Unprecedented

ACCURATE ESTIMATING IN THE HYPERSONICS ERA

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I. Executive Summary

Many cutting-edge programs and emergent domains, have few- if any- direct historical precedents. Practical data applicability is of great concern for such systems but must be considered relative to the volume of historical programs; for less populous domains, such as for air vehicle programs, the lack of historical precedent is compounded by the general lack of data to begin with. Early concept development programs further exacerbate the issue- adding uncertainty in operating parameters, and additional data availability and applicability concerns- culminating in parametric cost estimation methods with unacceptably broad variance of the estimate. The challenges presented by advanced development of novel capability systems are significant and difficult to overcome with conventional system-level parametric cost estimation.

A viable alternative is to employ conventional parametric cost estimating techniques at a lower level of the Work Breakdown Structure (WBS). While the system-level design of a cutting-edge program may be immature and inherit little Non-Recurring Engineering (NRE) from prior effort, this is often not the case with assemblies and components. Many of the lower WBS level elements on these novel systems have been implemented on numerous other historical programs; a landing gear may be a reinforced strike fighter nose gear, the avionics LRU may be a stripped-down version of one housed on a cruise missile, etc. Distinct, even disparate, precedents of limited applicability to the overall system can be recontextualized as direct analogies to the individual components and assemblies. In this manner, the volume of applicable data which a cost estimator can leverage skyrockets.

Shifting the viewpoint from the system level to the subsystem, assembly, or even component level of the design has proven especially valuable in predicting advanced aerospace programs. In particular, hypersonics- aircraft and missiles which can exceed Mach 10- and transatmospherics- vehicles which operate near space equivalent altitudes- are examples of cutting-edge programs with little to no precedent. Successful application of these estimating methods has been employed for such systems and other advanced development programs systems of similar complexity, including: Experimental Space Plane, Tactical Boost Glide, Advanced Full Range Engine, the Hypersonic Airbreathing Weapon Concept, SCIFiRE, and others.

II. Introduction

The 1967 film The Graduate is about a young man, Benjamin Braddock, who has recently graduated from college and is still trying to figure out what he wants to do in life. At his graduation party hosted by his parents, one of his father's friends, Mr. McGuire takes him aside and provides him with some advice:

Mr. McGuire : "I just want to say one word to you. Just one word."

Benjamin : "Yes, sir."

Mr. McGuire : "Are you listening?"

Benjamin : "Yes, I am."

Mr. McGuire : "Plastics."

Benjamin : "Exactly how do you mean?"

Mr. McGuire : "There's a great future in plastics. Think about it. Will you think about it?"

At that time, the plastics industry was cutting edge. These days if you had to talk about one word that is an advanced, emerging technology and that is important to our national security, you might think about hypersonics. Hypersonic aircraft and missiles reach speeds greater than five times the speed of sound. If you have seen the recent film Top Gun: Maverick, the test plane that Tom Cruise's character flew at the beginning of the film reached a top speed of Mach 10 before breaking apart. Hypersonics is a cutting-edge technology and the United States has fallen behind other countries in the race for fielding hypersonic weapons, notably China and Russia.

The challenge in estimating systems that are novel and relatively unprecedented, such as hypersonics, is that there is little directly applicable, relevant data.

III. Conventional Estimation Methods

A. Parametrics and The Problems of Data

Parametric methods have traditionally used classical frequentist statistical methods. Frequentist statistics is the classical method that uses a sample of data as inputs. If you have taken Statistics 101 in college, most if not all the class was oriented towards this approach. For example, traditional linear and nonlinear regression analysis is a frequentist approach. The challenge with frequentist statistics is that it requires a large amount of data. As mentioned in the Introduction, for many applications we do not have a significant amount of data.

The Law of Small Numbers, a term coined by the psychologists Amos Tversky and Daniel Kahneman, is the belief that large sample methods and rules (like the Law of Large Numbers) apply to small data sets. This common belief is problematic when applying traditional statistics to the development of cost estimating relationships for small data sets – as it leads to inaccurate estimates that are based more on noise than signal.

For small data sets like these, there are two potential pitfalls. One is the tendency to avoid using parametric approaches to estimation and rely on subjective judgment. The other is to mis-use traditional statistical techniques and overfit – leading to models that do not work well in practice.

