Estimating Future Air Dominance

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ABSTRACT:

Estimating the cost of aircraft programs early in development presents special challenges. The process requires a consideration of the content of the program and various methods to be employed. The Air Force Cost Analysis Agency recently provided cost advice to the Scientific Advisory Board on how aircraft programs are estimated, recent historical experience/lessons learned, and approaches to reduce life cycle costs while the program is in the conceptual design stage.

BACKGROUND:

What will the next generation fighter or penetrating counter aircraft cost? What are some of the considerations that should be made early on that could affect the cost of whatever new program comes about? How will the costs for the next generation aircraft be estimated? The Air Force Scientific Advisory Board (SAB) recently asked these questions to help them determine what approaches should be considered to enable air superiority against increasingly sophisticated air defenses for the Air Superiority 2030 Enterprise Capability Collaboration Team. This brief provides the Air Force Cost Analysis Agency's (AFCAA) advice on cost considerations. It details the difficulties and methods of estimating life cycle costs for aircraft programs when the design concept is still being formulated. Recent experiences from reference programs is detailed to provide a framework for contributors to costs and past lessons learned. Further, it suggests innovative approaches/considerations to reduce the cost in all phases of the life cycle.

DIFFICULTIES IN COST ESTIMATING

Military aircraft have been historically designed to push the cutting edge of technology to gain an advantage over potential adversaries. Since World War II, the push in need for advanced aircraft have been manifest in changing performance goals and technology drives to meet those goals. Table 1 depicts these changes by era.

Table 1: Performance and Technology for Military Aircraft By Era

Timeframe	Dominant Performance Goals	Technology Drivers
1940s-1950s (1st^st^ and 2nd^nd^ Generation)	Speed Ceiling Rate of Climb	Aerodynamics Propulsion Materials
1960s-1970s (3rd^rd^ and 4th^th^ Generation	Maneuverability Agility Flexibility Multi-role	Mission Systems Systems Integration Propulsion
1970s-1990s (5th^th^ Generation)	Stealth	Airframe Shaping Materials Mission Systems
2000s-Beyond	Affordable Stealth Data Fusion Connectivity Persistence	Optimized airframe design Open Mission Systems Networked Operations Unmanned Operations

This constant change in performance desires and the methods of utilizing the current state of the art technology combine to make it difficult to estimate the cost of the next generation of military aircraft. Typically cost analysis is an empirically-based forecasting approach that uses historical data from prior programs to predict the cost of future programs. Since these programs are rather expensive and take several years to complete, the data set of completed programs is small and often seems out of date.

As anyone reading news reports can attest, the DoD military aircraft programs have been plagued by cost growth and schedule delays. The B-2, F-22, and F-35 all experienced these problems during development phase which continued into production. The B-2 bomber was the first time that stealth techniques were used in a manner that was conducive to aerodynamic design and utilized composite structural materials for both reduced radar signature and reduced weight. The F-22 was a fighter design that pushed the edge in materials technology for stealth and speed, increased the performance of the engine for super-cruise capability, and used an integrated avionics architecture to perform super computer like performance inside the aircraft. The F-35 carried stealth design further trying to achieve affordability by designing three different aircraft in the same development program for the Air Force, Navy, Marines, and international partners. Additionally, the F-35 advanced the engine from the F-22 to allow short take off and vertical landing as well as even more advanced avionics that were fuzed in the smaller airframe. Each of these programs had some relationship to programs that preceded them, but in several important ways, they were different.

All of these programs also included an early prediction for Operating and Support (O&S) costs. These costs can be the largest part of the life cycle (averaging 63%) and are usually far in the future from when the aircraft are being designed. However, the design and build decisions being made early on have a large impact on the costs that the DoD will pay in the future. Much of the O&S costs is based on the reliability and the cost of the items that will need repaired during the life of the aircraft. Some newer design concepts can help to reduce cost, for example composite parts which are lighter, can help the overall fuel usage on aircraft. However, as aircraft have been asked to have higher performance and capability, the unit costs for the repairable items have increased.

STEPS OF A HIGH QUALITY COST ESTIMATE

One way to address the difficulties in developing cost estimates is to use a disciplined approach to achieving the result. The General Accounting Office (GAO) develop a cost guide published in 2009 that lists the twelve steps in developing a high quality cost estimate. They are shown below.

