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Cost Estimating and Affordability Case Study: Air-to-Ground Missile Program

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Abstract

This case study is written to produce an active learning environment to increase the capability of acquisition and program management professionals regarding cost estimating and the program decision-making. The Joint Common Missile is the program of record used for the case study due to the variance of its program office estimate and the independent cost estimate (ICE). Both estimates were developed in preparation for program decision review and were critical to the decision-making process used by the milestone decision authority and the program manager. Affordability is always a major factor in development and procurement decisions for defense acquisition programs. All programs procured with taxpayer dollars for use within the Department of Defense are constrained by budgeted dollars. Cost estimates aid in decision-making along a program's timeline at key program milestones with a prediction of future program costs and inform milestone decision authority about the program's affordability.

Case Study Learning Objectives:

- Demonstrate understanding of acquisition program cost estimating and how they are applied in acquisition program baseline planning and decision-making.
- Demonstrate an understanding of the difference between the learning rate effect (improvement curve) and the production rate effect when applied in production cost estimates in acquisition programs.
- Enhance critical thinking, problem-solving, resource management, and stakeholder management skills to develop recommendations for affordability decision-making that are defensible based on data and the acquisition sciences.

Keywords: cost estimating, affordability, decision-making, critical thinking, project management

Situation

It was beautiful Friday afternoon, and Colonel Nicole Smits was looking forward to a great weekend until the phone rang. The caller ID indicated that it was from the Pentagon. "Why would the Pentagon be calling directly?" she thought as she answered the call. The call was from the Office of the Under Secretary of Defense for Acquisition and Sustainment (OUSD[A&S]). The chief of staff for the Under Secretary of Defense for Acquisition and Sustainment (USD[A&S]) indicated that the USD(A&S), as the milestone decision authority (MDA), cancelled the planned Defense Acquisition Board (DAB) review scheduled to approve entry of the Joint Common Missile (JCM) program of record into the engineering and manufacturing development (EMD) phase due to funding concerns. Colonel Smits was a newly assigned project manager (PM), and the DAB review was planned before her assumption of the charter, giving her responsibility for the total life cycle systems management. She knew she'd have to bring in her project management office (PMO) team, as well as all the other stakeholder representatives, to address the program affordability concerns of the USD(A&S) and reschedule the DAB review. She wondered, "How could the program be facing issues before even being formally initiated as a program of record?"

Background

Colonel Smits contacted her user counterparts (customers) to explain the DAB review delay. The user counterparts for the Army, Navy, and Marine Corps represented the warfighters in the acquisition process and were responsible for the JCM program requirements. The user representatives understood the affordability concerns of the MDA but stressed that the operational need for the JCM remained a top priority. The Department of Defense (DoD) had a growing need to replace its family of aviation-launched missiles, including the Hellfire missile, the tube-launched, optically-tracked, wire-guided (TOW) missile, and Maverick missile systems. The JCM would enable the Army, Navy, and Marine Corps rotary-wing aircraft (helicopters) as well as Navy fixed-wing aircraft (fighter jets) to execute numerous missions with one common missile—the JCM—greatly increasing capability and reducing the DoD logistics footprint across military operating environments. Figure 1 shows the current missiles being replaced by the JCM. The single JCM was replacing variants of Hellfire, Maverick, and TOW missiles, and provided the Army, Navy, and Marine Corps warfighting communities increased range, lethality, and force protection with ability to operate in austere battle environments. The following was a summary of aviation-launched missiles fired from platforms (prior to JCM):