When there is a small number of data points is that it might be possible to think that you have found a signal when there is only noise. In Figure 1 below, there is a strong correlation between the variate and its covariate.

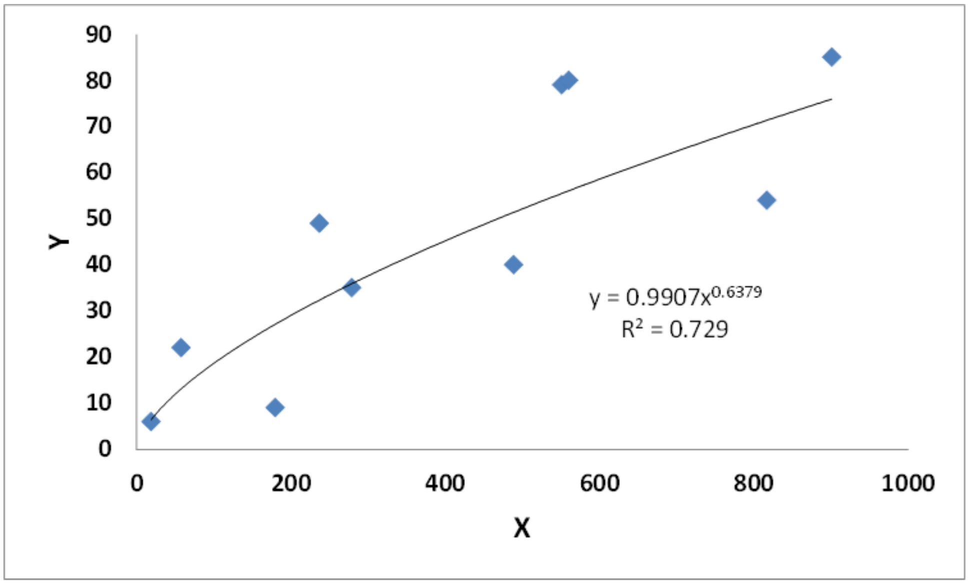

Figure 1: There is a strong correlation between the two variables in the graph

It's only 10 data points but surely there is a strong connection between these two variables, right? There is a clear upward pattern. But the truth is that we randomly generated these 10 points. You wouldn't likely see this in larger data sets, but it is easier to find these in small data sets.

Correlations between variables that have no connection are referred to as "spurious correlations." It is easy to find spurious correlations for small data sets. Tyler Vigen has built a website and has published a book devoted to the subject. It shows that there are high correlations between seemingly unrelated statistics, such as the yearly number of math PhDs awarded and the amount of uranium stored at US nuclear power plants. There is a 95% correlation between these two from 1996 to 2008. There is a 95% correlation between per capita cheese consumption and the number of people who died by becoming entangled in their bedsheets between 2000 and 2009. What these spurious correlations all have in common is that they are small data sets, tending to be around 10-15 data points.

B. System-Level Parametric Cost Estimation

It is well known that advanced development programs suffer from a lack of technical specification fidelity. This limitation is hardly unique to hypersonic and transatmospheric vehicles, or even to aerospace programs as a whole. Rather, this is simply an artifact of the uncertainty inherent at this stage of maturity. This uncertainty can be compounded by other data limitations[1] which reduce the availability, accessibility, or validity of costing data or otherwise place constraints on the cost estimation process. These considerations may manifest as adverse early-lifetime factors such as: unfinalized teaming agreements, organizational restructuring, IPT misalignment, or even limitations stemming from program management prioritization. Oftentimes, immature programs suffer from system requirements which are not even fully defined and may be subject to future change, negotiation, or trade-off flexibility. As a

[1] *Cost Estimating Body of Knowledge Module 2, Data Collection and Normalization.* International Cost Estimating and Analysis Association, 21 Feb 2023. https://wikidev.iceaaonline.com/wiki/Data_Collection_and_Normalization

result of these factors- as well as many others- efforts to characterize program cost at early stages of development are constrained to vague operating parameters.

