Cost Estimation: A Psychological Framework for Mitigating Bias

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Abstract— **Developing robust cost estimates early in the acquisition life cycle is difficult. Mission needs are driving numerous concept architectures that are circulating within the minds of stakeholders, unknowns flourish throughout the solution space, budgets are being formulated and everyone wants immediate answers. Within the thought leader communities' there is optimism (for a perfect solution), risk aversion and/or ignorance, new or enhanced system capability and latent estimating bias. Arriving at a balanced, low, or non-bias solutions and cost estimates that accurately reflect system scope, critical technologies, risks, schedules, and realistic and defendable costs that provide a viable program and stand the test of time are difficult to develop. Recognizing biases among stake holders is not always apparent and can impact objective cost estimate outcomes (will cost) from desired outputs or driven by budget-based estimates that are in the minds of thought leaders (should cost). Obtaining robust cost estimates requires following a rigorous process culminating in an initial point estimate, then expanding it with uncertainties, risks, and other factors that result in, simple averaging, analogies and perhaps the mean of a Monte Carlo solution result among other probabilistic solutions. In all cases, the ground rules, and assumptions, often justified, may be biased with expert opinion, a drive to meet notional budgets, a need to implement the latest system design approach or other influences. As a result, there may be implicit flaws that do not surface until much later in the lifecycle, leading to cost growth and schedule delays. This paper investigates common psychological bias types in decision making, assesses root causes, and evaluates resulting impacts to cost estimates; then we provide methods to identify and apply corrective action that can minimize bias within the initial cost estimate. We will assess historical cost growth in Department of Defense programs; then investigate some common behavioral model tools such as "Judge-Advisor System", "Weight-of-Advice", Averaging, and Overconfidence characteristics that can simultaneously influence an estimate outcome. Two examples will provide methods to implement tools that result in an approach to support development of non-bias, high quality, and defendable cost estimates early in program formulation. Furthermore, we will provide an approach to support clear alignment of mission scope, technology development and fielding schedules to the forecast cost estimates. Future work will investigate less common and unconventional biases, the Analytical Hierarchy Process, Bayesian models, and human versus algorithm advice that may influence robust and enduring cost estimates throughout the life cycle.**

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1. INTRODUCTION

Recognizing bias in general is not always easy. When developing cost estimates, identifying bias can be even more difficult due to the complexity of assembling an estimate from multiple sources. For example, historical data, similar programs, analogies, subject matter expert opinion and inputs to parametric models among others. As far back as 1993 Drezner, et al in their RAND report states, "A systematic bias in cost estimates can undermine the basis of resource allocation decisions, an important problem in a tight budget environment." [1] They go on to say that "…cost estimates are systematically biased (low) because of the intense competition between new programs for resources and the desire to win new contracts in competitive environments. Thus, industry is expected to underbid the true cost of the program…However, little quantitative evidence has supported this assertion." At the time there were many more Major Capability Acquisition (MCA)[1] "new program starts" than today. New start "roll offs" began in the 2000's when sequestration, recurring continuing resolutions and significant cost overruns and schedule delays were common.

[1] The MCA is one of a recent DoD Adaptive Acquisition Pathway, also known as a Major Defense Acquisition Program (MDAP).

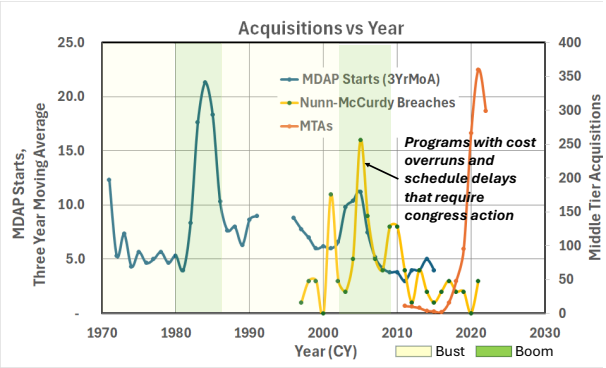


Figure 1. Major Acquisition and AAFP new starts with Nun-McCurdy breaches overlay

As a result, the Adaptive Acquisition Framework Pathways (AAFP) were developed to provide DoD streamlined acquisition methods to meet mission needs and improve rapid capability deployment using a Minimum Viable Product (MVP) model. The MDAP and AAFP new starts with the Nunn-McCurdy Breaches[2] are illustrated in Figure 1. Now, there are many more Middle Tier Acquisitions (MTAs) due to the need for speedy acquisitions. These MTAs are designed to have reduced qualifications, durations and milestone reviews to provide more efficient acquisitions and risk reduction prior to entering an MCA. Although, regardless of the acquisition format, bias in estimating is still prevalent and should be addressed. This is evidenced by the 2024 GAO "Weapon Systems Annual Assessment" report to congressional committees. [2] The recent MTAs continue to report (schedule) delays to key milestones intended to demonstrate capability. As a result, there may be cost growth.

Improving the quality of cost estimates, is important. We will investigate sources of bias and cognitive bias found in estimates, provide the common impact(s) (like a Nunn-McCurdy breach or delays in capability fielding), provide recommendations to minimize bias with examples and discuss future research. Future work will investigate less common and unconventional biases. Additionally, we will evaluate the implementation of the analytical hierarchy process (AHP), Bayesian models, and human versus algorithm advice that may influence robust and enduring cost estimates throughout the life cycle.

2. SOURCES

Bias types number the hundreds. Two main categories are conscious and unconscious. Murphy groups them into five areas: 1) cognitive, 2) prejudice, 3) contextual, 4) implicit and 5) statistical. [3]

Dror in his description, provides three groups divided into categories of cognitive biases that can be broken down into eight fundamental factors in expert decision making which is more aligned with technical decision making like cost estimating. These are illustrated in Figure 2. [4] He goes on to point out the categories: a) case specific, b) environment, culture and experience driven, and c) human nature and behavior.

