The Psychology of Cost Estimating

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Introduction

Cost estimation for large (and even not so large) government programs is a challenge. The number and magnitude of cost overruns associated with large Department of Defense (DoD) and National Aeronautics and Space Administration (NASA) programs highlight the difficulties in developing and promulgating accurate cost estimates. These overruns can be the result of inadequate technology readiness or requirements definition, the whims of politicians or government bureaucrats, or even as failures of the cost estimating profession itself. However, there may be another reason for cost overruns that is right in front of us, but only recently have we begun to grasp it: the fact that cost estimators and their customers are human.

The last 70+ years of research into human psychology and behavioral economics have yielded amazing findings into how we humans process and use information to make judgments and decisions. What these scientists have uncovered is surprising: humans are often irrational and illogical beings, making decisions based on factors such as emotion and perception, rather than facts and data. These built-in biases to our thinking directly affect how we develop our cost estimates and how those cost estimates are used.

We cost estimators can use this knowledge of biases to improve our cost estimates and also to improve how we communicate and work with our customers. By understanding how our customers think, and more importantly, why they think the way they do, we can have more productive relationships and greater influence. By using psychology to our advantage, we can more effectively help the decision maker and our organizations make fact-based decisions.

This paper is structured into three parts. Part 1 provides a discussion of the problem of cost overruns in the aerospace industry and some of the findings from traditional cost overrun studies. Part 2 talks about human irrationality and how that opens the door to biasing the estimate. Findings from psychology and behavioral economics are used to describe how biases and faulty logic on the part of the estimator and the customer can lead to poor cost estimates and a failure on the part of the cost estimator to add value. In Part 3 I discuss practical techniques and approaches that can drive rationality into the estimate, thus changing the conversion to one that is productive and influential, leading ultimately to better decisions and fewer cost overruns.

One final note, my experiences and observations are drawn from almost 31 years working as a NASA cost estimator. While I know that cost overruns are a common problem across the Federal Government and industry, everyone has a unique perspective. All I ask is that as you read this paper you keep an open mind. If you don't think what I have to say is useful or applicable to your situation, that's fine. As a wise instructor of mine once said, "I am offering you a buffet, feel free to take what speaks to you and leave the rest."

Part 1: The Problem

Cost estimators face a challenging environment when trying to predict the cost of large, technologically sophisticated government programs. Early in the design process,

requirements are often poorly defined or understood. Incorporation of new technologies creates estimating uncertainties. The underlying industrial base (at least for NASA) is small and highly specialized, creating a "use it or lose it" mentality which leads to a focus on maintaining the industrial base at the expense of program efficiency.

The overarching business environment has its own set of issues. Program funding, schedules, and requirements are driven by political and budgetary considerations. Large bureaucracies in government and industry tend to focus on process versus outcome –making hard decisions difficult and creating programmatic inertia. The culture within government agencies can be to strive for consensus, even if that consensus comes at the expense of healthy conflict and an honest discussion of what something will truly cost.

The estimating profession itself has challenges brought about by small, noisy data sets and models which are sometimes mysterious (PRICE & SEER) or may not be adequately validated. We in the community have few models that can claim to account for the physics of the systems they are estimating or the underlying industrial processes for developing and producing the hardware.

A result of this challenging estimating environment is that cost overruns have become institutionalized within the Federal Government. As can be seen in Figure 1, a cost growth history of 156 NASA projects shows that 84% have some level of cost growth, and almost 30% have cost growth of 50% or more. While NASA is making a serious attempt (and showing early progress) to control costs through the use of the joint cost schedule confidence level (JCL) analysis, cost growth continues to be a significant issue as illustrated by projects such as the James Webb Space Telescope (JWST).

Cost overruns create obvious problems for government agencies. In the current environment of flat or declining budgets, cost overruns in existing projects mean that new projects will be starved of funds (leading to possible cost growth later) or will unable to begin development. Delaying the development of capabilities needed by warfighters or scientists is not in anyone's best interest. Nor is it in the best interest of government agencies to disappoint Congress or the Office of Management and Budget (OMB). Excessive cost growth invites the scrutiny of Congress, the Government Accountability Office

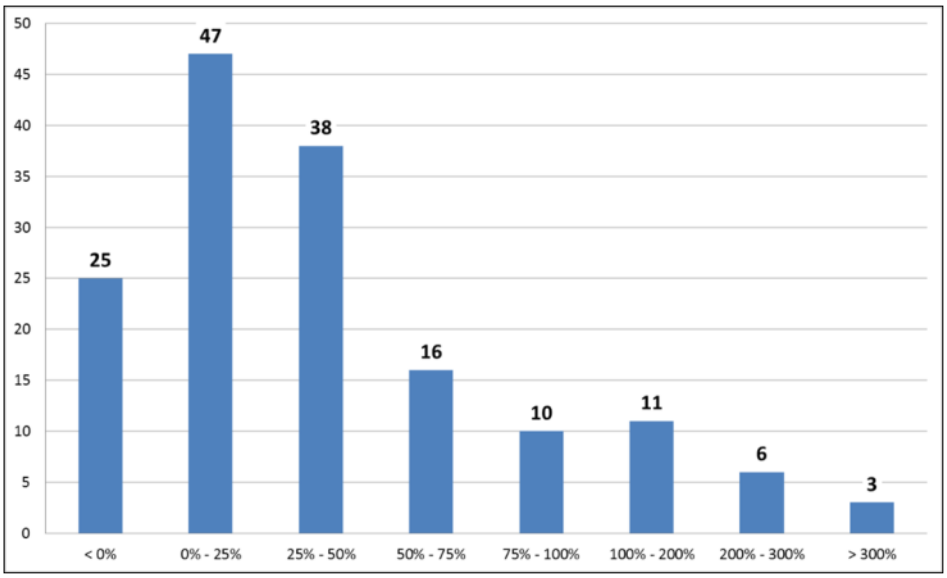

Figure 1. NASA Cost Growth History.

(GAO), and the press. Perceptions of management incompetence brought about by program overruns can lead to project terminations and agency funding cuts.