In general, the earlier in the development life cycle an estimate is performed, the less information is available to the cost estimator. For programs in the concept development stage or earlier, the maturity and availability of data has historically limited cost estimation techniques to broad Rough Order-of-Magnitude (ROM) approaches. This is commonly split between analogy estimating and parametric methods, which typically align with the vehicle-equivalent Work Breakdown Structure (WBS) level. For the majority of programs undergoing concept development, top-down parametrics of this level, or system-level parametrics, are considered optimal. This is a natural consequence of the strategic objectives of most programs, which predominantly target pre-existing or upcoming capability gaps.

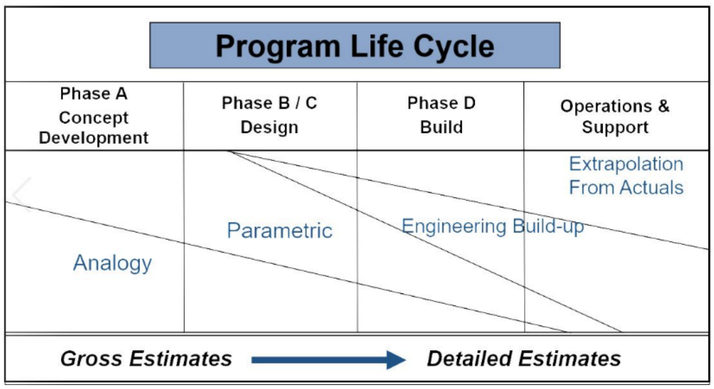

Figure 2: Estimating Techniques Across the DoD Program Life Cycle[2]

Programs do not exist in a vacuum nor are they spontaneous. Programs are contrived, created to fulfill a specific purpose to address a perceived need. For those programs not formulated directly at the behest of a customer, they are still born out of an opportunity available due to a capability gap[3], the inability to meet or exceed a capability requirement, resulting in an associated operational risk until closed or mitigated. Such opportunities could present as: a follow-on to a legacy program approaching obsolescence, a more efficient solution than current options, or an answer to a currently unaddressed capability. However, as the name suggests, most capability gaps are just that- gaps; most opportunities present themselves as a particular bandwidth of missing performance capability between preexisting solutions.

As demand increases and technical challenges are solved, the number of similar programs within a particular region of capabilities reaches critical mass and a capability domain emerges. That is, for some cost-performance relationship, a capability frontier will become more pronounced over time. These distributions of at-least roughly analogous programs within a particular region of performance can be used to extrapolate forward cost-performance for similar future programs. Over time, capability domains become more saturated and

[2] Adapted from "Integrated Defense Acquisition, Technology, and Logistics Life Cycle Management Framework chart," as reproduced in the International Cost Estimating and Analysis Association's "Cost Estimating Body of Knowledge Module 3, Parametric Estimating." DAU, 21 Feb 2023. https://www.dau.mil/tools/t/Department-of-Defense-Acquisition-Life-Cycle-Chart

[3] *DAU Glossary*. DAU, 21 Feb 2023. https://www.dau.edu/glossary/Pages/Glossary.aspx

opportunities become more difficult to explore as these capability gaps narrow. However, as a capability domain becomes more populated, the volume of historical cost data which a cost estimator may leverage towards system-level parametric estimation increases. In general, the more mature- and thus, more populated- the capability domain, the more likely it will be that costing data is both available and valid.