The Twelve Steps of High-Quality Cost Estimating

1. Define the estimate's purpose
2. Develop the estimating plan
3. Define the program characteristics, the technical baseline
4. Determine the estimating structure, the WBS
5. Identify ground rules and assumptions
6. Obtain the data
7. Develop the point estimate and compare it to an independent cost estimate
8. Conduct sensitivity analysis
9. Conduct a risk and uncertainty analysis

10. Document the estimate
11. Present the estimate to management for approval
12. Update the estimate to reflect actual costs and changes

This list shows the key features and helps to provide some discipline in devising the estimate. The first two items of determining the purpose and plan help to guide the overall objective for analysis. Items 3, 4, and 5 are used to define the work content and point the analyst to what are the important parts that help to define the item being estimated. Once this structure exists, items 6 and 7 guide the data analysis and quantify the results into an initial point estimate. The point estimate only represents one possible outcome given the uncertainty of forecasting future costs. Items 8 and 9 are key to quantifying the range of possible outcomes and where the point estimate lies on that continuum of possibilities. Steps 10 and 11 communicate the results of the analysis to decision makers. Finally, step 12 is the feedback mechanism for checking the estimate as actual cost information is obtained.

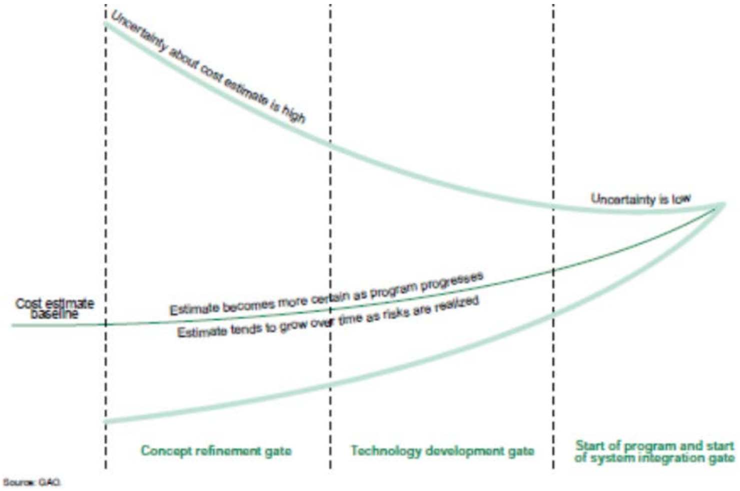
Cost estimating methods have advantages and disadvantages and should vary as the program being estimated matures. Table 2 depicts the various methods for estimating along with the advantages and disadvantages. Parametric approaches use statistical relationships between cost and various independent variables when not much is known about the program being estimated. They are easy to implement, but are high-level and may not predict radical change from the data used to develop them. Analogy methods use data from one or a few completed programs with detailed adjustments to account for differences. This method requires some expert judgement knowing the past program and the new program and can be easy to show the cause and effect. However, it requires the prior program to be similar and may constrain the expert opinion and may lose the greater context. An engineering estimate breaks the cost down into low level cost components (such as direct labor, direct material, overhead, etc.) and use industry standards for determining costs. This method is useful for knowing the details of the work, associating the cause and effect, and can be used for measuring schedule and work performance. However, it requires detailed knowledge of how the work will be accomplished, is time consuming to implement, and may not account for unanticipated work that could be picked up by the data used in the parametric or analogy approaches. Finally, the actual costs method uses cost data from the same program being estimated to generally predict future production costs for additional items. The uncertainty of using data from other programs is eliminated and low-level adjustments can be made. However, this method requires excellent knowledge of the costs of the program which are not available for an immature program. It does not totally eliminate the need for projections if changes are required (such as make vs buy changes or new manufacturing approaches) that weren’t used in the actual cost data).

Table 2: Cost Estimating Methods: Advantages and Disadvantages

Cost Estimate Method	Advantages	Disadvantages
Parametric - method uses statistical analysis to relate cost to one or more independent variables	* Easy to perform and quickly adjust * Can be done early when little tech definition * Uses actual history from several programs	* Relationships may be associative but not causual * May not be able to predict radical change * Typically higher level in nature
Analogy - method uses historical data from analogous system or subsystem that is similar to one being estimated and uses adjustments to account for differences using factors based on quantitative measure or expert judgement	* Easy to associate cause and effect * Easier to get judgement based on experience from prior known program * Not as much detail knowledge required as engineering estimate method	* Must have similar baseline program data * Requires technical insight at a higher level than in the case of parametric method * Expert opinion can be constrained and may not have greater context
Engineering Estimate - method uses low-level component breakout each is which is estimated by the functions (direct labor, direct material, o/h, other) using drawings and industry standards	* Easy to associate cause and effect * Very detailed with ability to drill down to specific work packages * Can be used with schedule analysis	* Difficult and time consuming to implement * Need detail knowledge of work scope and resources * May not account for unanticipated work that may be included in overall data used for analogy/parametric
Actual Costs - method uses actual costs from early units or production units to estimate future costs of the same system (note: contract price may not reflect actual cost)	* Eliminates uncertainty from using data from other programs or contractors * Can be detailed enough to have high confidence in low-level adjustments	* Data not available early in the program life * May still require projections to account for new approaches and make vs buy changes

As mentioned in the GAO Cost Estimating Assessment Guide, the cost of a program generally has some level of uncertainty about it. This level of uncertainty is deemed to be the most at the very start of the program. As the program proceeds from concept refinement to technology development and systems integration, the level of uncertainty tends to decrease. However, at the same time, as more risks are realized the baseline estimate tends to grow as well. This behavior is depicted in Figure 1.

