PCEC	Project Cost Estimating Capability
SEITPM	Systems Engineering/Integration & Test/Program Management
SPACEFRAME	Space Parametric Estimating Framework
STE	Special Test Equipment
T1	Theoretical First Unit Cost
USCM	Unmanned Space Cost Model
WBS	Work Breakdown Structure

8.2. Space System Definitions

The authors thought it would be beneficial to document some common space system definitions and terms as they appear in MIL-STD-881F [8]. Appendix F of this document provides the DoD standard for Work Breakdown Structures of space systems. For reference, we've included abridged standard definitions for all the scope of space systems discussed in the Case Studies section.

Space Vehicle - This WBS element is intended for space vehicle(s) that are unmanned satellites orbiting the Earth. It contains all of the resources associated with the design, development, production, integration, assembly, and test to include verification testing of each space vehicle as required. Includes, for example:

a. SEITPM, including the systems engineering, program management, integration, assembly, test, and checkout of complete elements (i.e., the prototype or operationally configured units, which satisfy the requirements of their applicable specification, regardless of end use), financial support, mission assurance, and many other tasks.

b. Sub-elements to the space vehicle, including the bus, payload, booster adapter, space vehicle storage, launch systems integration, launch operations, and mission operations support

Bus - The portion of the space vehicle that serves as a housing or platform for carrying payloads and provides necessary support functions (power, thermal control, etc.). It also interfaces with the launch vehicle via the booster adapter. Includes, for example:

a. Structures and Mechanisms (S&Ms), Thermal Control (TCs), Electrical Power (EPs), Attitude Control (ACs), Propulsion (PS), Telemetry, Tracking, and Command (TT&C) subsystems; and bus flight software.
b. All design, development, production, integration, assembly, test, and checkout efforts to provide the bus as an entity or as subsystems for integration with other WBS Level 3 elements (i.e., payload equipment) hardware elements.

Structures and Mechanisms Subsystem (SMS) - This subsystem provides structural support, deployment and locking functions for the space vehicle.

Thermal Control Subsystem (TCS) - This subsystem maintains the temperatures of all bus components, and those payload suites without their own thermal control provisions, within acceptable limits.

Attitude Control Subsystem (ACS) - This element determines and controls space vehicle orbital positions, attitudes, velocities, and angular rates using onboard sensors and torque application devices. It may also send control signals to propulsion subsystem components (e.g., thrusters), the electrical power subsystem, solar array positioners, and communication/payload positioner electronics.

Propulsion Subsystem (PS) - This subsystem provides thrust for attitude control and orbit corrections as required to accomplish the specified mission. It may also provide thrust for orbit injection and changes. Includes, for example: tanks, plumbing, thrusters, solid rocket motors, liquid propellant, and pressurant.

Telemetry, Tracking, and Command Subsystem (TT&C) - This element performs functions such as: formatting and transmitting telemetry (typically on narrowband links); accepting, decoding, verifying, and storing uplink commands; and generating command and control signals for the bus and payload suites based on uplink commands and/or internally generated data. The TT&C subsystem may also: provide central processing functions, provide timing signals to the bus and payload suites; perform on-board attitude determination, ephemeris calculations and attitude control equipment control; and perform thruster control, positioner control, electrical power monitoring and control.

Payload - Payloads are the sets of hardware and software on a space vehicle that perform mission functions. Examples of space system mission functions are communications, remote sensing, surveillance and scientific exploration. A space vehicle may have multiple payloads.

SEITPM – Including the systems engineering, program management, integration, assembly, test, and checkout of complete elements (i.e., the prototype or operationally configured units, which satisfy the requirements of their applicable specification, regardless of end use), financial support, mission assurance, and many other tasks. This work can be done at multiple levels of assembly (e.g. Space Vehicle, Bus, Payload, Subsystem, Box).

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