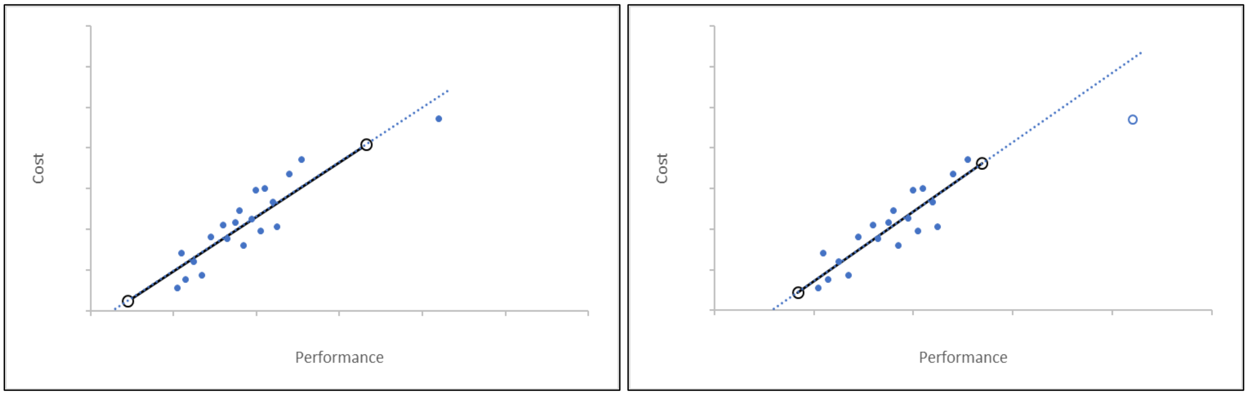

Figure 3: Cost-Performance Capability Domain

Consider the leftmost example in Figure 3, a hypothetical capability domain defined by a single metric, the Key Performance Parameter (KPP), which is- relatively- densely populated (n = 20) with similar programs of varying performance and cost. It is observed that these mutually analogous prior programs fall along some cost-performance curve, so it follows that the majority of such programs are neighbored by adjacent capabilities. Most programs here have at least some rough analogy or precedent; there are very few programs which are outliers, disparate in nature or existing at the ends of this cost-performance continuum. A rough sanity check confirms this: all data points save for one fall within Q3 + 1.5 IQR. However, this data point falls >3 sample standard deviations away from the mean.

If a cost estimator were to use the data in Figure 3 to predict the cost for a program with similar defining characteristics, there would be sufficient data to estimate the cost, provided the new system falls within an applicable range of performance from the prior programs. The ideal case occurs when the predicted system exists at or near the performance of the bulk of prior programs. In such cases, the data is highly applicable, and analogies and system-level parametric estimates are justifiable and easy to implement. Cost estimators can leverage this to estimate the system cost at an early stage of development.

After consideration is given towards whether or not to omit the potential outlier, the data may be used directly in a regression to generate a system-level parametric Cost Estimating Relationship (CER). As demonstrated in the rightmost Figure 3, dropping the potential outlier, while it does tighten the variation of data points, will have only a minor impact on the predicted cost when the performance of the system is at or near the mean value. Conversely, when the predicted system performance is far from the mean, then the impact of the potential outlier becomes much greater. If the outlier is directly applicable to the predicted system, dropping the potential outlier may reduce the predictive capability of the cost model.

For hypersonic or transatmospheric systems, this concern is even more significant, as the predicted performance is typically far outside of the range of available data. Conventional performance metrics such as thrust, max speed, cruise speed, operational altitude, and altitude ceiling are all so far outside of the performance ranges observed in historical systems that historical data cannot be directly applied. To address this, cost estimators are left with several estimating approaches, each with their own drawbacks. The following methods are not regression methods, but approaches which may be applied in CER development alongside traditional regression methods. Not discussed here are alternatives to traditional regression methods when working with limited data, such as Bayesian[4] techniques.

C. Limited Data Scale and Scope

Because hypersonic and transatmospheric systems exist far outside the bounds of the majority of historical data, such systems are particularly vulnerable to the risk of overfitting the cost model to a given data set. As such, cost estimators must be cognizant of the appropriate degrees of freedom for their model, ensuring that system-level parametric analysis be restricted in the number of parameters analyzed. Multivariate CERs must be limited in cost driver terms based on the quantity of data points available. As a result, regression may be restricted to only the most pertinent of cost drivers.

To ensure that the given data set is still characteristic of the estimated system, and thus applicable, notional secondary parameters may still be identified to establish a basis of comparison. The similarities of secondary parameter values are then individually or collectively assessed against a desired similarity threshold. Historical programs which do not pass the similarity test are then omitted from the analysis.

For more qualitative metrics, such as the type of onboard propulsion system, proxy criteria may be established to judge overall similarity. For example, a turbofan engine is more similar to a turbojet engine than to a solid rocket motor by some percent, *x*. A solid rocket system may then need to be *x* percent closer to an estimated turbofan system in other regards to meet the same level of similarity as a turbojet system. As this injects subjectivity into the analysis, the cost estimator may instead elect to reparametrize these characteristics as some quantitative measure. An elegant solution to the engine type comparison would be to compare thrust-to-weight ratios and Thrust Specific Fuel Consumption (TSFC).