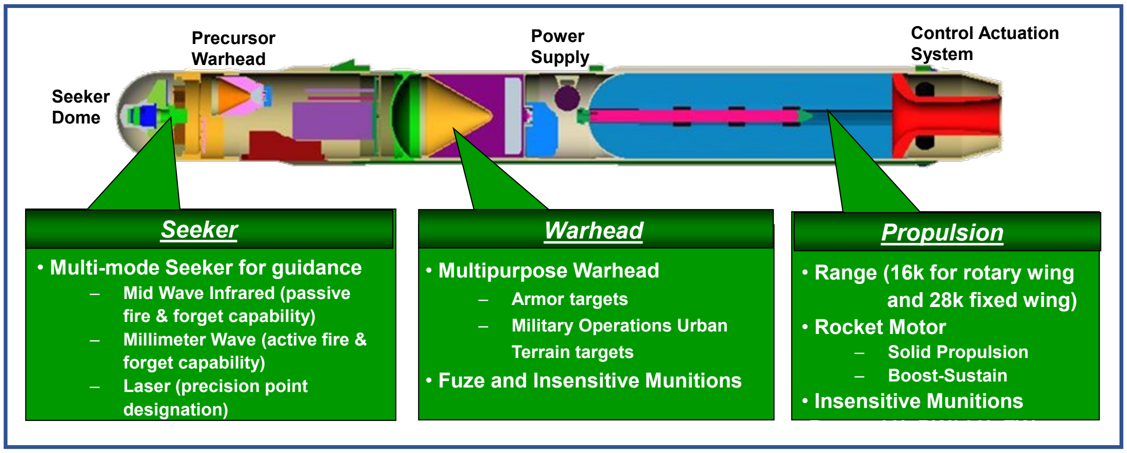
- Army AH-64 Apache helicopters fired multiple versions of the Hellfire missile with either precision point (PP) targeting, using laser designation technology, or fire and forget (active) targeting, using millimeter wavelength (MMW) radar technology and separate warheads for different target sets. The Hellfire average unit procurement cost (AUPC) was $86,900.
- Marine Corps AH-1Z Cobra helicopters fired all versions of the Hellfire missiles and TOW missiles with wire guided targeting technology. The TOW AUPC was $78,100.
- Navy MH-60 Seahawk helicopters fired the Hellfire missiles and TOW missiles.
- Navy F/A-18 E/F Super Hornet fighter jets fired Maverick missiles with either PP or fire and forget (passive) targeting using infrared (IR) technology with separate warheads for different target sets. The Maverick AUPC averaged $179,000.

Each version of the current missiles was limited to operating with a single mode seeking capability and single warheads destroying a specific set of targets. Replacement of these missile variants meant integration of tri-mode seeker, multipurpose warhead, and common propulsion technologies. Luckily, the MDA was not questioning the need for the JCM or the JCM performance requirements. The MDA was questioning the JCM affordability.

Figure 1. Missile Being Replaced by JCM
(Joint Requirements Oversight Council [JROC], 2004)

JCM Program Details

At the materiel development decision (MDD), the JCM program MDA (USD[A&S], also designated as the Defense Acquisition Executive [DAE]), determined that the JCM should become a program of record and officially enter the acquisition framework at Milestone (MS) B to begin the EMD phase. The decision was based on the urgency of need, available resources, and technology maturity level of critical missile components. Figure 2 displays the notional proposed JCM design and highlights the three critical technology areas of the missile: seeker, warhead, and propulsion. Not unlike all programs within the DoD, affordability was a concern with the JCM program. The Army and Navy were fully committed to the program and issued affordability memoranda stating that the JCM program was affordable within the services' planned budgets. The Army and Navy acquisition executives supported the joint cost position (JCP). Based on the JCP, the proposed acquisition program baseline (APB), contained a 48-month EMD phase with an AUPC of $108,000 and an acquisition procurement objective of 48,613 missiles. Refer to Exhibit 1 for the JCM program APB details.



Seeker

- Multi-mode Seeker for guidance
  - Mid Wave Infrared (passive fire & forget capability)
  - Millimeter Wave (active fire & forget capability)
  - Laser (precision point designation)

Warhead

- Multipurpose Warhead
  - Armor targets
  - Military Operations Urban Terrain targets
- Fuze and Insensitive Munitions

Propulsion

- Range (16k for rotary wing and 28k fixed wing)
- Rocket Motor
  - Solid Propulsion
  - Boost-Sustain
- Insensitive Munitions

Figure 2. Notional JCM Design
(Common Missile Project Office, 2003)

The JCM program completed a successful technical maturation and risk reduction (TMRR) phase, meeting the exit criteria in which all critical technologies were assessed as mature. The program's integrated product team conducted a thorough risk assessment approved by the appropriate Army and Navy stakeholders, informed by the results of the multiyear science and technology effort and a 3-year TMRR phase, with multiple vendors demonstrating competitive prototypes through experimentation, extensive modeling and simulation, and early warfighter demonstrations. (Refer to Exhibit 2 for a summary risk assessment.) Figure 3 shows JCM critical technology strategy used to mature the seeker, warhead, and propulsion technologies to the level required (technology readiness level [TRL] 6) to initiate system integration and demonstration efforts (the EMD acquisition phase). The capabilities-based assessment documented the need for JCM, and an analysis of alternatives solidified the requirements, including the key performance parameters (KPPs). The JCM requirements traced to a simplified work breakdown structure (WBS) that highlighted the three critical technologies in the system design (refer to Figure 4).