Summarizing, 1) The data considers specific analysis and how the raw data is processed, 2) Reference materials can be how the content is interpreted, 3) Contextual information can be information that is not necessarily relevant to the subject but may assist (or hinder) bias, 4) Base rate is expert opinion based on experience, 5) Organizational factors are centered on domain type such as a government or commercial organization where goals may vary, 6) Education and training play an important role in how work (analysis) is conducted, 7) Personal factors include personality, motivation, ideology and beliefs as well as level of risk taking, 8) Human and cognitive factors and the brain include workings of the brain, capacity and how it processes information (including group settings).

All of these cases can play a part in estimating bias at some level due to human nature. To support our effort, we look at the Government Accountability Office's (GAO) guidance. The GAO Cost Estimating and Assessment Guide provides the following: Cost estimating *"[b]ias can originate from different sources, such as over-optimism, group think, dominating personalities, inexperience, or pressure from management."* As a result, understanding where bias within an estimate is can be difficult to identify and mitigate. Although there are mitigation strategies, used today. Most commonly is the risk adjusted estimate (e.g., Monte Carlo analysis). However, it may not always capture all bias. [5]

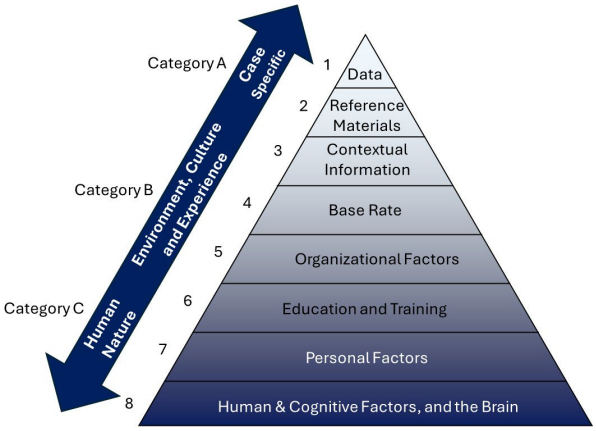


Figure 2. Dror's hierarchy of cognitive bias types

Bias sources identified in the GAO guidebook can be mapped to Dror's eight cognitive biases when developing cost estimates. Table 1 provides a summary highlighting Dror bias to specific GAO sources that may drive cost estimate outcomes. In Section 3 we discuss some of impacts that can

[2] A Nunn-McCurdy breach is when the Department of Defense (DOD) is required to report to Congress whenever a Major Defense Acquisition Program (MDAP) experiences cost overruns that exceed certain thresholds. More information can be found at: https://www.dau.edu/glossary/nunn-mccurdy-breach.

occur within bias is shown to be present. And then we evaluate them, and address mitigation strategies to support robust cost estimates that can "stand the test of time".

For over-optimism, four bias types dominate. In a group think scenario there are five bias drivers that can dominate. Dominating personalities is driven by one. Inexperience has two. Pressure from management contain two. Data bias have three dominant bias drivers.

Table 1. GAO to Dror Biases

Item	Bias Sources	1. Data	2. Reference Materials	3. Contectual Information	4. Base Rate	5. Organizational Factors	6. Education and Training	7. Personal Factors	8. Human & Cognitive Factors, and the Brain
A	Over-Optimism	◆	◆		◆			◆	
B	Group Think			◆	◆	◆		◆	◆
C	Dominating Personalities							◆	
D	Inexperience		◆				◆		
E	Pressure from Managmenet					◆		◆	
F	Data Bias	◆	◆	◆					

3. IMPACTS

This section investigates bias impacts related to cost estimating development. Section 4 further evaluates the bias and provides representative impacts and mitigation strategies.

Over-Optimism

Having data that is optimistic can influence estimates to support a higher technology readiness level (TRL) or manufacturing readiness level (MRL) rather than a more realistic rating or capability respectively. The result will likely be higher development costs and schedule delays due to the additional TRL advancement required and increase in MRL process maturity. In other cases, the estimator/analyst(s) may claim the available knowledge is more than claimed leading to higher programmatic maturity levels. Unfortunately, over-optimism leads to inefficiency during program execution. In other cases, using reference materials that are adjacent to, or not directly relevant to the capability being estimated may lead the team to make incorrect assumptions about key technical performance. In the case of a base rate (also known as subject matter experts [SME]), which is an important asset that subject matter experts bring from prior work experience, may try to apply a solution that is not appropriate to the capability need or may have a flawed approach. This could result in more complexity or require more development. Personal factors can significantly impact decisions both favorable and unfavorable based on data and their experience. [4]

Group Think

Group Think, is the practice of thinking or making decisions as a group in a way that discourages creativity or individual responsibility. Stated another way, it is a psychological and sociological phenomenon in which members of a group will conform to majority opinion to maintain group harmony rather than stating their own opinions. This can happen if many of the stakeholders (participants) are of similar disposition (for example like the group leader or dominant personality). The result is that team members may offer irrelevant information to estimators or may not accurately capture all key information for the estimate. A SME may offer an expert solution that may not fit the requirements. Team members may suggest using the standard organizational solutions rather than providing a more creative or tailored solution limiting capability. Team members may have another agenda or dominant personality driving to specific solutions or inputs. Other cognitive factors may simplify system architectures or suppress creative solutions. In all instants, cost estimates can be guided in anomalous directions due to limited creativity, misguided information or efforts to maintain group harmony.

Dominating Personalities

Participants within a dominate personality often display assertiveness, aggressiveness, confidence and/or a strong presence. As a result, they may dominate conversations or group dominance resulting in opinions that may or may not be based on sound logic and relevant offerings. This can lead to misguided or incorrect cost inputs.

Inexperience

The basic definition of inexperience is lacking knowledge, skill or wisdom gained from experience. In the field of cost estimating, inexperience is generally not having the skills and understanding of how to assemble a cost estimate from technical inputs, understanding of a system lifecycle and knowledge of historical data and estimating relationships among others. It can be a detriment to developing a complete, robust and defendable estimate.