While this does limit the number of data points used in the analysis, it ensures that only the most pertinent data is used. Due to the limited number of data points, the resulting CER will feature a great deal of variance but this is not unrealistic for this stage of development and the corresponding lack of maturity in the design and novelty of the capability domain as a whole.

The drawback of this method is the dearth of available costing data for novel domains. Cost estimators may not have the luxury to be so discerning when there exists so little data to begin with. In many such cases, data applicability will have to be sacrificed to some degree to maintain a wide enough dataset for analysis.

D. Weighted Parametric Analysis

Weighted parametric analysis is similar to the previous limited dataset approach, however it is far more inclusive from a data applicability standpoint. Secondary parameters are

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[4] *Joint Agency Cost Estimating Relationship Handbook*. DAU, 21 Feb 2023. https://www.dau.edu/tools/Lists/DAUTools/Attachments/387/CER_Dev_Handbook_Feb2018_Final.pdf

also identified and used to generate a net similarity factor to the system being estimated. However, rather than feature an arbitrary threshold which serves as the basis for data inclusion or omission, the similarity of data points to the estimated system determines their respective weighted impacts on the derived CER.

Data weighting may be established on a per-datapoint basis or groups of data points may share weighting across families of programs. One such approach involves weights which are applied to the residual terms in CER generation. This is meaningfully distinct from the Weighted Least Squares (WLS) *W*, as this weighting is derived from an independent, or several independent, variables which are specifically not used in the regression. In fact, this weighting method is independent of the functional form and error method of the regression and can be employed in tandem with any regression method which minimizes an objective function.

Alternatively, the cost estimator may first run distinct regressions across different sets of data. The independent CERs calculated are then weighted by applicability to the estimated system and combined. For example, independent CERs may be derived from a set of air to air missile data and cruise missile data, respectively. These CERs are multiplicatively modified by some measure of the validity of their source data and then aggregated. This method is also independent of the functional form and error method of the regressions utilized and benefits from the additional advantage that each group of data may be of a different form/error method.

When the weights are equivalent, the objective function reduces to that of the base regression method. As such, the variance explained by weighted regressions will always be less than that of the base regression method[5]. For limited data of variable applicability, these methods allow for increased predictive capability at the expense of injection of subjectivity.

E. Cost Calibration

Consider Figure 4, a capability domain such that there exists sufficient information to derive an analogy costing basis, but available data is insufficient to establish a robust CER. Instead, the cost estimator may omit the analogy point from the regression datasets and then calibrate said costing relationships by extrapolating the CERs vertically to the analogy point.

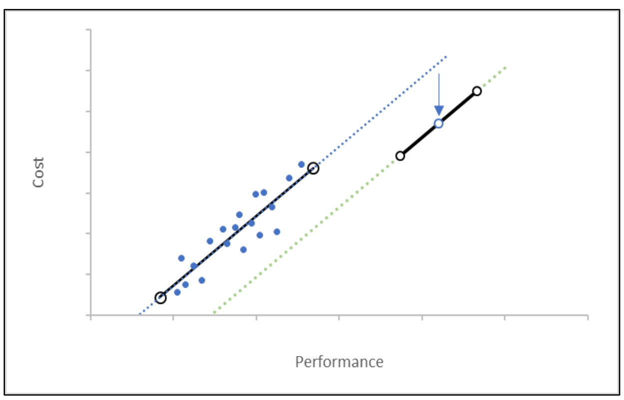

Figure 4: Cost Calibration

[5] *Joint Agency Cost Estimating Relationship Handbook*. DAU, 21 Feb 2023. https://www.dau.edu/tools/Lists/DAUTools/Attachments/387/CER_Dev_Handbook_Feb2018_Final.pdf

The general idea behind calibration is that: (A) The nearest neighbor, the analogy data point, is most characteristic of the system-to-be-estimated and differs from the remainder of data in some manner. These differences may be ineffable, unknowable due to data availability constraints, or unquantifiable in nature. As a result, these differences are not captured in the independent variables of the regression and so the default regression does not account for the estimated cost impacts of these differences. And (B) the default CER estimates a particular cost-response which is relevant to the system-to-be-estimated. When there is sufficient reason to believe the cost impacts of other, established cost drivers may follow previously established trends but there exists no known basis for costing the idiosyncratic aspects of the unique system, then calibration allows the cost estimator to leverage the analogy point as a proxy for the unique aspects of the domain, while still retaining the cost response of the performance parameters of interest as dictated by a wider set of data.