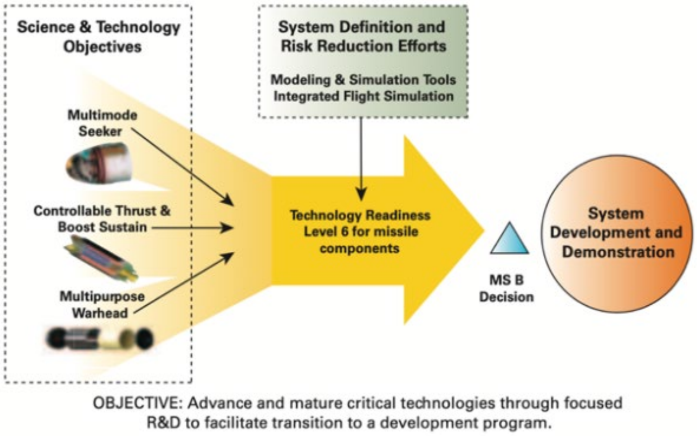


Figure 3. JCM Critical Technologies Maturation Strategy
(Mortlock, 2005)

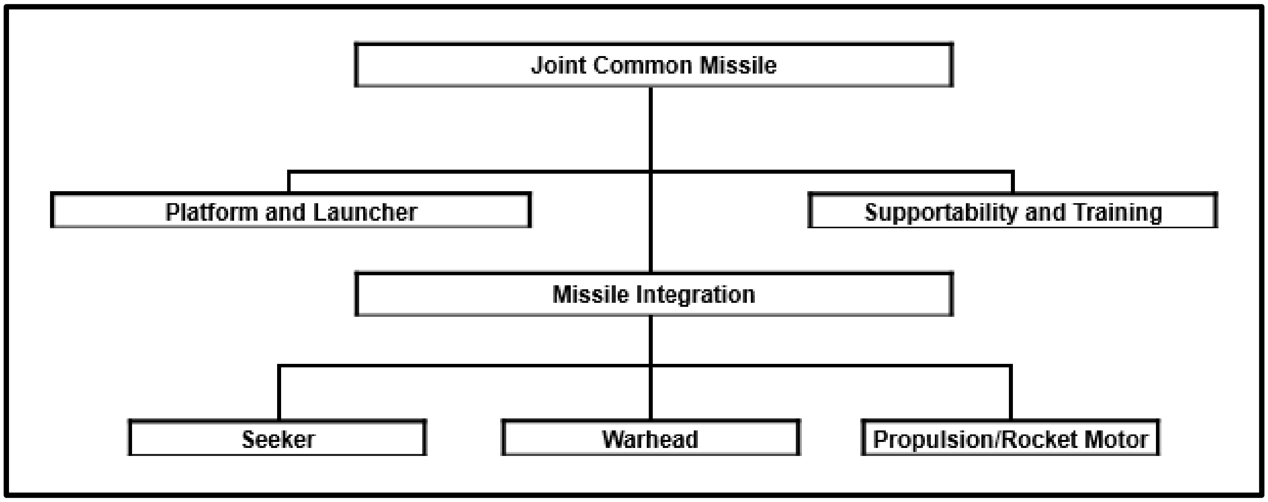


Figure 4. JCM Design Work Breakdown Structure
(Sleevi & Mount, 2003)

Dilemma

The proposed JCM APB was approved by the Army and Navy, which incorporated and funded a 48-month EMD phase and AUPC of $108,000. Every major defense acquisition program was required by law to have an independent cost estimate (ICE) to support MDA decision reviews. In the ICE developed by the Cost Analysis Improvement Group (CAIG), the recommended JCM EMD phase length was from 72 to 144 months with an estimated AUPC of $153,000, raising affordability concerns.

Given the differences between the JCP and ICE, the JCM business and financial management director provided the details of the cost estimates (CEs). The impending DAB review required the following cost estimating documents: program office estimate (POE), JCP, cost analysis requirements description (CARD), and ICE. The draft CARD developed for the JCM program was based on the approved requirements document resulting in a proposed design (depicted in Figures 2 and 4). The CARD prepared for the JCM program formed the basis for the JCP and the ICE. Exhibit 3 provides an overview of DoD cost estimating policies and procedures.

The JCM JCP combined an Army POE and Navy POE that was reconciled through the Cost Review Board Working Group (CRBWG). The JCP documented the multiple cost estimating methodologies, including analogy, engineering, and actuals, as well as expert opinion. The estimated costs developed in the JCP broken down by appropriation categories (DoD "colors" of money) is depicted in Table 1. The two areas to highlight within the JCP are research, development, test, and evaluation (RDT&E) costs and procurement costs (funds production and manufacturing). The RTDE costs relied heavily on the analogy cost estimating method, specifically analogies to Hellfire and Javelin missile development efforts. The most important cost driver to procurement was recurring production, estimated to be $4.79 billion for the JCM program in the JCP. It was within recurring production that the learning curves and production rates greatly impacted the cost estimates. The JCP estimate derived theoretical first unit cost values (T1s) for the components and subcomponents of recurring production based on comparisons to the Javelin and Hellfire missile programs.