Figure 1: GAO Cost Estimate Uncertainty as Program Matures



Source: GAO.

When estimating aircraft development programs, it is often useful to think of the major "chunks" that are required to be covered. Typically, a good way to think of development is to design, build, and test units that will eventually be produced in larger quantities as production proceeds. Design is the nonrecurring effort to translate requirements into a material solution. Design engineering is typically composed of both hardware and software detailed design where drawings and software lines of code are used to describe the structure of the end item. It also includes systems engineering to understand the requirements, decompose them, and flow them down to specific work to be done as portrayed by the work breakdown structure. Systems engineers and design engineers work together to ensure the design will meet the requirements. Once reviews have been made, a few items of the design need to be built and programmed with the software to manage the systems. Finally the test phase is used to compare the performance of the build times to the original requirements to ensure the production items will meet the consumer's (government's) need.

DESIGN ESTIMATING METHODS

Cost estimates for the "design" chunk are performed in a variety of ways. For the hardware design, the nonrecurring costs can be related to the technical or performance characteristics of the aircraft. Technical parameters such as weight and material mix are used to define the concrete design aspects of the aircraft. Performance parameters such as speed, radar cross section, ceiling, turning loads, or carrier usage can also be used to further define the system. For high-level estimates time-related parameters such as first flight date can be used to capture the general change in technology as time progresses. The parametric approach requires historical cost and technical information that resembles the new program being estimated to be statistically brought together to form relationships to forecast costs.

Another approach for estimating the design chunk for hardware is to price out the cost of the staffing required by using headcounts. This method requires data on a detailed level from a prior program such that the composition of the staffing used can be broken out. The staffing levels and durations are then adjusted as necessary to account for complexity differences and schedule differences between the analogy program and the program to be estimated. This method is useful in that the data is generally something that is tracked by programs and is available. It allows for a simple comparison to a predecessor program that is known and the schedule can reflect the new program. Downfalls of this method are that the complexities that drive staffing comparisons between programs may not well be understood at the outset of the program. Also, the schedule is typically the one that is assumed to be correct and does not account for unknown delays that have not yet been anticipated. It also is difficult to draw a direct comparison of the technical and performance parameters that are desired.

Besides for the airframe cost, the propulsion system is usually an important piece of the aircraft design phase and has its own methods for estimating the cost. These methods generally resemble the ones used for airframe such as parametric using technical and performance measures (thrust, airflow, overall pressure ratio, afterburner, etc.) or analogy using schedule as a way of adjusting the cost. The difference is the analogy approach is used at the module level where differences can be accounted for in using subcomponent cost information.

Given the increase in functionality of aircraft, software has become a large driver in cost estimates. The use of Source Lines of Code (SLOC) and productivity measures (hrs/SLOC) are one way that the cost of the work can be directly tied to the scope of the work. Parametric models are also used but these need to be calibrated using information from known programs. Lately agile software development has become popular. The methods for predicting this software development approach are still evolving.

BUILD ESTIMATING METHODS

The "build" part of the development estimate is associated with the fabrication and assembly of units that will be used for testing to verify that the design meets the requirements specified at the beginning of the project. This part of the estimate generally is done similar to production estimates. They typically are done at the air vehicle level and are based on the functional elements the costs are composed of (manufacturing labor, engineering labor, raw material costs, subcontracted equipment costs, etc.). The metric of dollars per pound ($/lb) are sometimes used where there is not much detail to make specific estimates of material costs. Priced bills of materials are also used for the major subcontracted items with analogous complexities to account for differences. Adjustments for the type of materials used in the structure can be made to account for raw material cost difference and for difficulty of manufacture. Oftentimes the production costs are first estimated at a stable point in production and cost improvement or learning curves are used to backwards project the cost of the development units. Some programs have prior prototype efforts where costs of the articles has been captured. However, often these costs are not representative of the ultimate aircraft in production since they generally only have to demonstrate a limited amount of capability and fly for only a limited amount of time. Also, subsystems on prototypes may come from other aircraft programs and may not be optimized for use on the future production design.