For hypersonic and transatmospheric vehicles, the allure of calibration is great. Previously established cost-performance relationships, for thrust, weight, etc. may hold true within these new domains, however there may exist some more qualitative aspect of such systems, such as extent of qualification, thermal control concerns, etc. for which there exists little to no historical precedent.

Unfortunately, since calibration relies on layered assumptions, it can be very difficult to justify. Cost estimators must be certain that the analogy point is relevant to the system-to-be-estimated, that the historical CER still applies within the desired performance region, and that differences between the historical performance relationship and the analogy are directly translatable to differences between the system-to-be-estimated and the historical data set.

For extreme outliers- for programs addressing gaps near the end of a capability curve or for an immature and emergent domain- the previously described methods of estimation are limited in applicability. For novel technology development programs there may exist no precedent, no system-level analogy from which to extrapolate costs. It is for these cases, such as for hypersonic and transatmospheric aerospace programs, where cost estimators must consider alternative means of cost estimation.

IV. Proposed Methodology

The goal of early development cost estimation is to provide a reasonable prediction of the cost of the future system. In other words, to minimize the prediction interval of the estimation method near the point of the estimated system. When estimating systems far outside of established domains, it is all the more imperative that cost estimators strive to maintain the fidelity of observed descriptive statistics by minimizing foundational assumptions, subjectivity, and heuristics. It then behooves the cost estimation process to utilize costing methods which account for small data sets with a fully justified and traceable process.

Given the lack of established historical hypersonic and transatmospheric systems, there exists little costing basis for estimating such systems. While there are several systems in development, there is little to no data which is reflective of mature systems of Technology Readiness Level (TRL) 9 and Manufacturing Readiness Level (MRL) 9+. Furthermore, the lack of costing analogies correlates with the lack of technical analogies for such systems; with no prior catalogue to draw upon, hypersonic and transatmospheric vehicle developing organizations have only in-house development to-date to draw upon. Such systems necessarily inherit less prior development and thus, experience greater costing uncertainty commensurate with the uncertainty in the design as well as that of the overall development and manufacturing processes.

However, this system-level scrutiny is apropos of system-level parametric costing approaches. If cost estimation is performed at a lower level of the system WBS, then the cost estimator must regard the maturity of the system on a similar basis. Most methods of quantifying maturity are benchmarking methods. TRL and MRL metrics are based on the element in question surpassing certain key thresholds such as: demonstration of breadboard validation in a relevant operational environment[6] or the capability to produce prototype components in a production-relevant environment[7]. Because system level maturity is thusly constrained by the lowest maturity element of the design, it is observed that the mean lower-level WBS item TRL is equal to or greater than the TRL of the system. As such, the mean design uncertainty for individual lower-level elements of the WBS is less than for that of the net system. By shifting analysis from the system level to lower-level WBS items, there is not only a more consistent technical heritage basis, but a broader and more fully defined costing analogy basis.

As such, the proposed approach for costing novel systems is to perform parametric costing techniques at a low level of the project WBS and then build up costs to the system level. When analyzing trends with respect to the level of WBS observed, the following rules of thumb apply. The lower the level of the WBS:

- The greater the mean WBS line-item TRL and MRL across the entire system
- The lower the likelihood that subordinate WBS items will be the critical TRL / MRL driving factors
- The more accurate WBS line-item TRL and MRL are with respect to the true state of development of the item in question

However, it is unfeasible to expect a detailed, component-level WBS breakout prior to the concept development stage. Therefore, it is advised to review WBS data inasmuch detail as is afforded for the current stage of development. While colloquially referred to as component-level parametric cost estimation, this method need not necessarily occur at the component level of the WBS. Although it benefits greatly from increased predictive capability the lower the cost estimator looks, albeit for the tradeoff of greatly increased data burden and timing constraints. As such, lower-level parametric build ups should proceed from the MIL-STD 881 level 3, or subsystem level[8], at a minimum. However, five is not right out. In fact, it is optimal for such efforts. Ideally, lower-level parametric estimates should be to a level of fidelity which is one level more detailed than as outlined in the MIL-STD 881, aligned with a notional WBS level 5. Any greater level of detail than this is often deleterious to the cost estimating effort, and it is highly advised that this decomposition not proceed to the Bill Of Materials (BOM) nuts and bolts level.