Table 1. JCP JCM Life-Cycle Costs
(Gregory, 2004)

Cost Element		**JCP (dollars in millions)**		
		Army POE	**Navy POE**	**Total**
1.0	Research, Development, Test & Evaluation	552	418	970
2.0	Procurement	2,162	3,861	6,023
4.0	Military Personnel	15	-	15
5.0	Operations and Maintenance	179	88	267
	Total Life-Cycle Costs	2,908	4,367	7,275

The following assumptions were factored into the cost estimates:

- Costs presented in constant fiscal year (FY) dollars
- EMD Phase: 48 months with a cost plus incentive fee-type contract
- Low-rate initial production: 1 year with fixed price incentive-type contract
- Full-rate production: 10 years with fixed price contract
- Army platform: Apache (AH-64D)
- Navy platforms: Cobra (AH-1Z), Super Hornet F/A-18 E/F, and Seahawk MH-60
- Acquisition objective (AO) of 48,613 missiles
- Assumed Production Profile

Fiscal Year	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Year 11
Production Quantity	220	1,519	2,511	3,217	5,030	5,367	5,587	5,908	6,483	6,089	6,682

Like the JCP, the ICE was also based on the CARD but differed substantially from the JCP. The ICE and JCP variance of life-cycle costs are depicted in Table 2. The primary differences between the two cost estimates were the estimated development time for the EMD phase and the recurring production costs for the missile. According to the Army and Navy, the critical technologies were matured in the previous TMRR effort to the recommended TRL 6 and did not require more than 48 months for system integration and development efforts. The CAIG disagreed with this assumption, using a review of historical missile programs that incorporated multimode seeker, multipurpose warhead, and common motor technologies. In doing so, the CAIG estimate determined a developmental effort lasting 26 months longer. This increase made the total time the JCM program required RDT&E funding to increase from 48 months to 74 months. The increase to 74 months was the primary driver for the 39% increase in forecasted dollars for RDT&E in the ICE. Although the CAIG settled on 74 months for development effort duration, they opined that the JCM program could easily incur a 147-month development effort given the complexity of the JCM and its requirements.

Table 2. JCM ICE and JCP Life-Cycle Cost Comparison
(Burke, 2004)

Cost Element		Cost Estimate Source		Difference (dollars in millions)
		JCP (dollars in millions)	**CAIG (dollars in millions)**	
1.0	RDT&E	970	1,350	380
2.0	Procurement	6,023	7,490	1,467
4.0	Military Personnel	15	20	5
5.0	Operations and Maintenance	267	270	3
	Total Life-Cycle Costs	7,275	9,130	1,840

The other difference between the JCP and the ICE rested with the recurring production cost estimates. The T1 used for the CAIG CE was lower than the T1 used in the JCP despite the overall increase the CAIG predicted recurring production costs 25% greater than recurring production estimated costs in the JCP. To compare the difference between the two estimates, the CAIG offered its method of application for the learning and production rates. The rate of learning applied by CAIG was 88% and a production rate effect of 90%. The CAIG developed these rates through regression analysis of 12 previous missile production programs. As the CAIG compared its rates to the JCP, it was determined that the JCP used T1s and cost progress curves for each component and subcomponent of production. For comparison purposes, the ICE determined that the JCP used a 93% learning curve rate and an 83% production rate effect. The CAIG also highlighted that the procurement profile of the JCM program was not typical for missile programs. According to the CAIG, missile programs normally desired to achieve a “tooled rate” earlier in production, and then have quantities at a level rate thereafter. The JCM production profile exhibited a continual increase in production amounts over 11 years.

Path Forward

With all this information, Colonel Smits knew her team was prepared to address the concerns of the MDA. Further coordination with the OUSD[A&S] revealed that the MDA wanted to discuss answers to the following before rescheduling the DAB review:

- What were the key differences between the joint cost position (JCP) and the independent cost estimate (ICE), and why did those differences exist?
- What should the program manager recommend for the length of the engineering and manufacturing (EMD) phase?

- What's the difference between the learning rate effect and the production rate effect in estimating recurring production costs?
- For recurring production,
  - How was the cost estimated for a specific missile from the production schedule?
  - What were the assumed T1 values used in the JCP and ICE?
  - Why would the JCP and ICE assume different learning rate effect values and different production rate values?
- What were the PM recommendations to the MDA on how to certify the JCM program as affordable and fully funded to Congress with the differences between the JCP and ICE?

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Exhibit 1. JCM Acquisition Program Baseline

The JCM program acquisition strategy outlined a 4-year EMD phase that met the warfighter required initial operational capability (IOC) dates and had support from the warfighting community, the services' requirements communities, the service chiefs, and service acquisition executives. The APB outlined the following performance, schedule, and cost constraints applied to the JCM program.