Causes of Cost Overruns

Numerous studies have been performed and reports have been written on the causes of cost growth in government programs. The causes identified in these reports tend to be depressingly consistent. For example, a National Academes report from 2010 titled "Controlling Cost Growth of NASA Earth and Space Science Missions" lists the following four commonly identified factors in cost growth:

- Overly optimistic and unrealistic initial cost estimates
- Project instability and funding issues
- Problems with the development of instruments and other spacecraft technology
- Launch service issues

A 2002 Booz Allen Hamilton presentation titled "Space Systems Development Growth Analysis" looked at Air Force space mission cost growth. Among its findings were:

- Initial cost estimates are based on inadequate data and do not capture total program cost
- Evolving technical requirements
- External program funding adjustments are frequent
- Optimistic acquisition strategies
- Overemphasis on bottom line cost versus cost realism
- Cost estimating capabilities that had been allowed to atrophy

Finally, a NASA Project Management Study dated January, 1981 identified the following four contributors to cost growth (obviously, not much has changed):

- Technical complexity of projects
- Inadequate definition prior to NASA's budget decision and external commitment
- Effect of NASA's tendency to select based on basis of bid price and the contractor low bids
- Poor tracking of contractor accomplishments against approved plans in a timely fashion

While I could list many more sources (such as the GAO) and their findings, in the interest of brevity I will proceed to a discussion of cost growth causes using a taxonomy that summarizes several factors into four broad categories or groups.

The first group that could be blamed for cost overruns is us, the professional cost estimator. If we are developing poor cost estimates; perhaps as a result of bad models, inadequate data, or poorly trained cost estimators, then our estimates could mislead management into believing that they have sufficient resources for successful project execution. While I certainly believe ample opportunity exists to improve government cost estimating, I don't believe that the cost estimators, the tools, or the data is the root cause of the problem.

The second category of factors causing cost overruns are those related to technical or managerial actions. Almost all cost overrun studies cite inadequate or poorly defined requirements or underestimated technical complexity or overestimated technology readiness as root causes. Several studies also mention poor project management and acquisition practices. And the impact of funding cuts on cost growth is a known fact. However, while these factors are a documented source of cost growth, I believe there is a more fundamental issue that is behind the cost overrun problem.

The third group that can be blamed is the corporate management community. In a paper written for the Journal of Parametrics ("What are Quality Cost Estimates or the 260 Hz Estimate,"

Spring 2007), Joe Hamaker, then the lead for cost estimating at NASA, explicitly relates the importance of management culture on the quality of the cost estimate.

> "I believe that actually, the first enabler for quality cost estimates in any organization is the state wherein the management of that organization actually wants to know at ATP what the projects are likely to cost. This is somewhat important. If management doesn't really want to know the truth, that fact flows down to the estimating community pretty quickly in the form that quality estimates aren't an important product anymore."

Obviously, a corporate culture that does not see value in cost estimating as means to improve performance is not going to support an estimating culture that provides realistic cost estimates.

Related to management culture is an organization's governance process. Governance here refers to the various boards and committees necessary to running a large organization. If the governance process is broken and does not get non-advocate cost estimates to right people at the right time, decision makers are making decisions with inadequate data. However, I believe that an unsupportive management culture or a broken governance process are symptoms, rather than the cause of cost overruns.

The fourth category are those factors that have nothing to do with cost estimating capabilities, technical definition, funding shortfalls, or management culture. Rather, these factors apply to all of us: estimators, technical experts, managers, and executives. This cause of cost overruns is the fact that everyone involved in the cost estimating process is human.

The remainder of this paper will explain how our own built-in human biases lead to poor, or poorly used cost estimates. These biases apply to all of us, no one is immune. But knowledge is power and knowledge of how these biases affect our estimates gives us, the estimating community, the power to add value even in the face of management resistance.

Part 2: The Irrational Human

Psychologists have discovered that human thought processes are surprisingly irrational. I use the word "surprisingly" because for many years, economists (and others) assumed that humans behaved in ways that are rational and predictable. Among some of the things these researchers have found are:

- We are unfailingly optimistic in our outlook on life
- We are overconfident in our abilities
- Our thinking is often shallow and colored by our current emotional state
- We prefer stories and anecdotes over facts and data
- Statistics are non-intuitive, so we either discount them or misuse them
- We have problems accepting randomness – everything must be explained
- We fear losses more than we value gains
- Personal experience and knowledge trumps everything

Psychologists have also learned that our irrational behavior is also predictable. In his book Predictably Irrational, Dan Ariely writes

> "…we are really far less rational than the standard economic theory assumes. Moreover, these irrational behaviors of ours are neither random nor senseless. They are systematic, and since we repeat them again and again, predictable."

So why do we behave in such an irrational manner? According to psychologists and others, it is a coping mechanism that allows us to adapt to

our environment. Douglas Hubbard, in his book How to Measure Anything, explains the how this coping mechanism works.

> "It's no revelation that the human mind is not a purely rational calculating machine. It is a complex system that seems to comprehend and adapt to its environment with an array of simplifying rules. Nearly all of these rules prefer simplicity over rationality. Those that are not quite rational but perhaps not a bad rule of thumb are called "heuristics." Those that fly in the face of reason are called "fallacies.""

Thus we are not thinking machines, processing information in a computer-like manner. Rather, our decision making process is much more complex and biased by extraneous information, beliefs, and unconscious thoughts. Our human thinking mechanism leads to irrational (or suboptimal) decisions. These irrational decisions affect cost estimates because cost estimates are predictions, and predictions are the result of decisions about how what is known today is going to lead to an outcome at some point in the future.

In his book Thinking, Fast and Slow, Nobel Laureate Daniel Kahneman explains how a common human thought process call "substitution" leads to biased predictions.

> "…the prediction of the future is not distinguished from an evaluation of the current evidence – prediction matches evaluation. This is perhaps the best evidence we have for the role of substitution. People are asked for a prediction but they substitute an evaluation of the evidence, without noticing that the question they answer is not the one they were asked. This process is guaranteed to generate predictions that are systematically biased; they completely ignore regression to the mean."

In other words, Kahneman is pointing out how this one flawed thought process can cause us to make decisions that lead to unsupported deviations from trends identified by the historical record. Our cost estimates are led astray because we believe the story we are told about the system we are estimating rather than what the historical data tells us the system should cost!

Biases

Psychologists have identified a number of common biases in how we think that affect all of us, or at least those of us who are human. These biases influence our decisions because they act on our subconscious and thus we are unaware that our decisions are being affected. These biases are comfortable because they cater to our self-image or they appeal to our desire to create an orderly, explainable world. All of these biases are well-known and understood by psychologists and the fact that we have them will probably not be a surprise to the observant reader.

***Optimism/Overconfidence**:* Most of us are optimistic by nature. We like to believe that to at least some extent, we are masters of our fate. In fact, research has shown that an absence of optimism can lead to depression. However, optimism is a form of self-delusion. Too much optimism leads to overconfidence and overconfidence leads to a poor understanding of risk and the underestimation of the probability of failure. Overconfidence affects estimators and managers alike. While we often accuse managers and study leads of being too optimistic about design complexities or technology, we estimators can also be overconfident in our ability to predict costs.