Ultimately, component-level parametric cost estimation is rooted in the same assumptions as system-level parametric CER calibration. Namely, that there exist some general cost-performance

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[6] *Technology Readiness Level.* NASA, 21 Feb 2023. https://www.nasa.gov/directorates/heo/scan/engineering/technology/technology_readiness_level

[7] *Introduction to Manufacturing Readiness Levels.* Defense Contract Management Agency, 21 Feb 2023. https://www.dodmrl.com/DCMA_training_SEP_26_16.pdf

[8] *Department of Defense Standard Practice Work Breakdown Structures for Defense Materiel Items.* DoD, 21 Feb 2023. https://cade.osd.mil/Content/cade/files/coplan/MIL-STD-881F_Final.pdf

relationships which still apply to capability domain outliers and that unique aspects of the system can be accounted for via scaling these historically observed relationships to the performance region of the system-to-be-estimated. Additionally, it is assumed that components are more universal in nature than systems as a whole, thereby affording a larger volume of costing data from which to draw. While system performance in a particular category may fall far outside of the historical range of capabilities- severely impinging system-level parametric costing- component performance tends to fall much closer to that of historical components. It is assumed that for hypersonic and transatmospheric systems, components still follow historically observed cost trends. However, there may exist some calibration which must be performed to scale the historical component effort to the hypersonic/transatmospheric domains.

Because there is a greater quantity of applicable low WBS level line-item data points than of applicable entire systems, component-level parametric cost estimation affords reduced variance of the final estimate. This increased data volume is partially offset due to the fact that many historical systems do not have significant detail available at lower WBS levels. However, this still translates to an increase in the overall degrees of freedom of the various CERs. Additionally, because the system has been recontextualized as a build up of its constituent elements, individual cost drivers need not be universal in nature. Cost drivers like thrust and TSFC need only apply to the propulsion system, surface area need only apply to aerodynamic structures, etc. Consequently, the cost estimator has a greater opportunity- within degrees of freedom constraints- to explore the cost correlation of potential cost drivers.

Of course, the utility of component-level parametric cost estimation is predicated on the cost estimator possessing the means to breakdown the system into its constituent elements. Depending on the current phase of development, system requirements definition may still be in flux. Nonetheless, requirements decomposition should still be possible to express in terms of some contingency and margin on top of threshold and objective performance respectively.

For most systems, including hypersonic and transatmospheric systems, there are notional WBS guidelines which may serve as a WBS reference for a generic system. For hypersonic and transatmospheric systems, the MIL-STD 881F Appendix A: Aircraft Systems- as shown in Figure 5- and Appendix C: Missile/Ordinance Systems are both highly relevant structural frameworks, although it is not necessary to follow these exact layouts. Regardless of the exact WBS format used, breaking down functional requirements and specifications along similar lines should be possible even at the program onset. The difficulty then lies in parsing these specifications, as immature low-level specifications may not align with conventional cost drivers.

Consider an example structural element with some loading requirement. At the current level of development, it may be unknown what the exact material composition will be, depending on a yet-to-be conducted tradeoff analysis on weight savings versus manufacturing complexity. However, the loading was found to not be a good predictor of element cost. While the engineering team cannot supply the cost estimator with the desired potential primary cost driver, which is ostensibly weight in this instance, they can provide a range of options. For example: a machined aluminum element must be of some such thickness, and thus weight, while a composite element must be of some other thickness, and thus other weight. If the regression is agnostic towards material composition- lacking some tangential specification like density, material strength, etc.- then the two different options may require different supporting datasets. Once the supporting data is sourced, each trade option can be costed independently. From this tradeoff analysis, the cost estimator can calculate the expected value of the element cost, as well as the cost distribution of the entire trade.