TEST ESTIMATING METHODS

The "test" chunk of the development program have several subparts that have their own methods. Usually, comparisons are made to prior programs to try to account for the scope of the effort. These comparisons are generally schedule related such as duration of the program, number of flight test hours require for the various parts of the aircraft to verify performance. Ground test costs are estimated using analogies to other programs to account for things such as Software in the Loop (SILs) labs, wind tunnel testing based on hours, or test article cost based on historical ratios to the cost of the flight test aircraft. Flight testing is typically based on the number of hours using a lower level break out of the tasks to be performed (typically derived from the Test and Evaluation Master Plan) and the productivity to achieve those flight tests. Analogous headcounts and predicted schedule can also be used to develop an estimate.

The test phase also has ties back to the design and build chunks of the estimate. Both hardware and software design need to be relatively complete to begin testing. Last minute changes to hardware and delays to software releases can delay full system level testing and cause major disruptions to the building of the test aircraft. As testing is done and problems are found, the cycle can feed on itself as redesign is required and changes to items already in the build phase need to be updated.

PRODUCTION ESTIMATING METHODS

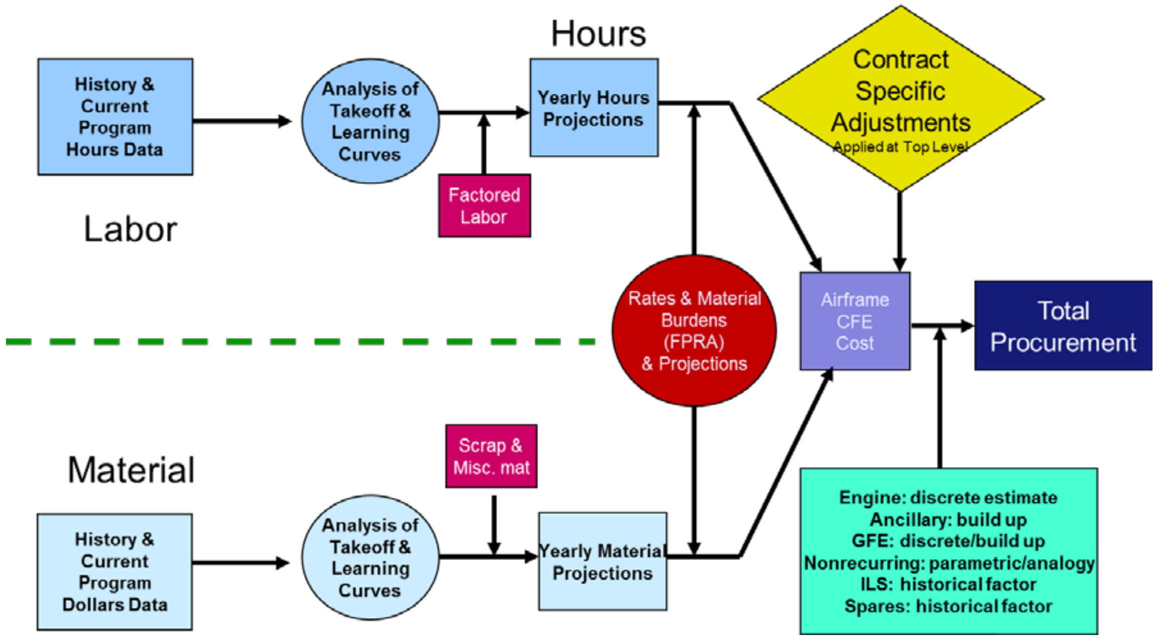
Estimates in the production phase of the life cycle aim to predict the yearly funding required given whatever quantity is selected to be bought in the future. The air vehicle costs are usually done at the functional level to estimate the costs of labor and materials to build the aircraft. The cost information can come from the program itself (from early developmental units or prior production lots) or from other analogous programs. Learning curves that use price decreases for increases in cumulative quantities and rate curves that use price decreases for increases in yearly quantities are typically used to predict the yearly funding required for each production lot. Current labor rates and material factors are used to bring to the estimate the latest economic information available.

Adjustments to production estimates also need to be considered. If a $/lb approach is used, the weight and possible weight growth are used to predict the final cost. If material type is deemed to be a determining factor in the cost of the airframe, then that adjustment also needs to be made. Often times, accounting systems of the prime contractors change and the hours or dollars estimate needs to be adjusted to line up with the latest rates and factors used.

The other cost elements that round out the full yearly procurement costs are based on several different approaches. Propulsion costs are estimated using cost data from analogous prior programs or cost estimating relationships that relate design features (e.g. thrust) to cost. Discrete estimates for specific equipment such as government funded items, ancillary equipment (such as weapons pylons and bomb racks/launchers), and production rate tooling. Before a full logistics plan is quantified, factors are typically used to estimate the support equipment and initial spares costs.