***Anchoring**:* Sometimes referred to as relativity, anchoring is the ability of a number to influence an analytical (or estimated) outcome. For example, if a cost estimator is told that the cost is expected to be $100M, the estimate will be significantly lower than if the estimator had been told the expected cost is $500M. Anchoring also works when we are told that what we are estimating is similar to a previous project, or that we are inheriting hardware, software, management team, etc. from a previous project.

***Availability**:* Psychologists have proven through experimentation that we will assign a higher probability of occurrence to information that is easy to retrieve. Therefore, what we are most familiar with will have the greatest impact on our cost estimates. For example, if we are told that Project X is going to use an inherited design, and we go and search our historical data and find several examples of projects that realized cost savings by using an inherited design, we are more likely to accept the proposition that the cost for Project X will be less than the historical average. Note that what we have done is merely confirm that an inherited design saves money, it says nothing about the ability of Project X to actually use an inherited design. Availability can also affect our customers. By repeating the same stories over and over to themselves ("we are TRL-6 or greater") they come to strongly believe what they want to believe.

***What you see is all there is (WYSIATI)**:* WYSIATI is a phrase coined by Daniel Kahneman to describe how our minds can quickly develop a coherent story out of limited information. Two surprising facts emerge from WYSIATI. First, the less information we have the more confident we are in our coherent story. Second, the coherent stories that we build often ignore probability and statistics. The danger with WYSIATI is that we will be overconfident in our knowledge, thinking we know that answer when in fact we are relying on a story that is plausible, supported by what our minds can readily recall, and is consistent with our worldview.

***Halo/Horns Effect**:* The Halo/Horns effect (also known as the confirmation bias) is our tendency to emphasize data that agrees with our belief or intuitive assessment, and to discount information that disagrees with our position. The Halo/Horns effect can also cause us to look for (or be more open to accepting) data that confirms our position or opinion. Obviously, the danger with this bias is that we will overlook or discount important information that is inconsistent with the desired outcome.

***Plausibility Effect**:* When we believe the more plausible outcome over the more probable outcome, we are falling victim to the plausibility effect. The Plausibility Effect occurs because we like explanations that address all of the facts, even if those facts are suspect or spurious. Cost estimators fall victim to the Plausibility Effect whenever we confuse a good story with a probable outcome (see WYSIATI).

***Bandwagon Bias**:* Humans have a strong need to conform. In a group setting it is not uncommon for the most vocal and outspoken members of the group to dominate the conversation. Typically, these vocal members will eventually bring the others around to their point of view. Cost estimators are human, too. We can easily be influenced by a strong, vocal project manager (are there any other kind?) and a project team that is already on-board with their leader's opinions.

***Attractiveness**:* Appearances matter. Psychologists have known for years that people assign more favorable characteristics to attractive people or products. We are also more likely to believe a good presenter over a poor presenter. Attractiveness and the Plausibility Effect and the Confirmation Bias are interrelated. We like a good (attractive) story that makes sense and explains all the data, especially if it confirms a previously held belief or opinion.

These biases and thought patterns do not operate independently. Rather, they interact with and reinforce each other, leading to poor decisions on the part of executives, managers, project leads, and cost estimators. For example, if the project team tells us a good story that is logical and plausible, if they all obviously believe it, if the data all lines up, then we are more likely than not to go along with the project and produce a cost estimate that is consistent with the project's expectations. In addition, we will probably feel very confident in the outcome. We all want to be good people and get along with everyone and be part of the team. The danger for the cost estimating profession is this: if we are not adding value by increasing the

probability that the project can be performed on budget, then we are at risk for losing support within our organizations.

Part 3: Antidotes to Biases

You, or your customer, cannot avoid being biased any more than you can avoid breathing. These biases are hardwired into our psyche and can only be overcome with great mental effort. What we can do, however; is to engage in actions that force us to approach cost estimating as analytically as possible. These actions can help us improve our estimates and add value to the products we provide our customers. They also give us the tools by which we can influence our customers into making better decisions. The six actions (or antidotes) I have identified are listed below.

- Have a good process
- Inject a healthy dose of reality
- Validate your results
- Embrace the uncertainty in your estimates
- Be the cost expert
- Build and tell your story

The following sections address in detail each one of these antidotes. However, let me say up-front that the common theme running through each of these actions is the desire to bring more data and information to bear on the estimate at hand. As Kahneman states on page 201 of "Thinking, Fast and Slow," ignorance creates the fertile ground for biases, and as humans we fail to appreciate how ignorant we can be.

> "At work here is that powerful WYSIATI rule. You cannot help dealing with the limited information you have as if it were all there is to know. You build the best possible story from the information available to you, and if it is a good story, you believe it. Paradoxically, it is easier to construct a coherent story when you know little, when there are fewer pieces to fit into the puzzle. Our comforting conviction that the world makes sense rests on a secure foundation: our almost unlimited ability to ignore our ignorance."

The other thing that Kahneman is telling us is the importance of stories. Everything done for a cost estimate can and should contribute towards the cost estimator telling his or her own story. We are more influenced by stories than we are by data, and the cost estimator should use that to their advantage.

A final theme not explicitly expressed in the bulleted list above, but one that I believe is very important to the work we do, is the opportunity to add value beyond the cost estimate. By adding value, I am saying that we, as cost estimators, need to look for opportunities to contribute to the success of whatever endeavor we are estimating. Contributing to success is providing analytical products and data that can increase the probability of the project accomplishing its cost, technical, and programmatic objectives. Contributing to success *is not* producing a cost estimate that meets the project's expectation so that everyone is happy.

The Cost Estimating Process

A good cost estimating process can improve the quality of an estimate and work to minimize biases. Every organization should develop a process or adopt a process from a known and recognized source, such as the GAO Cost Estimating and Assessment Guide. A standard process provides traceability and repeatability, keeping the estimator focused on the task at hand and creating a documented basis of estimate. The process should capture best practices and include activities that counteract biases and keep the estimate as objective as possible. Finally, the process forms the foundation of the cost estimator's own story: a story that will describe how the estimator has used the facts, data, and

subjective assessments to build a credible estimate.