Pressure from Management

In general, managers (leadership) at all levels have good intentions. However, in some cases leadership, for some requirements, goals, or competitions may impose pressure to be successful demanding unrealistic targets, deadlines, or performance expectations to "win". In many cases, cost estimates can be biased based on this pressure. In other cases, (the pressure) can cause workplace stress which in turn can be causal to other groups to make erroneous decisions that can jeopardize projects or competitions.

Data Bias

Incomplete or inaccurate data collection and/or analysis can lead to data bias that, if not crosschecked, can lead to misinformation and corrupt inputs to cost estimates. In recent times, some types of data bias include five common types: 1)

confirmation bias, 2) historical bias, 3) selection bias, 4) survivorship bias, and 5) availability bias. [6]

The impacts of bias have strong interactions with each other. One can influence another driving ground rules and assumptions. (GR&A).

4. Evaluating and Mitigating

All estimates contain bias. [7] Moreover, the human interaction of each is interrelated and can influence each other driving cost estimates. To overcome this, acknowledgement of the existence of bias is needed to move beyond it, and develop mitigation strategies to apply objective data driven inputs. Second, when "blind" bias is present, a logical process can be used to mitigate some of these short comings. [4] Third, to support objective evaluation and mitigation of cost bias, estimators need to sort out data and focus solely on the relevant data and not "back into a solution". The following provides guidance to bias mitigating strategies to common estimating bias within the GAO cost estimating process.

A first step in developing an objective balanced cost estimate is to gather and structure the estimate using proven processes. [5] Next, in the assessment phase, using the data obtained, assemble the relevant cost estimating inputs. This is also the when the estimator will "establish the estimate's boundaries using a common set of standards and judgments about past, present, or future conditions" inserting bias within those judgements. Figure 3 illustrates a bias evaluation process following point estimate development to determine a) if there is bias and b) where bias might be present.

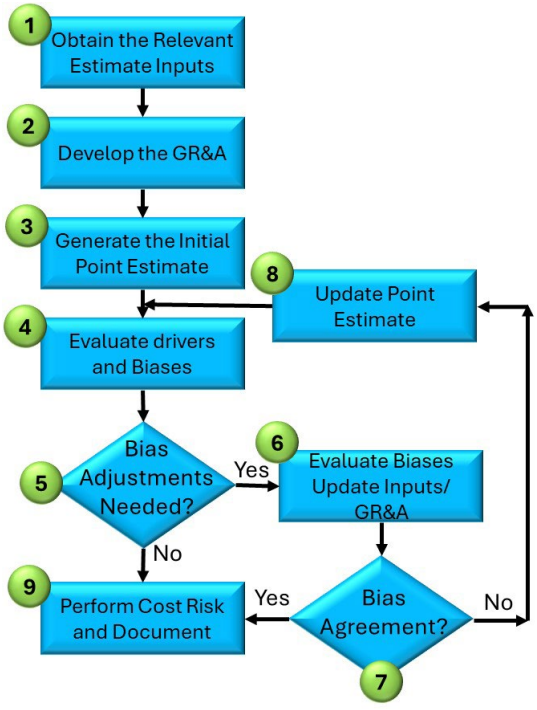


Figure 3. Bias evaluation process

The bias sources identified in Table 1 show that some evaluations and mitigation strategies may overlap with others. To organize these, they are listed within each bias source group but may apply to one or more of the sources. Appendix B provides a recap of the sources and is expanded to include possible impacts and mitigation strategies outlined in Table 1. They are expanded in this section. Following a discussion of bias mitigations, we provide additional tools to validate the recommended advice that may be provided. Using the Weight-of-Advice (WOA) and Judge Advisor System (JAS) we can augment the bias sources with credible inputs from the human factor point of view with the inclusion of the experience and skills of the participants. Last, we introduce how further objective decision making can be obtained when integrating the analytical hierarchy process (AHP) into the lower-level elements of the decision-making process.

Over-Optimism

Mitigating over-optimism when reviewing information alone or within a group is essential for making balanced decisions. [8,9,10] The following three strategies can help:

1) Use of encouragement of critical thinking and dissent (differ in opinion) in a courteous and structured environment can expose blind spots and provide a more realistic view or possible technical inputs and ranges for cost risk.

2) Establishment of one or more pre-mortem scenarios can be used by the group to imagine the project has failed. Then working backward, identify potential root causes of the failure. This method forces stakeholders to think of potential risks and how to mitigate them (early) and provide guidance to the cost risk analysis.

3) Provide a set conservative benchmarks versus setting aggressive cost, schedule or technical goals that may be significantly "out of family" from historical solutions. Instead, adopt a more conservative approaches to forecasting performance outcomes, timelines, and budgets.[3] Implementing more conservative guidelines helps avoid setting unrealistic expectations, and adds realism and credibility to the estimates.

4) When attempting to understand the impact cognition can have on decision making and the development of biases, it is important to be familiar with the fallible nature of human perception. Due to biological, environmental, and psychological factors, perceptions of reality can become distorted leading individuals to come to false conclusions based on a limited amount of information. These cognitive distortions are irrational thought patterns that

[3] This can be modeled using the Space Development Agency (SDA) Tranche approach, delivering new defense space capabilities in two-year tranches - with each tranche improving upon the last - and informing the development

can skew perception and lead to faulty reasoning. They often manifest as negative or exaggerated interpretations of reality, influencing how individuals process information, react to situations, and make decisions. While not an exhaustive list, the table in Appendix C provides samples of some of the common distortions and their impact on individual decision making.

If gone unchecked, cognitive distortions can significantly affect decision-making bias in several ways:

1. Confirmation Bias:

   Impact: Distorted thinking can cause individuals to focus on information that confirms their existing beliefs while ignoring contradictory evidence. This can lead to poor decision-making, as critical viewpoints may be overlooked.

2. Anchoring Bias:

   Impact: Initial thoughts or experiences may disproportionately influence subsequent judgments. If a person's first impression is based on a cognitive distortion, all related decisions might be skewed in the same direction.

3. Framing Effect:

   Impact: The way information is presented can trigger cognitive distortions. For example, framing a choice in terms of potential loss may lead to more risk-averse decisions, while presenting it as a gain may encourage risk-taking.