Lastly, adjustments are made to accommodate specifics of the contracting approach used. For example, multi-year and block-buys where multiple production lots are to be procured in one large contract often imply that there will be nonrecurring upfront costs to implement changes to the production approach and economic order quantity (EOQ) to buy material up front in an economic fashion. Also, if there are long-lead items that require additional time to feed the production lots, advance procurement costs are included in each year before the buy year. This amount needs to be credited back to the production buy year. Figure 2 shows a flowchart of the methods used for production cost estimating.

Figure 2: Flowchart of Production Cost Estimating Methods



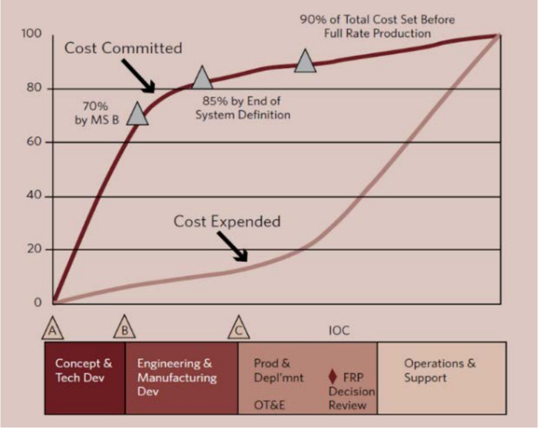
OPERATING AND SUPPORT COST ESTIMATING METHODS

The operating and support (O&S) cost phase represents the costs of the program from initial deployment to termination. It is the costs of operating, maintaining, and supporting the system. It includes both direct costs of operations (such as manning and fuel costs) but also the indirect costs (such as medical support to direct operators). There can also be contractor logistics support costs that are paid to the contractor to support the fielded system.

In 2007, OSD's Cost Assessment and Program Evaluation (CAPE) group provided a guide to estimating the costs associated with operating and supporting programs. In the guide, the elements of O&S costs are defined. Unit level manpower consists of the operations and maintenance costs at the operating units. Unit operations is the costs of consumption of materials during operations such as fuel, electricity, expendable stores, and other operating materials. Maintenance is the costs of labor and materials to keep the system going and includes costs for items that need to be replaced or fixed. Sustaining support is the cost of centrally managed support outside of the unit operations and attributable to the specific system. Continuing Systems Improvements is the cost category used to estimate the costs of hardware and software updates after the system is deployed. Finally indirect support are installation and personnel support costs which cannot be directly related to the operations of the unit

Although O&S costs make up the largest amount of the life cycle costs, decisions made very early in the life cycle affect these large costs and progressively more program costs are committed as the program matures. At MS A, early decisions are made on CONOPS and mission requirements. During this phase, there is little funding actually *expended*, but a large amount of cost is *committed*. From MS A to MS B, more decisions that further define the airframe, subsystems, propulsion systems, and software are made that expend some additional dollars, but it further commits the future costs of the program. By the time the program reaches MS C and is in initial production, only quantities and flying hour adjustments can be made to refine the committed program costs. Figure 3 shows this comparison of expended and committed program costs as the life cycle progresses.

Figure 3: Cost Committed vs Cost Expended through the Life Cycle[1]



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[1] *Designing for Supportability: Driving Reliability, Availability, and Maintainability In While Driving Costs Out* by Dallosta & Simcik, published in Defense AT&L, Mar-Apr 2012, Figure 4, page 37.

RECENT AIRCRAFT DEVELOPMENT PROGRAMS – COST CONTRIBUTORS

The three most recent Air Force military aircraft development programs (B-2, F-22, and F-35) all experienced major issues with the cost during the development contract. Each one started with its own requirement that was somewhat comparable to prior programs, but was not quite the same. Usually, a newer program needs to be superior to the old one to buy its way into the budget for funding. One approach that has been used to reduce the risk of the new development programs is to establish technical maturation demonstration programs. Each of the three above programs had their own demonstration programs that, to some extent, built a prototype. However, these risk reduction and prototype phases didn't guarantee success for the rest of the life cycle. Each program had different contributors that increased the cost, delayed the schedule, and continued the need for follow on development well into the production phase and beyond.