Injecting Reality

The cost estimating process provides a means to achieve an outcome, but the process may not lead the estimator to consider all the possible dimensions of the problem at hand. One can take a very narrow focus of the cost estimating problem: the customer wants an estimate – I will deliver an estimate. Or, the estimator/analyst can take a broader point of view. This broader point of view considers not only the data at hand (WYSIATI) but enables the estimator to seek out and consider data that exists beyond what is needed to perform the job. By looking at the bigger picture the estimator is forced to incorporate a reality that is larger and more complex. By increasing the breadth and depth of the information used in the analysis, the effect of biases can be reduced simply by broadening the estimator's perspective.

I have identified four general sources of information that can inject a dose of reality into an analysis. The first of these, historical data, is worthy of a more detailed discussion and thus, will be covered comprehensively in the next section. The second source of reality is the technical and programmatic experts who are supporting the project or study. These individuals often have extremely useful information, information that may not be shared in team meetings or short sidebar conversations. I strongly suggest that you meet with these individuals one-on-one. One-on-one meetings minimize the effect of group think and may encourage a more open conversation. However, experts are subject to the same biases discussed earlier, so take what you learn and compare it to data from history, cost experts, and other technical and programmatic experts. Remember that facts are unbiased but that the context within which those facts are communicated may be biased. Try to understand their motivations and factor that into how you use their input.

All of us who work in the field know and understand the value of discussing our estimates and analyses with other cost professionals. I simply mention it here for the sake of completeness. However, I do want to emphasize that having another cost professional, preferably someone who is considered the expert in your organization, review and critique your estimate is an excellent way to get an outside point of view. An outside point of view can be invaluable for finding areas of questionable judgment and methodology. A good cost expert can also identify other analyses, data, and techniques that can improve the estimate.

Events that take place outside our organizations can have a meaningful impact on our estimates. Our various organizations do not exist in a vacuum. Actions by national and international leaders directly affect the perceptions and decisions of our political leaders. Broader economic trends directly affect decisions by companies. A prime example of this is what happened after Russia's annexation of Crimea and fomentation of instability in Ukraine. Russia's actions highlighted our dependence on the Russian RD-180 rocket engine used in the Atlas V launch vehicle and our dependence on the Russian Soyuz for astronaut transportation to the International Space Station (ISS). Congress, unhappy with Russia's actions, has chosen to address these dependencies by encouraging the development of a domestic counterpart to the Russian RD-180 and providing greater support for the NASA Commercial Crew Program. United Launch Alliance (ULA), the company responsible for the Atlas V, has responded by partnering with a company called Blue Origin to develop an RD-180 replacement that uses different fuel. How all these actions will impact future cost estimates is unclear at this time. However, the potential for impacts must be recognized and addressed.

When gathering additional information, the analyst needs to be aware that a couple of biases can creep in. As we began to incorporate outside information into our analysis we cannot help but

evaluate how this information fits into the story we are telling ourselves about our estimate. If the information fits, we readily accept it. However, if the information is counter to our story, we will tend to reject or minimize it. This is the confirmation bias in action. Therefore, be open minded to information that does not "fit" and aware of actions that lead to the elimination or minimization of inconvenient data.

The second bias is actually a very interesting paradox that psychologists have observed. If we know little about a subject area, our predictive ability in that subject area is very low and our confidence in our predictions is correspondingly low. As we gain more knowledge and data, our predictions improve and so does our confidence. However, at some point, additional knowledge does not improve our predictions, but it does increase our confidence in our predictions. We therefore become stronger advocates for our estimate without improving the quality of our estimate. As we gather more information and broaden our perspective we must be aware of the potential for this "overconfidence bias" and take care not to place more confidence in our estimate than what is directly supported by the data.

History

In my opinion the cost community's greatest asset is our historical data and perspective. We have access to information on all types of projects that document the what, when, why, who, and how. And because of the internet, we are no longer limited to the information we have in our libraries and data bases, or what we can learn through our personal contacts. The amount of information available to the professional cost estimator has never been greater, and the volume grows daily. One word of caution. As you study history be aware of your mind's attempts to confirm preconceived notions (confirmation bias) and a growing sense of rightness as your knowledge increases (overconfidence).

So what can be learned from studying history? Well for starters, we can learn how projects are managed and systems are developed. We can learn about typical problems and issues. We can learn about the challenges that projects have faced and how they have achieved success despite these challenges. We can also learn why projects fail, what were the root causes, what did and did not work. All of this information provides background and context. Background and context broaden our perspective and strengthen the foundation of our own story.

Studying history brings a dose of reality to our estimates. By examining specific technical and programmatic analogies to our estimating problem we anchor ourselves in actual results. We also gain knowledge about realistic boundary conditions for subjective assessments – highly useful for performing sensitivity and uncertainty analyses. History can provide data for developing and supporting ground rules and assumptions (it was done like this in the past, so we can assume it will be done like this in the future).

One of the most important benefits of studying history is the ability to use real cost data to establish base rates. Base rates are simply prior knowledge, such as the knowledge of what it cost to develop analogous systems, calculated values based on a sample such as average cost per pound for developing new spacecraft, or factors or ratios (for example, project management is 10% of the hardware cost) based on actual data. Base rates are extremely useful for quick sanity checks to tell if an estimate is reasonable and thus as a check against rampant optimism. Base rates can also be used to quickly provide decision makers with information that enables real-time decisions, eliminating the need for more time-consuming detailed analyses.

Historical project data will tell you what worked, what did not work, and what unforeseen problems were encountered. This information can be helpful in finding ways to be useful and add value beyond the cost estimate. So how does

this work? Let's say, for example, that you are doing an estimate for a project that is using a certain type of detector. You know from looking at your historical data that this type of detector proved to be a manufacturing challenge on a previous project, causing schedule slips and cost overruns. You take this knowledge to the detector expert on the study team, using it to engage in a conversation around the current state of the art and any changes to the technology since the previous project. What you learn can then be used to inform and substantiate your cost estimate, providing a more credible, supportable, and defendable result. You are adding value because you are putting forth the effort identify and understand the technical challenges and, by sharing this information with the study team, you are making everyone aware of the issue and creating the opportunity to address and solve a specific problem.

Validation

How do you answer the question "is my estimate reasonable?" One way to determine the reasonableness of any estimate is to validate the estimate relative to historical experience. Figure 2 shows an estimate for a science mission plotted against weight. Also on the plot are costs for several completed science missions as well as a trend line.

The simple comparison shown in Figure 2 can be used both as a check and as a communications tool to demonstrate the validity of the estimate. By using a plot like this you can determine if the estimate is consistent with actual costs for similar projects or graphically compare the costs to close analogies. If significant deviations are present you can evaluate the rationale for the deviations and determine if they are credible. Finally, you can demonstrate to the customer the reasonableness of the estimate relative to similar past projects.