4. Availability Heuristic:

   Impact: Cognitive distortions can affect how readily examples come to mind. If someone has had a particularly negative experience, they might overestimate the likelihood of that event happening again, leading to overly cautious decisions.

5. Emotional Reasoning:

   Impact: Decisions based on feelings rather than facts can be heavily influenced by cognitive distortions. If someone feels anxious about a situation, they might perceive it as more dangerous than it actually is, leading to avoidance rather than constructive action.

6. Self-fulfilling Prophecies:

   Impact: Distorted beliefs can lead to behaviors that reinforce those beliefs. For example, if someone believes they will fail, they might not prepare adequately, thus increasing the likelihood of failure.

7. Sunk Cost Fallacy:

   Impact: Cognitive distortions can make individuals cling to past decisions, leading them to continue investing time or resources into failing projects due to the fear of loss rather than evaluating current merits.

Recognizing cognitive distortions is crucial for mitigating their impact on decision-making. By challenging these irrational thought patterns, individuals can improve their judgment and make more balanced, rational choices. Combating decision-making bias involves several strategies that promote critical thinking and reduce the influence of cognitive distortions. Here are some effective approaches:

1. Awareness and Education:

   Recognize Biases: Learn about common cognitive biases and distortions. Understanding them is the first step to mitigating their effects.

   Self-Reflection: Regularly evaluate your thought processes and decisions to identify any biases that may be influencing them.

2. Structured Decision-Making:

   Use Decision-Making Frameworks: Implement frameworks like SWOT analysis (Strengths, Weaknesses, Opportunities, Threats) or a decision matrix to systematically evaluate options.

   List Pros and Cons: Write down the advantages and disadvantages of each choice to visualize the decision clearly.

3. Seek Diverse Perspectives:

   Consult Others: Engage with colleagues, friends, or mentors who may have different viewpoints. This can help identify biases you might overlook.

   Encourage Dissent: Create an environment where questioning and challenging ideas is welcomed to prevent groupthink.

4. Gather Data and Evidence:

   Base Decisions on Data: Use empirical evidence and data analysis to inform your decisions, rather than relying solely on intuition or feelings.

   Challenge Assumptions: Verify the facts behind your assumptions before acting on them.

5. Pause and Reflect:

   Take Your Time: Avoid snap decisions. Allow time for reflection to process information more thoroughly.

   Use "Cooling-Off" Periods: If emotions are running high, take a break before making a decision to prevent emotional reasoning.

6. Develop Critical Thinking Skills:

   Question Your Thought Processes: Ask yourself whether your thoughts are based on facts or distortions.

   Practice Cognitive Restructuring: Challenge negative thoughts and replace them with more balanced, rational ones.

7. Set Clear Criteria:

   Define Decision Criteria: Establish clear, objective criteria for evaluating options ahead of time to reduce subjective biases.

   Stick to the Criteria: Use your established criteria as a guide during the decision-making process.

of those capabilities with the latest available technology advancements and intelligence assessments. https://www.sda.mil/

8. Limit Information Overload:

   Prioritize Information: Focus on the most relevant data to avoid being overwhelmed by excessive information that can lead to paralysis by analysis.

   Avoid Confirmation Bias: Seek out information that contradicts your views to gain a more balanced perspective.

9. Regular Review and Adjustment:

   Evaluate Outcomes: After a decision is made, review the outcomes to assess the effectiveness of your choice and learn from mistakes.

   Be Open to Change: Be willing to adjust your decisions based on new information or changing circumstances.

By applying these strategies, one can enhance their decision-making processes, reduce biases, and ultimately make more informed and rational choices. Additionally, having an awareness and understanding of cognitive distortions allows the individual to avoid drawing false conclusions or applying faulty logic when deriving conclusions throughout the estimating process. This is helpful in the development of efficient workflow and creating systems to enhance the accuracy and value of the product being produced.

Group Think

When meeting with a group of stakeholders, discouraging tendency toward group think (that can take a myopic view or limit creativity) is essential for fostering diverse perspectives and healthy decision-making. If there are dominate personalities, then this becomes even more relevant. The following are possible group think mitigation strategies:

1) Implementing a structured "turn taking" approach where everyone has an opportunity to contribute can help minimize bias in discussions. For example, using a "round-robin" format where each participant has equal time to share their views before open discussion begins can support a creative, multi-viewpoint set of inputs.

2) Encourage and normalize dissent, to create an environment where questioning and constructive criticism are valued. The designated lead should actively engage alternative viewpoints from stakeholders and encourage participants to challenge dominant perspectives without fear of judgment. This can expedite the team's ability to collect relevant inputs.

3) Set specific discussion ground rules for the discussion(s). Establishing common norms at the outset of the group discussion such as limiting how long each person can speak, active listening, and respecting all opinions will help prevent a single person(s) from dominating the conversation and ensure that less vocal or those with indifferent opinions are heard. The result will be a less biased discussion.

4) Encourage reflective (active) listening. A common method is to have participants paraphrase others' contributions before adding their own. This practice ensures clarity and understanding of the other persons perspective and helps redirect focus from dominant voices to the group's overall ideas.

Dominating Personalities

In situations that have dominant personalities where they want to control a group can be challenging. To mitigate dominant effects requires skillful facilitation and clear guidelines. Below are several methods to mitigate control and provide a balanced discussion:

1) Use a well-structured agenda to control the discussion flow. Have the agenda objective highlighted and clearly allocate time for each topic. Then designate specific points where everyone is invited to contribute. Stick to the agenda to avoid one person steering the conversation.

2) Ask a direct question to a specific individual. When it is noticed that a dominant personality taking control, pause, then direct questions specifically to quieter members. For example, "I'd like to hear what [name] thinks about this issue." This balances participation and helps other voices emerge to encourage participation and normalizes dominate personalities. The result will be a richer conversation with insights from a different point of view.

3) Rotate leadership roles to dilute dominant personalities. If there are multiple sessions or even during the same session, rotate who leads the meeting(s) or discussion(s). The result will help dilute dominant personalities. In addition, it will also build leadership skills across the group.