The B-2 development was started as the Advanced Technology Bomber in 1979. Although Northrop had prior experience in developing and building flying wing aircraft and some prior experimental test beds (Tacit Blue) had helped to prove the technology, it did not prevent cost and schedule growth on the design that was ultimately built. After the contract was awarded and the design staff was ramping up, the mission profile for the design was changed from high-altitude penetrating strategic bombing to low-altitude, terrain following[2]. After an initial Preliminary Design Review (PDR) was completed, this mission change required a second PDR two years later. This change in mission necessitated major design changes which added years of delay and billions of dollars of cost growth. The difficulty in designing an all aspect stealth design and the push for production resulted in only a small fraction of the drawings being completed by the Critical Design Review (CDR) where the design should be ready for building test units. The high development cost also ran into high production costs that further eroded political support and caused the production to be reduced from 132 to 20 aircraft. After initial development and production, the program continued its development requiring modifications to its structure and mission systems such as mission computers, communications links, and radar until the current day, twenty years after the initial development contract ended.

The F-22 program also experienced an extended development program but for different reasons than the B-2. The development program began after the Advanced Tactical Fighter (ATF) competition ended, where two prototype aircraft were flown. The prototypes looked similar to the aircraft from the main development, but was different in many ways. Soon after the full development contract was awarded, the program design team was moved from California to Georgia (it is estimated that only 10% of the staff made the move) and was composed of three prime-level teammates who were prior competitors. The allocation of work among the three teammates was somewhat artificial and was used to spread the work evenly across them (not necessarily based on specific competency)[3]. Even at the subsystem level (e.g. the radar) had a work split between two competing contractors (Northrop and Raytheon) for parts of the system based on contract dollar value[4]. The aircraft also pushed technology in many areas of the air vehicle at the same time. The airframe continued to use advance composites and

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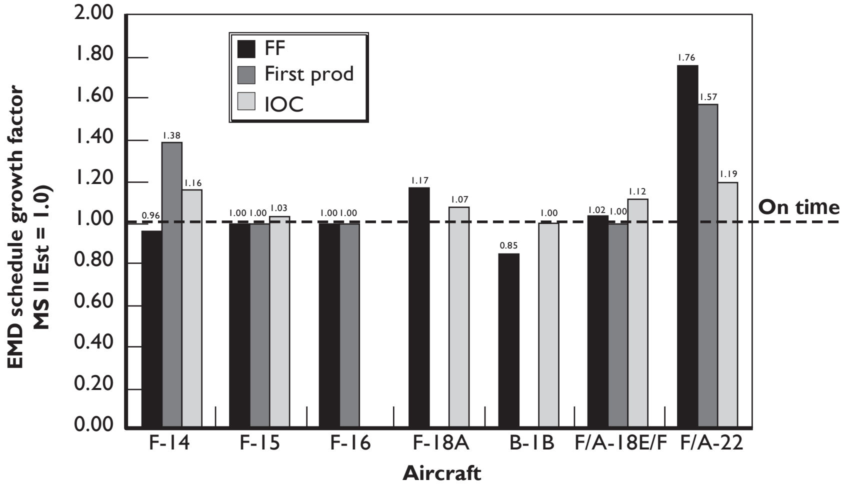
[2] http://www.airvectors.net/avb2.html

[3] For more information on the F-22 teaming and development, see *Lessons Learned from the F/A-22 and F/A-18E/F Development Programs*, by Younossi, Stem, Lorell, Lussier, RAND Corporation, 2005.

[4] See Appendix D in *A Cost, Technical, and Industrial-Base Review of Select Airborne Radars*, by Stem, Dryden, Balakrishnan, RAND Corporation, 2008.

radar reduction materials. The propulsion system used an advanced super-cruise engine with thrust vectoring. A new integrated avionics suite was used for the first time which required more software than what had ever been required for a fighter aircraft and included cutting edge technologies such as the active electronically scanned array radar. The weight of the air vehicle was much higher at the start of the development, which lead to a redesign to reduce the weight; it remained an issue after the major design reviews. Compared to prior fighter aircraft development programs, the F-22 experienced more schedule growth as compared to its estimated schedule at the start of development. Figure 4 compares F-22 development schedule to other military aircraft development programs normalized to the schedule at the outset of the program.

Figure 4: Military Aircraft Development Schedule Growth Comparison[5]



NOTE: Numbers on top of bars reflect current estimate.
RAND *MG276-1.6*

After the experiences of high cost growth on the B-2 and the F-22, the next aircraft program goal was to attempt to develop a low-cost, affordable fighter design that could be used for multiple US armed services and our allies. The effort started with a prototype phase called the Joint Advanced Strike Technology (JAST) program that flew two competing aircraft to demonstrate each design. This initial phase was followed by Systems Design and Demonstration (SDD) phase where the program attempted to develop three different air vehicle variants in the same development contract by using different levels of common parts. The thought was that three aircraft could be designed for the cost of two aircraft due to the inherent commonality. Although two aircraft were built and flown in the prototype phase, that design did not represent the final design in the SDD phase or built in the production phase of the program. Figure 5 shows the side-by-side comparison of the X vs the F version of the aircraft. It is evident that the design changed greatly across the entire aircraft including the STOVL propulsion system that was the heart of the prototype phase effort.