PERFORMANCE: The Joint Requirements Oversight Council–approved JCM capability development document (CDD) contained the KPPs that formed the basis for the performance section of the APB.

#	Key Performance Parameter	Performance
1	**Targeting**	Precision Point (Laser Designated / Guided)
		Fire & Forget – Active (Radar Designated / Guided)
		Fire & Forget – Passive (Infrared Designated / Guided)
2	**Combat Effectiveness**	Anti-tank (T-90 Soviet tanks)
		Anti-personnel behind triple brick & concrete walls in military operations in urban terrain (MOUT)
3	**Range**	Rotary wing (RW): 16 Km
		Fixed wing (FW): 28 Km
4	**Interoperability (Platforms)**	AH-64D (Apache), AH-1Z (Cobra), F/A-18 (E/F) Super Hornet, MH-60R Seahawk
5	**Carrier / Shipboard Capibility**	F/A-18 (E/F) Super Hornet, MH-60R Seahawk

SCHEDULE: The approved CDD documented an IOC for the JCM at MS B + 5 years (60 months) based on the urgency of the need. The EMD phase was planned for 4 years (48 months). The schedule part of the APB had the following events: critical design review (CDR) at MS B + 2 years (24 months), MS C at MS B + 4 years (48 months), and IOC at MS B + 5 years (60 months).

COST: The approved CDD specified an acquisition objective for the JCM of 48,613 missiles to be procured for the Army and Navy. Cost estimates from the JCP determined an AUPC of $108,000. The program funding was incorporated into the approved services' program objective memoranda. The JCP was approved by the Army and Navy that funded a 48-month EMD phase with RDT&E funding and a 11-year production and deployment (P&D) phase with procurement funding.

Exhibit 2. JCM Technology Risk Assessment

The JCM program stakeholders collectively assessed the TRLs of the three critical technologies and other risks based on the JCM WBS (Sleevi & Mount, 2003).

- Risk 1: Seeker Technology Maturity—The JCM employed precision point, fire and forget passive, and fire and forget active targeting capability (mandated by KPP 1) that required the development of a tri-mode seeker. A tri-mode seeker required the integration of hardware and software for real time acquisition and tracking of targets in each of the three seeker modes and integrated with guidance and control (G&C) and inertial navigation system (INS). Additionally, the seeker radiation dome (Radome) had to transmit radiation for the millimeter wave radar, infrared signature, and laser designations.

  Tri-mode Seeker—TRL 6 (prototype demonstrated in militarily relevant operational environment)

- Risk 2: Warhead Technical Maturity—The JCM was designed to defeat a wide array of targets (mandated by KPP 2), including threat tanks and threat personnel in bunkers that required the development of a multipurpose warhead and fuse. The warhead technology was highly complex because each target requires different engagement mechanisms to achieve the required lethality effectiveness.

  Multipurpose Warhead—TRL 6 (prototype demonstrated in militarily relevant operational environment)

- Risk 3: Propulsion / Rocket Motor Technology Maturity—The JCM was to be fired from both rotary wing and fixed wing aircraft (required by KPP 3). The boost and sustain technology required high turn down ratios to adjust the propulsion nozzle to achieve rotary and fixed wing ranges. The JCM required a turn down ratio of approximately double that of existing missiles from current platforms. In addition, the wide range of environmental conditions as well as vibration and shock constraints for both rotary and fixed wing platforms was challenging to address in a single common motor.

  Common Rocket Motor—TRL 6 (demonstrated in militarily relevant operational environment)

- Risk 4: Missile Integration—The tri-mode seeker, multipurpose warhead, and common rocket motor system required intensive software synchronization.

- Risk 5: Platform Integration—The missile was to be integrated with the on-board fire control systems and launcher systems for each of the service platforms (required by KPP 4).

Exhibit 3. Basics of DoD Cost Estimating

The planning, programing, budgeting, and execution (PPBE) process was implemented before the start of the Vietnam conflict as the DoD's revolutionary budget process (Srull, 1998). The resourcing of acquisition programs in the DoD occurs through the decision support systems referred to as the PPBE process. Refer the Exhibit 4 for an explanation of how the PPBE process fits within DoD big "A" acquisition system. The purpose of the PPBE process is to ensure that resources are properly allocated within the DoD to support the National Defense Strategy and National Security Strategy objectives. Within the PPBE process, acquisition professionals rely on cost estimates to inform decision-making and determine the APB. At each program milestone, the MDA must certify to Congress the program is affordable and fully funded in the services' programmed annual budgets.