Inexperience

When there are inexperienced group members, balancing contributions from them can be tricky. It is a mentoring opportunity and should be an inclusive environment while ensuring that discussions remain productive. Below are several methods to support a productive environment:

1) Encourage mentorship and paring inexperience with experience. Pair inexperienced members with more experienced ones. If possible, align similar areas of interest between the participants. This allows them to contribute while learning in a more guided setting. It also helps their (the inexperienced members) ideas to be framed and refined before being presented to the larger group. The result is a comprehensive learning experience.

2) Provide context, education (on-the job training) and guidance to add richness to the discussion. When there are inexperienced members, ensure that everyone is well-informed about the topics being discussed, goals of the discussion and the "end game". The leader should provide a brief background of the project (or estimate) and share relevant resources in advance so that the less experienced members can be up to speed. The result will allow them to contribute more effectively.

3) Provide feedback and coaching to less experienced members. During or following the discussion, offer constructive feedback to the inexperienced members on how to improve their contributions; it is one of the best ways is to provide positive reinforcement. When they make valuable points highlight them; it builds their confidence while guiding them on how to be more effective when other contributions could have been stated more clearly. The result will provide a nurturing environment from which confidence of the inexperienced member can build.

Pressure from Management

Balancing pressure from management to integrate a decision in a group requires tact, transparency, and strategic facilitation to be effective. The following methods support this effort:

1) Provide clarifying rationale to assure management understands drivers. There are two parts to this effort. One is that the group understands management's strategic goals and motivations. The other is for management to understand the direction and rationale the group is working on. Then both need to assure there is alignment so that the overall objectives are met (both company and project). This can be expanded to ensure that the group understands why management is pushing for a particular decision. Providing clear reasoning, such as alignment with broader business objectives or addressing specific challenges and gaps that need to be overcome. The result is a solution (estimate) that will be complete, credible and defendable.

2) Frame the discussion within the groups goals so management understands the basis for decisions. As stated in the prior paragraph, demonstrate how the management's decision aligns with the group's goals or long-term objectives. This helps reframe the directive as something that can benefit the group's work, rather than as an external imposition.

3) Involve the group in problem-solving with management to support decision making credibility. Frame the directive as a challenge for the group to creatively solve the issues at hand. Engage the group in brainstorming how to best achieve management's goal while incorporating their own ideas and approaches. This increases engagement and fosters a sense of shared responsibility. The result will be a verifiable set of solutions (costs and drivers) to be used in the decision set (final point estimate).

4) Recognize and address resistance within the group. During group discussions, if there is any resistance apparent, acknowledge it. Then, directly address it openly. Discussing any discomfort, hesitation or angst can help identify underlying issues. Once revealed, create a path forward that minimizes conflict. The result will be a more collaborative environment to accomplish the groups goals.

Data Bias

Understanding and communicating information when there is known bias in the data is a critical skill. The following can help understand information bias and minimize the influences to provide and objective and realistic solution(s):

1) Identify and acknowledge the bias(es). There are two parts to this approach: 1) understand the bias and 2) acknowledge the bias. Understand the source of bias and origination. This can be from data collection methods, sampling errors, reporting bias, analysis bias, or another source. Acknowledge bias explicitly. Communicate any insights and openly state that the data has some inherent biases that could influence outcomes. It is important to provide transparency about this bias to build trust and provide context for the findings. The result will support an ability to compensate and include the bias elements in the risk analysis.

2) Communicate any caveats and contextual anomalies. Based on the data that will be used for the estimate, frame recommendations carefully when presenting results. Provide clear indications as to how the bias may influence the outcomes. Highlight and convey cautions, including "The results suggest…" rather than definitive statements like "The results show…". Next, provide contextual information. That is, explain the conditions under which the data was collected and how those conditions might have introduced bias (e.g., "This data collection activity did not include some of the sunk costs already expended during system development, which might exclude some key risk reduction activity"). The result will provide the analysts with additional guidance and notes when assembling the estimate.

3) Adjust Analysis Techniques. Apply common corrective analytical methods. For example, use statistical techniques to adjust for known biases, like weighting samples to better reflect any regression errors. Consider eliminating "outliers" in the data. Segment the data where possible. If biases are concentrated in certain elements, break down the analysis further to focus on those elements to see where the bias is most pronounced. This will support objective solutions when finalizing the estimate.

4) Document any choices and rational in the GR&A. Provide a detailed list of the GR&A including any bias and how it was handled. The result will allow future reviewers clear and contextual information to understand the decisions that were made.

Integrating External Tools

The prior subsections have shown that there are numerous methods to support objective decision-making with minimum bias in recommended solutions. It is also shown that many of these methods have a common structure. Providing a

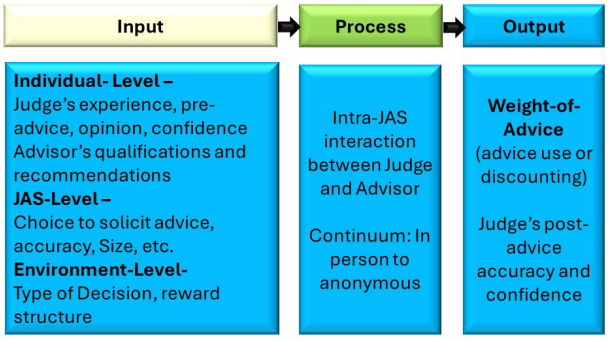


Figure 4. Judge-Advisor System within the IPO integrating the WOA Output

consistent integrated solution can be enhanced using two methods in concert. They are Judge-Advisor system (JAS) and weight-of-advice (WOA).

Integrating the processes can be shown as an input—process-output (IPO) model for explaining and supporting JAS/WOA within the framework. This is illustrated in Figure 4. The Input contains three levels, individual, JAS and Environment. The process category accounts for interactions between the judge and advisor and can range from in person to an anonymous group. The output draws from the input and process to provide the WOA and the Judge's post advice accuracy and confidence.