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[5] From RAND Report, *Lessons Learned from the F/A-22 and F/A-18E/F Development Programs,*2005.

Figure 5: X-35 vs F-35 Side-by-Side Comparison[6]

Although some aspects of this design concept were achieved, the program experienced probably the largest cost and schedule growth of any fighter program prior to its inception and was exacerbated by doing three designs in the same contract. The strict requirements for short take off and vertical landing for the USMC variant became an overwhelming issue and caused the program to require a full redesign. The program decided to allow the initial design for the Air Force variant to be built as a way to gain further design understanding, knowing that it did not represent the final production configuration. However, all three variants of the aircraft required redesign including the subsystems used in each variant. A large amount of software (both air and ground) were required to be written to support the highly integrated avionics suite. The propulsion system (both the cruise engine, based on the F-22 engine, and the STOVL lift equipment) required redesign during development.

The desire to enter production before development was completed resulted in a concurrency between the two phases of the program where design changes were being fed to aircraft already in production. Traveled work, essentially manufacturing retrofits, plagued the test aircraft as they were being produced causing delays in the flight testing. It also caused early production aircraft to be delivered that did not meet the full capability as outlined in the SDD contract.

In development programs which are defined by large design staffs required for both initial design and design changes, the largest cost driver is time. At the peak of development, the prime staffing level amounted to thousands of people working on the program; additionally, subcontractor staff were charging to the program and needed to accommodate continued design changes. SDD has continued as several hundred Low Rate Initial Production (LRIP) aircraft have been delivered to the customers. The design phase will continue into the future through follow-on development to incorporate updates for some years into the future.

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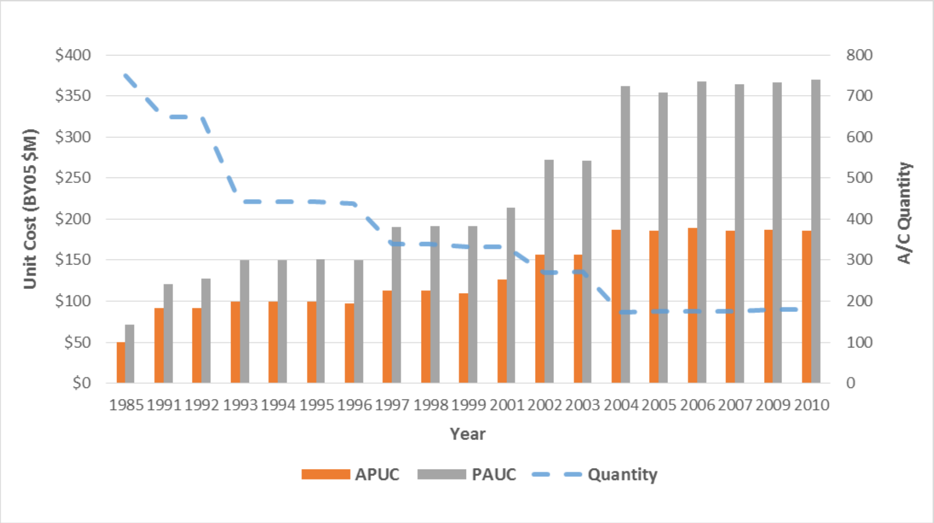
[6] Source: *X to F: F-35 Lightening II and Its Predecessors,* Code One, Second Quarter 2008, page 19.

Besides for development uncertainties being present, early estimates for aircraft production are based on historical information and rely on predictions of cost improvement or "learning curves" to predict the future costs. For example the F-22 was originally estimated to cost $50M (FY2005$) per unit[7] based on historical information from the aircraft programs that occurred in the 1960s-1980s. However, the data used for predicting the costs did not include any designs similar to the F-22 that was pushing the extremes in all aspects of the air vehicle. Similar to the F-22, the F-35 used history from the "teen series" programs for its original cost estimates, but soon switched methods to using cost history from the F-22 and F/A-18E/F programs. Although the two newer programs allowed for capture of more up-to-date costs for newer materials, propulsion, and avionics, they were not totally complete such that the full production learning curve was available for predictive use. Additionally, the commonality and the international production on the F-35 further complicated the predictive complexity of production costs estimates.

In addition to using historical data that may not capture the complexities of the new design aircraft, cost growth on the program typically has a compounding effect by driving down production quantities. The F-22 production cost estimate history from Selected Acquisition Reports is depicted in Figure 6. The SAR publishes two unit costs to measure cost growth: the average procurement unit cost (APUC) which is the average of the production phase and program average unit cost (PAUC) which includes development costs. As these unit costs increased, cuts in production quantities were made. Production at the onset was for 750 aircraft to replace the aging F-15 fleet, but ended up with only 187 aircraft produced. The cut in quantities only added to the increased unit cost being reported. The 2010 SAR estimated the APUC for the program to be $186M/unit (BY 2005$) after the effect of cost growth and procurement quantities are taken into effect – 3.5 times higher than the initial APUC estimate.