In December 1971, the CAIG was established to assist the DoD with estimating costs early and often within the acquisition life cycle (Srull, 1998). The CAIG began comparing initial cost estimates with actual program costs to better understand the cost breaches of the APBs. The application of cost estimating requires the understanding of a CE's function within the acquisition framework as well as the methods used to produce these snapshots in time. Regardless of one's understanding, cost estimates are critical for effective MDA acquisition oversight and decision-making (Office of Cost Assessment and Program Evaluation [CAPE], 2017). The GAO guidebook states that CEs also support the cyclical DoD budget cycle, impacting budget requests and proper alignment of resources, and seek to improve the financial performance of the DoD (Richey et al., 2009).

According to *Cost Estimation Methods and Tools* (Mislick & Nussbaum, 2015), some general principles exist to use CEs as a method to assist in decision-making. The first is that cost estimates are *not* precise, but rather are thorough and complete, meaning they possess key characteristics: completeness, reasonableness, credibility, and analytical defensibility. Second, despite being thorough and complete, CEs require assumptions. Understanding the assumptions within the CEs is critical to sound decision-making. Third, change will occur that affects the accuracy of CEs over time. Fourth, "cost issues are always a *major* concern, but they are almost never the *only* concern" (Mislick & Nussbaum, 2015, p. 4). Fifth, CEs are "guides" to enable a more-informed decision, not the answer. And last, CEs are an amalgamation of people, processes, and the data. Each of these elements is a product of its time and likely to change as newer technology creates ways to capture and apply data, people receive higher levels of education, and newer ways to analyze the data become available (Mislick & Nussbaum, 2015).

As required by the Weapons Systems Acquisition Reform Act (WSARA) of 2009, in response to continued congressional and constituent concerns about mismanagement of taxpayer dollars, the CAIG was replaced with the office of the Cost Assessment and Program Evaluation (CAPE), the organization now charged with developing independent government cost estimates for acquisition programs. CAPE executes the statutory guidance and regulatory requirements found within DoD Directive 5000.01 and DoD Instruction 5000.02 to support MDAs and acquisition professionals in sound data-driven decision-making practices. As a result of the requirements to influence broader objectives, CAPE is deliberately intertwined throughout the defense acquisition framework to ensure compliance.

The program management office coordinates with CAPE for support of major events and with the development of the CARD that contains the data about the program necessary to develop CEs. Before the PMO is authorized to begin its POE, the CARD must be deemed sufficient by CAPE. The final outputs required by the PMO include a completed POE and a full funding memorandum used to grant approval at the upcoming milestone. CAPE not only supports review of the CARD developed by the PMO, but it also produces the required ICE at major decision points.

The DoD utilizes five common methods when needed to develop CEs. Each method used carries different risks for the decision-maker regarding its utility for program decision making. A good understanding of the cost estimation methods may effectively reduce the risk of a program setting unrealistic cost and schedule parts of the APB. Selecting the appropriate CE methodology, and likely combination of methods, may likely yield the greatest quality CE (NASA Cost Analysis Division, 2015). Figure 5 shows where each method is likely used with respect to the acquisition phases. This figure highlights the relationship between the CE method and the amount of detail an estimate may produce given the program's position across the life cycle.

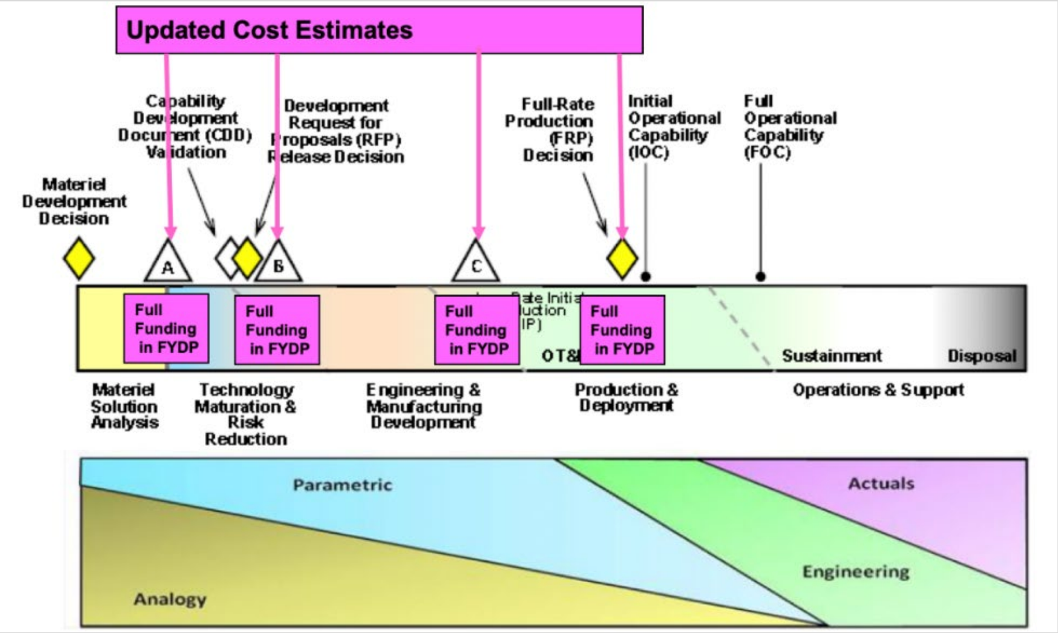

Figure 5. Cost Estimates Required and Methods Used
(Defense Manufacturing Management Guide for Program Managers, 2012)