Obviously, you should not limit yourself to basic cost versus weight plots when doing validation. What is important is that you compare your cost estimate to the cost of historical analogs. If your estimate seems reasonable when compared to these analogs, then you can validate, for yourself and for your customer, that you have a credible estimate.

Validation by comparison to historical experience is an excellent way to determine the

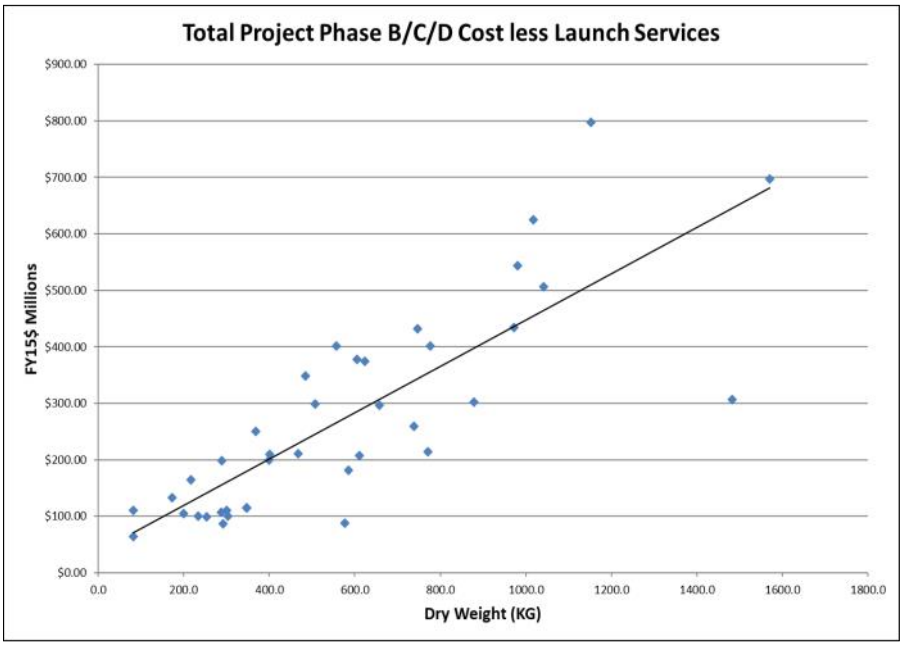

Figure 2. Example of Graphical Estimate Validation.

reasonableness of a cost estimate, but requires that the estimator have access to either a large data set of similar projects or a few close analogies or both. However, we often find ourselves in the difficult position of doing a cost estimate for a project for which we have little or no relevant historical experience. How can the estimator handle this problem?

The first step is to study the data you have. Look for parallels and similarities, if not in whole then at least in part. For example, the systems engineering processes for all large research and development programs should generally be the same. Another example, while the overall system may be different from anything done in the past, certain subsystems or even components might be similar to past efforts.

If you are presented an estimate from another source (remember Anchoring?), an approach that I have used in the past is one I call calibrate and evaluate. In calibrate and evaluate you take the existing estimate along with its technical and programmatic data and reproduce it using a known cost model. You could use PRICE TruePlanning or SEER-H or an in-house model. What is important is that the model gives you the ability to adjust complexity or new design parameters to make the model match the estimate. Once you have calibrated the model to the estimate, you can evaluate the model settings for reasonableness relative to the project's known challenges. You can share this information with the customer. This approach also gives you a model for developing your cost estimate and a mechanism for explaining your estimate relative to previous estimate.

Another approach that we have used is called disaggregation. In disaggregation you take your cost estimate and decompose it into function elements based on historical data. The end product might look something like Figure 3.

Once you have the disaggregated cost you can review the estimate with functional experts, which can be very enlightening. They may be able to validate the results or you can use their knowledge and experience to modify your functional estimate. In either case you will have valuable input that you can use to demonstrate credibility.

One final approach to validating an estimate is to use a Bayesian approach. Bayes Theorem is based on conditional probability, the chance that something is true given a prior state or condition. At the heart of the Bayesian approach is the concept of that there is existing knowledge. Another term for this existing knowledge is the base rate. Now, in the Bayesian world, base rate is used to refer to a probability or a proportion for a population (such as, 30 out of 100 people will get cancer over their lifetime). The way that I am defining base rate for this paper is different. I consider a base rate to be any cost data, model, average, or factor that can be used to quickly evaluate an estimate. For example, the simple linear CER in Figure 2 could be a base rate, or an average cost per pound for a certain type of hardware, or the ratio of project management/

	OCM WBS	Booster Motor	First Stage	Booster Hardware	-	Upper Stage Engine	First Stage Engine	-	-	-	Integ Vehicle	Cost Element TOTAL
V	VEHICLE SEGMENT	$ 338	$ 248	$ 112	$ -	$ 256	$ 399	$ -	$ -	$ -	$ -	$ 1,353
V1	Expendable Hardware Mfg	$ 39	$ 188	$ 14	$ -	$ 98	$ 199	$ -	$ -	$ -		$ 538
V2	Reusable Hdwe Refurb	$ 200	$ -	$ 44	$ -	$ -	$ -	$ -	$ -	$ -		$ 243
V3	Vehicle Spares	$ 13	$ -	$ 8	$ -	$ -	$ -	$ -	$ -	$ -		$ 21
V4	Vehicle Overhauls	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -		$ -
V5	Acceptance Test	$ -	$ -	$ -	$ -	$ 21	$ 32	$ -	$ -	$ -		$ 53
V6	Sustaining Engineering	$ 48	$ 23	$ 18	$ -	$ 82	$ 108	$ -	$ -	$ -		$ 279
V7	Program Mgt & Support	$ 38	$ 37	$ 29	$ -	$ 55	$ 60	$ -	$ -	$ -		$ 218

Figure 3. Example Disaggregation Output.

systems engineering cost to subsystem hardware. When an estimate is close to a base rate that should increase confidence that it is reasonable. When an estimate deviates significantly that should raise questions. Deviation from a base rate does not mean the estimate is incorrect; however, you must be able to explain the rationale for the deviation.

In his award-winning paper, "Bayesian Parametrics, How to Develop a CER with Limited Data, and Even without Data," Christian Smart discusses how Bayesian approaches can be used to estimate cost. I will not attempt go into detail on Christian's methods or findings, only to say that he puts forth an interesting and useful way to apply Bayes' Theorem to the problem of cost estimating with very little data. The same approach could possibly be used to validate an estimate when there is little or no directly applicable historical data by analytically comparing related historical information to the estimate.