The WOA method is a structured way to gather, assess, integrate and grade input from different stakeholders (group members). It ensures that decisions are made based on the quality and relevance of advice rather than simply following the loudest or most dominant voices. The WOA can be calculated using the following equation:

$$\mathbf{WOA} = (\mathbf{FE} - \mathbf{IE}) / (\mathbf{Advice} - \mathbf{IE}) \qquad (1)$$

Where:

IE = Initial Estimate
FE = Final Estimate
Advice = Output from Judge
WOA = Output Weighting Factor

The outcome scale is generally between 0 and 1 where a <=0 means the advice was completely ignored and a >=1 means the advice was completely used. In between 0 and 1 the weight is forecast.

Moreover, Bailey, Leon, et al provide the following framework to capture the WOA method. 1) define the decision context, 2) gather the advice from all stakeholders, 3) assess the quality of each input, 4) assign weightings to each advisor, 5) integrate the solutions, and 6) make a recommended decision. [11]

The JAS is a decision-making approach where a designated "judge" (decision-maker) makes the final decision, while one or more "advisors" provide input, guidance, or recommendations. The judge retains control over the decision but benefits from the insights of the advisors. Implementing this system effectively in a group setting requires clear roles, structured processes, and balanced communication.

When integrating these methods, the decision-making process becomes more robust within the structured framework and deliberate qualification of the group inputs to develop an unbiased decision portfolio.

In an estimating scenario using the GAO cost estimating process, the initial point estimate is developed in Step 7 based on inputs from the group. Then within the analysis phase, a risk and uncertainty analysis is performed, and another recommendation is provided. Using the integrated JAS/WOA methods (with respective WOA weightings of stakeholders, etc.) additional advice is provided to determine the final estimate and documentation.

It is important to note that the use of the WOA method with or without the JAS method is not a guarantee of unbiased decision-making. It does provide the tools to support objective and unbiased evidence for decision-making.

Although not the focus of this paper, integrating objective methods like the analytic hierarchy process with WOA and JAS can significantly add to the objectiveness of recommended solutions. [12] This will be discussed in Section 7, Future Work.

5. EXAMPLES

This section provides two examples of implementing bias mitigation approaches. The first example shows common bias issues in cost estimating. The second example applies the JAS/WOA solution to illustrate the method.

Example 1 –

In this setting, the group engaged in a discussion about cost inputs that will be used based on the cost analysis requirements description (CARD) for a new space mission. The system being estimated is a space bus with three payloads. Two of the payloads are being modified while one is a new design. The group is comprised of six participants, deputy program manager (DPM), chief engineer (CE) and four analysts. The analysts are split with half experienced (AE) and half that are relatively new to the cost and system engineering environment (AN). There are several items that will be discussed: 1) maturity of the system being estimated, 2) the availability and validity of data for some of the payloads based on historical data and 3) the operational concept and space environment.

Discussions: After some discussion it was found that the DPM was clearly acting as the Judge, while the CE had a dominant personality driving part of the discussion. One of the AE's also had a dominant personality also driving part of the discussion. The remaining participants were relatively balanced with some occasionally offering input. As the discussion progressed, most of the bus inputs were agreed to.

However, there were some disagreements on the modified and new payloads regarding heritage, complexity and maturity as well as the space environment. All of these could drive the cost estimate. After a time, the group was in a "stalemate". The DPM recommended adjourn, "sleep on it", and meet the next day.

Analysis: In this scenario there a number of dynamics. From Table 1, concurrently, there is optimism, some level of group think, dominating personalities and possibly some data uncertainty or bias, though not yet determined. To support an objective (unbiased) solution, the DPM decided to develop a structured, time phased agenda that addressed specific participants and requested them to contribute at specific times with a specific question or scope. Further, the DPM requested the AE's team with the AN's and assigned them specific tasks. The DPM sent out the agenda with the other requirements and asked that the participants be prepared to use this guidance during the discussion the following day.

Results: The following day, the participants reconvened and were prepared. Using the approach highlighted in this paper the meeting, as it concluded, had agreement on payload inputs, the space environment, and a list of encompassing risks that will be used for the cost risk activities.

What did the DPM do? Here was the strategy used:

Sensing multiple dominant personalities, the DPM developed a specific time driven agenda to keep opinions neutral. Furthermore, the DPM added specific questions for different smaller groups to research and answer.

The smaller groups were able to determine that data for the environment and modified payloads were available and determined to be relevant, validated, and unbiased. The result was that the environment and the modified payloads obtained adequate input information with appropriate risks ranges. However, the new payload lacked any relevant heritage. The team agreed to break the new payload product-based work breakdown structure (WBS) down into smaller elements and estimate the new payload at a lower level where there was some heritage. Where there was missing information, they would look for analogous items or obtain SME input for the specific elements, then apply a set of risks around each.

Example 2-

In this example we use the requirements from Example 1 and implement the JAS/WOA methods. Using Saaty's AHP objective weighting approach, we provide the following information. [9]

At the end of the first group session of Example 1 and prior to adjourning, the DPM asked the participants to rate each member on their ability to objectively contribute to the decision-making process to obtain the required cost estimating inputs. In a blind rating approach on a scale of 1 – 9, he asked each member to rate the other on their technical capability, and ability to collaborate within the group. That evening, after obtaining the ratings from each member, he developed priority weights for each of the participants supporting the weight-of-advice and how the DPM might evaluate the final inputs serving as the judge.

Using the methods highlighted in this paper, the DPM defined the agenda in the same fashion as Example 1. In this scenario, the DPM now had new information on the capabilities of the AE2 and AN2 to balance the dominate personalities of the CE and AE1. From the blind test the WOA results are presented in Figure 5.