The analogy cost-estimating methodology is typically used early in a program's life cycle due to the lack of specific data relating to the actual program. With the lack of a clearly defined system, analogy cost estimating seeks to find a previously fielded system that is comparable and is an aspect that reliably drives cost, then baselines those costs subjectively and accepts the former program's costs as a basis for the estimate. This method often relies heavily on the expertise of the cost estimate team (CET) to subjectively adjust upward or downward depending on the complexity of the comparable systems (Richey et al., 2009).

The *Parametric Estimating Handbook* (International Society of Parametric Analysts [ISPA], 2008) is a complete guide to the application of what is considered the "top down" approach to cost estimating—parametric methodology. It uses statistical relationships between key data of cost drivers within like programs. Understanding the cost drivers of similar programs enables the CET to develop a hypothesis to predict the future costs of the current program. The historical data in comparison that used the same cost drivers is normalized before conducting a regression analysis (ISPA, 2008).

Considered a "bottom up" estimate, the engineering cost estimate methodology requires significant amounts of data. Engineering CEs require a WBS at the lowest levels, historical data of similar programs, and actual costs. Engineers familiar with the work being analyzed assist the CET in developing the CE. This method is typically used once a program has entered production or after the program has gone through either a preliminary or critical design review.

Often referred to as extrapolation from actual costs, this methodology uses the current program's costs to predict future costs of the same item(s). The most common actual CEs are those predicting costs through improvement curves, commonly known as learning curves. Estimating costs using learning curve theory can increase the accuracy of the CE. Advancements in cost theory have led to an added variable to the improvement curve calculations. That variable becomes the production rate, indicating the number of units produced during the period. Use of production rates to influence CEs is applicable where large production occurs at various rates (ISPA, 2008).

Although entirely subjective in nature, expert opinion is used when necessary. Typically, expert opinion is leveraged when no historical data is available, although the CET pays attention to the expert's credibility to derive the source of the expert's opinion. This method is not synonymous with the expertise applied by the CET to develop cost estimates.

In *Better Business Decisions Using Cost Modeling for Procurement, Operations, and Supply Chain Professionals*, the example of performing a task repetitively results in a reduced amount of time for future executions of the same task (Sower & Sower, 2015). This is learning curve theory in practice. The reduction in time per repetition represents the learning rates. The same principle applies the reduction in the unit cost of an item as more items are produced. Figure 6 highlights the learning rate and its effect. In this example, the first unit (referred to as T1) costs 1,000. With a 90% learning curve (10% learning), the unit cost decreases by 90% for every doubling of the number of units. Therefore, Unit #4 costs 810 (1,000 x .9 x .9) and Unit #8 costs 729. A 70% percent curve (30% learning) represents a steeper drop in unit costs for every doubling of the quantity.

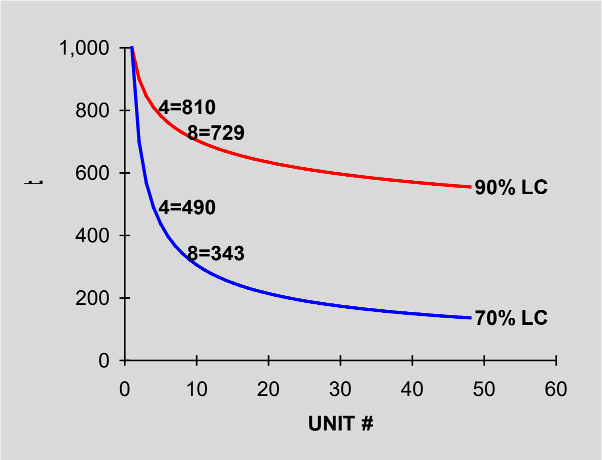

Figure 6. Example of Learning Rate on Unit Cost

According to the *FORSCOM Handbook for Cost and Price Analysis* (Forces Command DCS for Logistics, 2000), aeronautical engineers, when analyzing historical labor data regarding aircraft production, determined that there were specific rates of improvement for each successful completion of production when the successive production quantities doubled. In other words, the number hours to complete a task deceases at a constant rate for each doubling of the task attempts. Furthermore, "The learning curve, as originally conceived, analyzed labor hours over successive production units of a manufactured item, but the theory behind it has now been adapted to account for cost improvement across the organization" (ISPA, 2008, p. 2-7). Improvement, or learning curve theory is demonstrated using the following equation from the ISPA (2008, pp. 2-7):

$$Y = AX^{b}$$

where:

Y = the cost of the X^{th} unit

A = (theoretical) first unit (T1) cost

X = unit number

b = the learning slope coefficient (defined as the Ln (slope) / Ln (2))

The ISPA handbook finds that

> In parametric models, the learning curve is often used to analyze the direct cost of successively manufactured units. Direct cost equals the cost of both touch labor and direct materials in fixed dollars. This is sometimes called an improvement curve. The slope is calculated using hours or constant year dollars. (ISPA, 2008, p. 2-7)

In addition to understanding the improvement curve theory formula, applying the right technique is appropriate. The *GAO Cost Estimating and Assessment Guide* (GAO, 2019a) orients estimators to analyze production environments after analyzing the following factors:

1. Analogous systems
2. Industry standards
3. Historic experiences
4. Anticipated production environment

The basic understanding of unit curve theory is that as the production doubles, the cost to produce that amount decreases by a constant percentage. That percentage is the inverse of the learn rate applied. For example, if an 80% learning rate is applied, the cost of producing those units is reduced by 20%. Unit curve theory is typically used when production is well-defined, design is stable, and production lead times are typically longer (Mislick & Nussbaum, 2015).

The production rate effect is an advancement of learning curve theory. As production increases, economies of scale are realized, thereby reducing costs. The inverse is also true: as breaks in production occur, or production rates decrease, costs tend to rise. The efficiency of production can be explained by adding a variable rate to the preexisting learning curve formula (Richey et al., 2009). This is demonstrated using the following equation:

$$Y = AX^{b}Q^{r}$$

where:

Y = the cost of the X^{th} unit

A = (theoretical) first unit (T1) cost

X = unit number

b = the learning slope coefficient (defined as the Ln (slope) / Ln (2))

Q = production rate (quantity produced during the period or lot)

r = production rate coefficient (Ln (production curve slope) / Ln (2))

The ISPA handbook recommends

> the equation is generally applicable only when there is substantial production at various rates. The production rate variable (Q^r) adjusts the first unit dollars (A) for various production rates during the life of the production effort. The equation also yields a rate-affected slope related to learning. (ISPA, 2008, p. 2-8)

Exhibit 4. U.S. Defense Acquisition Institution—Decision Framework

Within the DoD, the development, testing, procurement, and fielding of capability for the warfighter operates within a decision-making framework that is complex. Within the private sector, similar frameworks exist. The U.S. defense acquisition institution has three fundamental support templates that provide requirements, funding, and management constraints. The executive branch, Congress, and industry work together to deliver capability with the program manager (PM) as the central person responsible for cost, schedule, and performance. Figure 7 depicts this framework.

Figure 7. Defense Acquisition Institution

The government PM is at the center of defense acquisition, which aims to deliver warfighter capability. The PM is responsible for cost, schedule, and performance (commonly referred to as the “triple constraint”) of assigned projects—usually combat systems within the

DoD. The executive branch of government provides the PM a formal chain of command in the DoD. The PM typically reports directly to a program executive officer, who reports to the service acquisition executive (an assistant secretary for that service—either Army, Navy, or Air Force), who reports to the defense acquisition executive (the Under Secretary of Defense for Acquisition and Sustainment). Depending on the program's visibility, importance, and/or funding levels, the program decision authority is assigned to the appropriate level of the chain of command.

Programs within defense acquisition require resources (for funding) and contracts (for execution of work) with industry. Congress provides the resources for the defense programs through the annual enactment of the Defense Authorization and Appropriation Acts, which become law and statutory requirements. The PM, through warranted contracting officers governed by the Federal Acquisition Regulation, enters contracts with private companies within the defense industry. Other important stakeholders include actual warfighters, the American public, the media, and functional experts (like engineers, testers, logisticians, cost estimators, etc.), as well as fiscal and regulatory lawyers.

As a backdrop to this complicated organizational structure for defense PMs, there are three decision support templates: one for the generation of requirements, a second for the management of program milestones and, and a third for the allocation of resources. Each of these decision support systems is fundamentally driven by different and often contradictory factors. The requirement generation system is driven primarily by a combination of capability needs and an adaptive, evolving threat. The resource allocation system is calendar-driven by Congress writing an appropriation bill—providing control of funding to Congress and transparency to the American public and media for taxpayer money. The defense acquisition management system (now referred to as the Adaptive Acquisition Framework) is event-driven by milestones based on commercial industry best practices of knowledge points and off-ramps supported by the design, development, and testing of the systems as technology matures.

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