The use of validation to counteract biases should be obvious. Validation offers a powerful means to battle any bias by injecting a dose of reality through the requirement that the estimate be explainable relative to past experience. When you have a large historical data set of comparable projects, validation is easy. However, when historical data is non-existent or lacking in some way (like age), the estimator must be creative in finding ways to use whatever information, techniques, and tools are available to determine if the estimate is reasonable. Always be aware that the less historical truth available for validation, the greater the likelihood of a biased estimate.

Risk and Uncertainty

In his book The Signal and the Noise, Nate Silver tells the story of a flood in Grand Forks, North Dakota. The flood forced the evacuation of nearly all of the city's 50,000 residents and caused billions of dollars in damage and clean-up costs. However, the flood was not a surprise. Due to unusually heavy snowfall (even by North Dakota standards) the National Weather Service had predicted that the nearby Red River would crest at 49 feet, two feet below the levee height of 51 feet. What the Weather Service did not tell the city leaders of Grand Forks is that the margin of error in their forecast was plus or minus 9 feet. In reality, the margin of error implied about a 35 percent chance of the river rising above the levee, and the actual crest was 54 feet, inundating the town.

Obviously, failing to communicate risk and uncertainty can have serious consequences when making predictions and cost estimates. Point estimates create a false sense of certainty and deprive decision makers of useful information. It is also hubris on our part to believe that we can forecast the financial outcome of a technically complex, multiyear project with such a high degree of accuracy.

For the purposes of this paper, I define risk as the chance of loss, the chance that something could go wrong or not work as planned. Uncertainty is the indefiniteness about the outcome, the margin of error. Most of the time cost estimators use the term Risk Analysis to cover both risk and uncertainty. However, I argue that the Confidence Level (CL) analysis is a broader and therefore more appropriate term.

One mistake estimators can make is to treat uncertainty as only model error and risk as only those items identified on the project's risk list (or 5x5 matrix). Uncertainty includes not only model error but also uncertainty on the model inputs, especially those inputs that are subjective. When the estimator limits the scope of the confidence level analysis it can create a false sense of security which can lead to uninformed decisions.

The focus of a sensitivity analysis should be on the subjective inputs that are incorporated into the analysis. As we well know, numerous

subjective judgments and assessments must be made in the development of a cost estimate. In many cases, these judgments have significant consequences on the final estimate value. A sensitivity analysis is an excellent way to quantify the impact of these judgments in a way that can be used to develop an uncertainty range around the point estimate, and identify which judgments have a significant impact on the cost.

By combining the results of the sensitivity analysis with a description of the conditions that describe the extreme points, the analyst is providing the decision maker with valuable context for understanding how different assumptions influence the possible cost outcomes. This helps the decision maker understand what is and what is not important to the estimate and what decisions could affect the outcome.

When we assign probability distribution functions to input or model settings, or when we assign probabilities to specific outcomes, we have moved into the realm of the confidence level analysis. A good confidence level analysis accounts for uncertainty in our inputs, uncertainty in our judgments, uncertainty in our estimating methods, and project risk. The assignment of probabilities (outside of those derived through statistical means) is often highly subjective. The human mind is not good with probabilities (if it were, then casinos and lotteries would not exist). We tend to overestimate the occurrence of low probability events and underestimate the occurrence of high probability events. Therefore, be clear with your customer or stakeholder on how you derived the uncertainties and probabilities.

Despite the sometimes highly subjective nature of a confidence level analysis, by providing a probabilistic range or s-curve, the estimator is giving the decision maker a sense of the risk exposure assumed when a project moves forward at a given funding level. Knowledge of this risk information will hopefully influence organizations to make more rationale, and less biased decisions around funding and project content.

One final note about risk and uncertainty. The NASA cost community has noticed that the implementation of a requirement for joint cost schedule confidence level analyses (JCL) on all major projects has changed the conversation about cost and schedule estimates. A shift has occurred from a discussion around the validity of the estimate to a discussion around the inputs to the JCL. This focus away from outcomes and towards the factors that affect the results appears to be leading to better overall management decisions on funding levels and project risk. Hopefully this represents a trend towards using cost estimating and analysis products to reduce cost overruns and schedule slips.

The Value of Expertise

The combination of simple mathematical models and expert opinion provides the best predictions. This observation has been made by experts in the field of human behavior and decision making such as Daniel Kahneman, Nate Silver, Malcolm Gladwell, and Douglas Hubbard. It has also been noted by leaders in the field of parametric estimating, such as Joe Hamaker. In his paper "What are Quality Cost Estimates or the 260 Hz Cost Estimate" Joe makes the following statement:

> "But my point is that many of us close to the practice do have some innate and intuitive ability, honed by years of being associated with the cost estimating game, that is usually pretty reliable when it comes to judging the quality of a cost estimate."

While this observation seems counterintuitive in light of all the previous discussions in this paper on biases in our thinking, there actually is strong evidence to support it. The key is that the models must be logical and the experts must be real experts. The models get you an answer, the expert evaluates that answer to see if it really fits the data.

You can apply your own expert judgment by simply asking the "why" question. For example, if you have an estimate that deviates significantly

from the validation data, you need to ask "why?" In asking "why" you are looking for technical or programmatic explanations for the deviations. The danger in asking the "why" question is that it can lead to the confirmation bias: you overemphasize data that supports your result while underemphasizing or dismissing data that might lead to a different outcome. However, don't let that concern stop you from questioning your estimates. One approach to counterbalance the tendency to confirm our judgments is to have a different expert examine our estimate and ask the "why not" question.

Our subconscious can process a tremendous amount of data and when properly trained and combined with our natural ability to simplify complex situations, becomes a powerful tool. In his book Blink, Malcolm Gladwell tells the story of an ancient Greek statue that was purchased by the Getty Museum for millions of dollars. The museum had carefully checked the history of the statue and had performed a sophisticated scientific investigation to determine its legitimacy. However, experts in ancient Greek artifacts who saw the statue knew almost immediately that it was a fake.

Just like experts in ancient Greek artifacts, our minds can be trained to recognize good cost estimates and bad cost estimates. Malcolm Gladwell makes this point in Blink: "Just as we can teach ourselves to think logically and deliberately, we can also teach ourselves to make better snap judgments." So how do we, as cost estimators and analysts, teach ourselves?