The next day, discussions continued. The DPM, now with new group dynamic information was able to weight the outcomes of the participants differently. There was more discussion now on the modifications that were required due to the radiation environment and the bus having three payloads. It was further found that modifications required for payloads 1 and 2 were thought to be more extensive than was thought earlier as. As the group discussed the radiation space environment, they found a higher radiation environment would be present for the proposed orbit. As a result, key electronics in the bus would need additional radiation protection (a cost driver) and the payloads would need some as well. As the meeting concluded, the group had agreement on the bus, payloads (the new payload solution would be estimated in the same way as in example 1), and the space environment, with a list of encompassing risks including those for the additional environmental requirements that will be used for the cost risk activities.

What did the DPM do? Here was the strategy used:

During discussion instead of relying on the dominant personalities from the CE and AE1, the DPM, using the WOA ratings of Figure 5 was able to take and evaluate input from the AE2 and AN2 to balance the discussion using the structured agenda and "turn taking" highlighted in the group think bias.

In a similar way smaller groups were able to determine data for the space environment and modified payloads were available but needed additional information for the radiation environment. This was compensated for in the additional risks identified. The new payload however, lacked any relevant heritage. The team agreed to break the WBS down into smaller elements and estimate the new payload at a lower level where there was some heritage and included the additional radiation requirements, they applied an expanded set of risks around each. The group agreed that there were correlations between elements. These would be considered during the risk analysis.

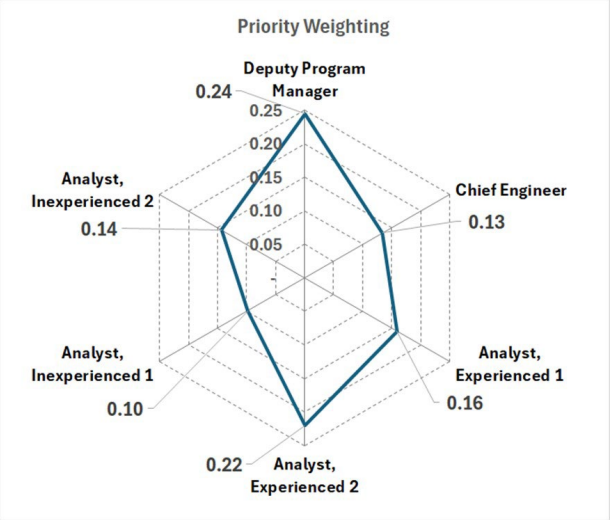


Figure 5. Weight-of-Advice rating based on participants input

6. SUMMARY

We have shown that early cost estimates for MDAPs, MCAs and MTAs may have bias when predicting cost, leading to cost over runs and schedule delays. Recognizing bias early, can help mitigate overly-optimistic estimates that are then used as an anchor for measurement across the lifecycle.

To support this effort, we provided methods to identify cogitative distortions that could, left unchecked, create or worsen biases. Once addressed and acknowledged, strategies to mitigate bias can be used to effectively.

A description of cost estimating bias sources were identified using the GAO guidance along with mapping the Dror impacts. Implementation of the common cognitive distortion's mitigations are used in the cost estimating process to minimize bias as well. Then, adding an additional tool, the JAS/WOA method was shown to enhance bias mitigation strategies. We demonstrated mitigation strategies and the use of JAS/WOA methods with two examples. The results were able to provide minimum bias, credible and defendable estimate inputs.

Moving forward as cost estimates are developed early in the lifecycle, implementation of bias mitigation strategies can support realistic cost estimates that can stand the test of time and reduce cost overruns and schedule delays.

7. FUTURE WORK

Future work will investigate additional cases using the JAS/WOA method and less common and unconventional biases. Additionally, we will evaluate the implementation of the analytical hierarchy process (AHP), Bayesian models, and human versus algorithm advice that may influence robust and enduring cost estimates throughout the life cycle.

APPENDICES

A. ACRONYMS

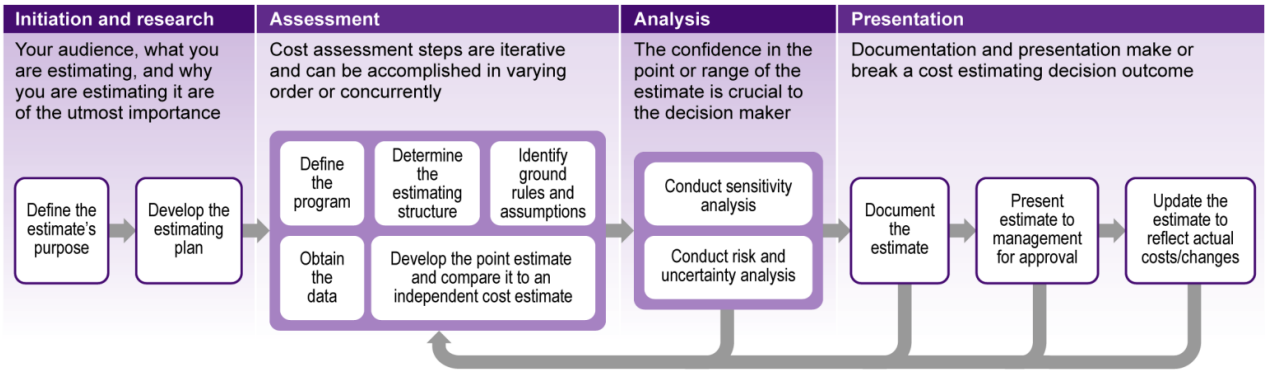
AAFP	Adaptive Acquisition Framework Pathways
AE	Analyst, Experienced
AHP	Analytic Hierarchy Process
AN	Analyst, New
CARD	Cost Analysis Requirements Description
CE	Chief Engineer
DoD	Department of Defense
DPM	Deputy Program Manager
FE	Final Estimate
GAO	Government Accountability Office
GR&A	Ground Rules and Assumptions
IE	Initial Estimate
MCA	Major Capability Acquisition
MDAP	Major Defense Acquisition Program
MRL	Manufacturing Readiness Level
MTA	Middle Tier Acquisition
MVP	Minimum Viable Product
SDA	Space Development Agency
TRL	Technology Readiness Level
WBS	Work Breakdown Structure