WBS#	Level 1	Level 2	Level 3	Level 4	Level 5
1.0	Aircraft System				
1.1		Aircraft System, Integration, Assembly, Test and Checkout			
1.2		Air Vehicle			
1.2.1			Air Vehicle Integration, Assembly, Test and Checkout		
1.2.2			Air Frame		
1.2.2.1				Airframe Integration, Assembly, Test, and Checkout	
1.2.2.2				Fuselage	
1.2.2.3				Wing	
1.2.2.4				Empennage	
1.2.2.5				Nacelle	
1.2.2.6				Other Airframe Components 1…n (Specify)	
1.2.3			Propulsion		
1.2.4			Vehicle Subsystems		
1.2.4.1				Vehicle Subsystem Integration, Assembly, Test, and Checkout	
1.2.4.2				Flight Control Subsystem	
1.2.4.3				Auxiliary Power Subsystem	
1.2.4.4				Hydraulic Subsystem	
1.2.4.5				Electrical Subsystem	
1.2.4.6				Crew Station Subsystem	
1.2.4.7				Environmental Control Subsystem	
1.2.4.8				Fuel Subsystem	
1.2.4.9				Landing Gear	
1.2.4.10				Rotor Group	
1.2.4.11				Drive Group	
1.2.4.12				Vehicle Subsystem Software Release 1...n (Specify)	
1.2.4.13				Other Subsystems 1...n (Specify)	
1.2.5			Avionics		
1.2.5.1				Avionics Integration, Assembly, Test, and Checkout	
1.2.5.2				Communication/Identification	
1.2.5.3				Navigation/Guidance	
1.2.5.4				Mission Computer/Processing	
1.2.5.5				Fire Control	
1.2.5.6				Data Display and Controls	
1.2.5.7				Survivability	
1.2.5.8				Reconnaissance	
1.2.5.9				Electronic Warfare	
1.2.5.10				Automatic Flight Control	
1.2.5.11				Health Monitoring System	
1.2.5.12				Stores Management	
1.2.5.13				Avionics Software Release 1...n (Specify)	
1.2.5.14				Other Avionics Subsystems 1...n (Specify)	
1.2.6			Armament/Weapons Delivery		
1.2.7			Auxiliary Equipment		
1.2.8			Furnishings and Equipment		
1.2.9			Air Vehicle Software Release 1...n (Specify)		
1.2.10			Other Air Vehicle 1...n (Specify)		

Figure 5: MIL-STD 881F Aircraft System Work Breakdown Structure[9]

The burden on the cost estimator then becomes an exercise in reparameterization. Indirect and calculated data must be explored in detail. All uncertainties which are qualitative in nature, such as in the previous example, must be replaced with some adjacent quantitative measure. Otherwise, differing supporting data sets must be employed for each option. Via the application of these principles, the overall system level specifications and performance parameters can be translated to the component-level.

For a recent transatmospheric program estimate, the component-level parametric estimate was validated to < 4% of the system-level parametric approach. This comes with a tighter prediction interval and additional sensitivity to secondary cost drivers excluded by the system-level model. Galorath has also used this approach in providing credible cost estimates for hypersonics and other systems. These include Experimental Space Plane, Tactical Boost Glide, Advanced Full Range Engine, the Hypersonic Airbreathing Weapon Concept, SCIFiRE, among others.

[9] *Department of Defense Standard Practice Work Breakdown Structures for Defense Materiel Items.* DoD, 21 Feb 2023. https://cade.osd.mil/Content/cade/files/coplan/MIL-STD-881F_Final.pdf

V. Conclusion

While the technical challenges which effect hypersonic and transatmospheric vehicle development are largely unique, the proposed cost estimating solutions are more universally applicable. One way to overcome the challenge of estimating systems that have little historical precedence is by focusing on the word *system*. While the United States has developed few hypersonics systems, if we break the system down to the subsystem or component level, there will be many more data points available. For example, breaking down a hypersonic system into subsystems such as structures, thermal, control, and avionics, there will be many more historical data points that can be used in estimating these individual parts.

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Acronym List

BOM	Bill Of Materials
CER	Cost Estimating Relationship
KPP	Key Performance Parameter
MRL	Manufacturing Readiness Level
NRE	Non-Recurring Engineering
ROM	Rough Order-of-Magnitude
TRL	Technology Readiness Level
TSFC	Thrust Specific Fuel Consumption
WLS	Weighted Least Squares
WBS	Work Breakdown Structure