As Joe Hamaker previously pointed out, it helps to have years of experience. Unfortunately, not everyone has years of experience. So if you are new to the profession, maximize the experiences that you have had. Learn as much as you can from them, not just how to use the models or develop and present estimates (and these are important skills), but also take the opportunity to learn something about technology, systems design, requirements, organizational behavior, management, etc. As Yogi Berra said, "you can observe a lot by just watching."

A great source of information for building up your expert knowledge are our databases and libraries. I have already covered the value of historical data, so I will not repeat it here. However, I do want to reiterate the value of using historical data to establish "base rates" that can be used to test the credibility of any estimate. You don't have to walk around with tables of numbers in your head, but you should be familiar enough with historical experience so that you can sense the value of a project to at least an order of magnitude.

My first job in the cost profession was in analyzing data and developing cost models. I quickly figured that to do that job, I had to learn something about the space systems I was analyzing. I did not have to know enough to actually design and build the systems, but I did need to have a layman's understanding of how they worked and what characteristics about them really drove cost. When I began working at NASA, I got the opportunity to spend more time talking to professionals in other technical disciplines. These experts filled in gaps in my knowledge and helped me understand the state of the art, and what was not difficult versus what was a real technical challenge. I strongly encourage every estimator to spend time talking to technical experts. Yes, they can be as biased as the rest of us. But by combining their knowledge and expertise with historical information, you can develop a good understanding of what is and is not important to the cost of a system.

Education is very beneficial and I certainly encourage everyone to get as much as possible. Obviously, science, math, and engineering are all extremely useful to the cost estimator. However, don't discount the value of non-technical courses, especially those that encourage creative thinking and develop communications skills. Also useful are courses that increase your technical knowledge in those systems that are the primary

focus of your cost estimates and analyses. As part of your education, you should take training in cost estimating and analysis as well as in related disciplines such as earned value management and scheduling. Becoming certified is a great way to demonstrate your knowledge and expertise.

Reading is a great way to increase your general knowledge. This paper is the result of an intentional effort I undertook several years ago to read more non-fiction. I started by reading books on the development of space systems, then I read books about the development of other technologies. I also read popular books about human behavior and decision making, such as "Freakonomics" by Steven Levitt and Stephen Dubner; and "The Wisdom of Crowds" by James Surowiecki. I began to discuss what I was reading with other cost professionals, and their own readings and feedback led me to discover several of the books that became the foundation for my understanding of how biases affect cost estimates.

When you look for what to read let curiosity be your guide. Obviously, books and articles that pertain to cost estimating, cost analysis, mathematical modeling, and relevant technical subjects are good places to start. However, don't overlook biographies, books on organizational behavior, or other fields of science. I have found that while the particulars may be different, other disciplines have dealt with problems and issues that are similar to those that we cost professionals face. We may have different jobs and responsibilities, but at the end of the day we are all human.

An excellent way to grow the knowledge needed to be a cost expert is to become engaged in the greater professional community. Through organizations such as ICEAA you are exposed to new ideas and ways of doing estimates and analyses. You can learn from the experiences of other professionals and use that knowledge to develop better cost estimates. You can also develop relationships with leaders in the cost profession, contacts who will prove useful in helping you perform better estimates or improve your estimating capabilities. As mentioned previously, ICEAA and other professional societies also offer training and certification, both valuable ways by which you can grow professionally.

Finally, allow me to add this one final recommendation: be open to new data, thoughts, and ideas. Our human nature is to think we have it all figured out. Our biases enable us to fool ourselves into believing that we are being rational when in fact we are only responding to the loudest voice in the room, looking for plausible explanations, and confirming what we already believe. It takes courage to question ourselves and such questioning can be downright uncomfortable. But it is only through an openness to the possibility that we could be wrong that we can create the space that enables us to grow and mature as professionals.

Telling Your Story

As I discussed earlier, we are more influenced by stories and anecdotes than we are by facts and data. Therefore, to make a convincing argument that your cost estimate is good, you have to tell a good story. What is a good story? In my opinion, it is one that relates facts and data to logical action and speaks in a language the customer understands.

Part of being able to tell a good story is understanding your customer, especially how your customer views the world. The most basic understanding of your customer begins with knowing what is and is not important to them. For example, are they trying to design a program to fit within a predetermined budget profile? At they trying to sell a new start? Is the estimate in support of a Key Decision Point (KDP)? Or are you doing an analysis of alternatives?

Each of these scenarios places different requirements on the project or team lead, and thus different requirements on the estimator. If

the goal is to fit a program within a predetermined budget, the estimating requirement becomes how much capability can be bought for the money. If the purpose is a new start, there will likely be pressure to keep the cost as low as possible. If the estimate is in support of a KDP, then the project manager will worry that an unfavorable outcome could derail the project or lead to cancellation. Knowing and understanding what your customer is facing can help you craft your story so that it aligns with your customer's goals. Your job is to help your customer succeed. But success is not telling them what they want to hear, but rather what they need to hear.

It is also important to try and have some idea of what your customer believes. Almost everyone who has had any experience in project management has stories of how cost was affected (or not affected) by something that happened. Often these experiences become beliefs, and once we believe in something it has a direct influence on how we respond to new information. In fact, psychological research shows that once we believe something, the confirmation bias kicks in, causing us to give more weight to information that agrees with our position and to discount or disregard information that disagrees with our belief (beliefs trump statistics). Thus, understanding your customer's belief system (at least with regards to project management and cost estimating) can help you prepare your story in a way that gives your estimate a higher probability of being understood.

So what do you do if your estimate runs counter to a customer's strongly held beliefs? Chris Mooney, in an article for *Mother Jones* titled "The Science of Why We Don't Believe Science" offers the following advice: "If you want someone to accept new evidence, make sure to present it to them in a context that doesn't trigger a defensive, emotional reaction." Thus it is important that your analysis is explained in the context of their worldview, using language and metaphors that they are comfortable with and therefore less likely to create a defensive reaction. Christie Aschwanden, writing for the website FiveThirtyEight gives similar advice in an article titled "Your Brain Is Primed To Reach False Conclusions." Here is what Christie has to say:

> If you want someone to accept information that contradicts what they already know, you have to find a story they can buy into. That requires bridging the narrative they've already constructed to a new one that is both true and allows them to remain the kind of person they believe themselves to be.

Therefore, to effectively tell your cost estimate story you must know what is important to your customer and understand and be sensitive to what your customer believes. With that knowledge you should begin your story with the facts and data used in your estimate. These should be the facts and data (including estimated parameters) on which everyone can agree. You can then introduce other pertinent information, such as base rates and historical experience. Be prepared to defend your decisions to include information that may contradict the customer's beliefs or worldview.