B. Evaluation and Mitigations Summary
C. Cognitive Distortions

Item	Bias Sources	1. Data	2. Reference Materials	3. Contextual	4. Base Rate	5. Organizational	6. Education and	7. Personal Factors	8. Human & Cognitive Factors, and the Brain	Impacts of Bias	Mitigation Strategies
A	Over-Optimism	◆	◆		◆			◆		Higher TRL than actual leading to higher development costs; lower team maturity leading to inefficiency; using adjacent materials may cause incorrect assumptions; subject matter expert incorrect assumptions causing incorrect solution recommendations; personality influences may provide erroneous direction.	- Encourage critical thinking and Dissent in a structured environment - Establish Pre-Mortem exercises and work backward to identify potential causes - Set conservative benchmarks versus ambitious goals to address realism
B	Group Think			◆	◆	◆		◆	◆	May offer irrelevant information to estimators that may not accurately capture all key information for the estimate; expert solution that may not fit the requirements; suggest using the standard organizational solutions rather than creative solutions limiting capability; other agendas or dominant personalities may limit creativity; some cognitive factors may limit system architectures or suppress creative solutions. Estimates can be anomalous due to limited creativity or efforts to maintain group harmony, discounting issues, causing cost growth and schedule delays.	- Implement structured "turn taking" where everyone has an opportunity to contribute - Encourage and normalize dissent, create a constructive environment to obtain various viewpoints - Set specific discussion ground rules for the discussion(s) to establish conversational limits at the outset - Encourage reflective (active) listening by paraphrasing other contributions
C	Dominating Personalities							◆		Drivers to simplify or drive to a target, incorrect assumptions my drive performance, cost and schedule.	-Use a well structured agenda to control the discussion flow - Implement a direct question to specific individuals to encourage participation and normalize dominate personalities - Rotate leadership roles to dilute dominant
D	Inexperience		◆				◆			Missing relevant elements or drivers, may be revealed after program start	- Encourage mentorship and paring inexperience with experience - Provide context and education (on-the job) training and guidance to add richness to the discussion - Provide feedback and coaching to less experienced members
E	Pressure from Management					◆		◆		Drive to simplify or reduce planning, less cost than will cost	- Provide clarifying rational to assure management understands drivers - Frame the discussion within the groups goals so management understands the basis for decisions - Involve the group in the problem-solving with management to support decision credibility - Recognize and address resistance within the group and openly discuss
F	Data Bias	◆	◆	◆						If data is used out of context or is irrelevant for the particular application, errors or erroneous assumptions can be made, incorrect operational concept or performance solutions may be recommended	- Identify and acknowledge the bias(es), then discuss impacts - Communicate any caveats and contextual anomalies from the current effort - Adjust analysis techniques to minimize bias and segment the data to reveal the elemental root cause - Document any choices and rational in the GR&A

Item	Cognitive Distortion	Description	Impact on decision making
1	All-or-Nothing thinking	Viewing situations in black and white terms	May lead to extreme decisions or avoidance of risks. Anything less than perfect is a failure
2	Overgeneralization	Making broad conclusions based on a single event	Can result in biased expectations about future events. Often leads to pessimism or avoidance
3	Mental Filtering	Focusing only negative aspects while ignoring positive ones	Can lead to a skewed perception of reality. Causes poor decision making based on incomplete information
4	Disqualifying the Positive	Dismissing positive experiences as "flukes"	Undervaluation of successes, which can impair confidence in decision making
5	Jumping to Conclusions	Making assumptions without evidence (mind reading or fortune telling)	Results in decisions based on unfounded fears or biases.
6	Catastrophizing	Expecting the worst possible outcome in a situation	Creates unnecessary anxiety and may lead to overly cautious or irrational decisions
7	Emotional Reasoning	Believing that feelings reflect reality	Decisions based on emotions rather than facts can lead to impulsive or irrational choices
8	"Should" Statements	Holding rigid rules about how oneself or others should behave	Can create frustration and resentment leading to biased judgments
9	Labeling	Assigning negative labels to oneself or others	May lead to fixed mindset and influence decisions based on stereotypes or prejudices
10	Personalization	Taking responsibility for events outside of one's control	Can lead to excessive guilt or shame, impacting confidence in decision making

D. GAO Cost Estimating Process



Source: GAO. | GAO-20-195G

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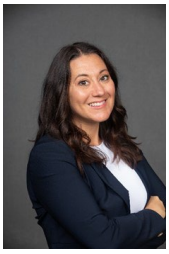

Christina Snyder*, is the current ICEAA Board President and a CCEA® certified cost analyst with 19 years of probabilistic modelling experience with Systems Planning & Analysis (SPA). Her recent research has focused on effective communication to decision makers. In 2021, she received a best paper award for "Does Cost Team Leadership Matter" – discovering that the soft skills of the cost team lead ultimately do impact team effectiveness. Knowing that technical skills alone will only take estimators so far, her 2022 paper "CE2: Communication and Empowerment for Cost Estimators" leveraged communication and empowerment training to demonstrate how all cost estimators can use soft skills to exponentially impact their analyses. Ms. Snyder holds a BS in Applied Computational Mathematics with a Concentration in Statistics from Virginia Tech.*

Ben Snyder

Dr. Benjamin Snyder earned his bachelor's degree in Psychology from Virginia Polytechnic Institute and State University in 2004. Dr. Snyder completed a master's degree in Counseling from the Johns Hopkins University in 2008, and finished his doctoral training in Counseling Psychology at the University of Georgia in 2012. Dr. Snyder successfully completed his internship at The Children's Home/Manatee Glens Consortium. His primary and secondary rotations consisted of providing individual, group, and family therapy to children with a variety of behavioral and emotional symptoms. Since that time, Dr. Snyder has worked in private practice to develop a specialization in the treatment of concerns related to sports and performance. Dr. Snyder is an active member of the Association for Applied Sport Psychology (AASP) and has extensive knowledge and experience with a wide range of competitive activities. Additionally, Dr. Snyder has extensive experience providing assessment and therapy with children, adolescents, and families in a variety of settings; including outpatient, in home, detention, and school based mental health counseling.

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