The next step in telling your story is to define the relationship between the objective information (facts, data, base rates, etc.) and your subjective assessments. My rule of thumb is to make this part transparent and keep it simple. At this point you introduce and review the ground rules and assumptions needed to facilitate the estimate.

Once you move into the subjective aspect of your analysis you have entered the realm where biases are more likely to occur. The best way to deal with possibility of biases and subjectivity is with an uncertainty analysis. As I stated earlier, by combining the results of the sensitivity analysis with a description of the conditions that describe the extreme points, the analyst is providing the decision maker with valuable context for understanding how different assumptions influence possible cost outcomes. By providing a

range of possible outcomes that vary depending upon one's beliefs, you are giving the decision maker the space to adjust their belief system without putting them in an overtly defensive position.

I want to reiterate the importance of validating your results to the telling of your story. Bear in mind that your customer will either accept your validation, question the data you use in your validation, or try to introduce new (and sometimes irrelevant) data into the discussion. Always be prepared to defend your approach to validation and be willing to address any new information.

The goal of your cost analysis story is to show that your estimate is a logical outcome of the evidence. Much like a lawyer, you have built your case around facts and data, relevant historical experience, consistent subjective assessments, an examination of the uncertainties, and a comparison to valid, real world experience. As one of our senior analysts, Richard Webb, likes to say, show that your estimate is credible, supportable, and defendable.

Signs of a (Possibly) Overtly Biased Estimate

Even if you do everything right, bias is going to creep into your estimate. After all, everyone involved in the cost estimate is human, and the psychological evidence is overwhelming: humans are irrational, biased creatures. If we accept for the moment that no estimate can be totally unbiased, how do we know if our estimate is too biased? While I don't have a foolproof tried and tested approach, I have identified four things to be on the lookout for. The appearance of any of these signs does not automatically mean your estimate is overtly biased. Use them as warning flags that something could be wrong, and that further analysis may be needed. Be aware that when you are trying to find support for a decision, it is easy to fall into the trap of the confirmation bias.

The first red flag that you (or someone) may have biased an estimate is the discarding of applicable data. In this case, I am talking about data that could be used for validation or as an analogy or as part of a data set for developing a cost estimating relationship (CER). An example of this would be ignoring an appropriate analogy that has a higher cost than your estimate.

A red flag that is in some ways the opposite of the previous one is the placing of significant emphasis on a single expert opinion, data point, or other bit of information. An example of this is when you base your estimate on one or two pieces of data while either failing to validate the information or ignoring other data that gives a contradictory conclusion. Because sometimes we do not have good historical data, this sign can be the result of severe limitations in your data set or other available information, and not the result of a bias.

The use of an inappropriate analogy or extrapolation to support, perform, or validate an estimate is a sign that you are trying to bias the estimate to obtain a certain outcome. An analogy should always embody key characteristics of the system being estimated such as function, performance, and development approach. If you cannot establish clear similarities between the system you are estimating and an analogy, you should not use that data. It would be like basing the cost of a rocket engine on a robotic spacecraft. Inappropriate extrapolation can occur when you try to use the cost experience of a small, simple system to estimate or validate the cost of a larger, more complex system. Over the years I have observed that small teams, given a focused task and assured funding, can accomplish amazing things, such as the development of a new technology or the building of a small spacecraft. While these experiences provide useful information for cost estimating, these experiences are not appropriate for estimating larger, more complex missions.

Anytime your estimate deviates significantly from the historical trend and/or reasonable analogs that is a sign of possible bias. There may be good reasons for the deviation. However, if the deviation is significantly below historical experience your estimate should be examined closely. Once again, it is all too easy to find evidence to support your position when you are looking for it, so I recommend having an independent set of eyes review your work.

Any estimate that depends on changes in historical business practices should immediately raise a red flag. Examples do exist of projects or companies (i.e. SpaceX) who were able, by doing things differently, to achieve success for significantly less money than the historical record would predict. Whenever I am faced with a customer who says that they can do it for significantly less than it has been done before, I simply ask them "how?" If the customer or study team can build a story of how they are going to operate differently, I will use that in the basis of my estimate. But I will also do a sensitivity analysis showing what will happen if they actually do "business as usual."

We are rightfully proud of our hard work. When you have put significant time and energy into an estimate or analysis you are going to naturally be defensive if your judgment is questioned. However, being unwilling to accept or incorporate new data into your analysis is usually a sign that you are overconfident and therefore biased. Not all new information is useful or appropriate, but neither should it be dismissed simply because it does not support your results. Anytime someone questions your judgment with regards to the subjective part of the estimate treat it as an opportunity to test your reasoning by telling your story and seeing if the audience supports your conclusions. Being open to new ideas or perspectives is an excellent way to guard against biases.

Summary and Conclusion

I realize that I covered a tremendous amount of material in this paper. I like to believe that all of it is useful to the cost analyst, however; there are four key points that I want everyone to remember.

First, we are all biased, and these biases affect how we do are estimates and how our estimates are received. These biases cause us to put too much faith in our own abilities, carefully select information that supports our conclusions, and be more influenced by what people tell us than by facts and data. We are not rationale thinkers. While we cannot force ourselves to become unbiased, we can learn to recognize what biases look like and take steps to minimize their impact.

Second, you can control your behavior, but you can only influence others. Being proactive to minimize the impact of bias on your cost estimates and analyses is smart. Trying to force others to do the same is futile. Focus on building a credible, supportable, and defendable estimate. Understand what your customer needs and why. Use that information to be add value and make a difference.

Third, the cost community's greatest asset is our historical data and perspective. Historical data provides background information that can increase knowledge and understanding. Historical data provides ground truth that can be used to balance information from other sources. Use historical data to bound uncertainty, validate your estimates, and establish base rates.

My final point is simply this: a valuable cost estimate (or analysis) is not one that gives the customer the answer they want, but gives them the answer they need. Dare to go beyond providing numbers (as valuable as those numbers might be) to providing true value to enabling customer success. That does not mean the customer will always agree with your answer. But, if you can get the customer to respect what you have done, to recognize that even in

disagreement you are working to further their objectives, they more likely to be influenced by your analysis.

Being a cost estimator is hard. Everything that goes into an estimate or analysis can be questioned. We are often pressured to reach a preconceived conclusion. It takes courage, it takes knowledge, and it takes experience to produce an objective result, a result that adds value. And it takes an understanding of how estimates can be biased and how to overcome those biases. I wish you well on your journey.

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