Figure 6: F-22 Unit Cost Over Time and Quantity Change



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[7] This cost represents the estimated Average Procurement Unit Cost (APUC) for 750 aircraft from the Selected Acquisition Report.

INNOVATIVE APPROACHES TO REDUCE DEVELOPMENT COST

Design requirements and acquisition approaches drive the design cost but both can also be used to manage costs. Requirements of what the aircraft has to accomplish are manifest in the design that ultimately comes about. Limiting the demand for increased capability can be accomplished in how much the new aircraft needs to push the envelope as compared to prior efforts. Acquisition approaches can be used help reduce cost growth as the program proceeds though the development phase.

Limiting the requirements of the new design can help to limit cost growth. The F-16 benefited from a specific requirement for a new lightweight fighter that used a prototype design that largely was unchanged when it went into full scale development and production. Another approach to limiting cost growth is to use an open, federated avionics suite. It can cost more to establish up front, but can be beneficial to the customer by not being locked into a design that is hard to modify and can allow for competition at the component level to reduce costs. A third technique to limiting cost growth is challenging the contractor to use less software which typically causes delays during development. Another requirement limitation is to relaxing the RCS requirements; this requirement drives many design trades such as internal avionics, internal payloads, and internal fuel that make it hard to accommodate changes. Also, using podded systems allows for equipment that can be changed for new missions and can be competed to other contractors. Finally, keeping the design and requirements stable while the program is at peak staffing can limit cost growth. If the design is off track, quickly realize that issue and don’t continue work on a design that won’t be produced as in the F-35 example.

Acquisition approaches can also be used to manage cost. As in the case of the F/A-18E/F, an incremental approach was followed that began with a new airframe but used existing avionics. As time progressed and avionics technology could be developed outside the main program, it could then be incorporated into the aircraft. If teaming arrangements are to be used, make them based on prior experience and clear lines of responsibility; don’t use artificial teaming to maintain equal funding across contractors. Since all development programs have uncertainty, start with a sufficient amount of management reserve that can be used as unknown issues arise. Finally, designing to the hardest mission for a family of aircraft and limiting the deviation from that design help to limit cost. One example of this approach was on the E-2 aircraft program. After the demanding surveillance version was designed, the less demanding C-2 cargo aircraft evolved from the E-2 design and was able to save on the cost and time to develop the aircraft. A similar approach was conceived for F-35 to use the Navy variant and slightly modify it for the Air Force to save some weight, but largely keep the structure common between the two versions. Unfortunately, this concept was never accepted by the program.

INNOVATIVE APPROACHES TO REDUCE PRODUCTION COST

As the program is being planned out, decisions can be made to reduce production costs. These decisions are controlled by both the customer and the contractor. Each one has control over some choices that will affect the production costs. The customer’s choices include:

1. Deciding the number of units required to perform the mission
2. Determining the approach used for contracting
3. Choosing to use missionized avionics vs tightly integrated avionics
4. Determining a program schedule to avoid concurrency between development and production

At program inception, deciding on the number of units needed is an obvious way to affect production costs. Things such as the concept of operations, the availability of the aircraft, and the capability of the aircraft can affect the number of units required. Understanding the concept of operations and how it fits in the larger force capabilities (including joint assets) can allow for trades on total quantity. If an aircraft is more available largely due to reliability of subsystems, fewer total aircraft are needed. Finally, a trade of capability vs cost needs to be considered; if a more capable aircraft is selected, it may allow for fewer total needed to perform the same mission.

Determining the contracting approach is also an important customer decision. Using fixed price contracts (as in the case of the KC-46) can limit the production cost growth and lock in prices. Another approach is to align the contractor and customer desires. For example, the F/A-18E/F program used a production multiyear contract to achieve both cost savings in the near term for the Navy and allow for Boeing to drive down the aircraft unit costs to make it more desirable for future competitive foreign military sales.

Since avionics is typically a complex part of the aircraft and drives both production and O&S costs, it is an important area to consider how they should be built. One choice that can be made is to build tightly integrated avionics. The problem with this approach is that any future upgrades or modifications to one part could cause a ripple affect of redesign other parts of the avionics suite and software. A solution to this problem is to use systems that are used on other aircraft (such as common radios and antennas) or podded systems that allow modular capability for the subset of the fleet that needs the specific capability. These methods also allow for competition for contractors besides the incumbent contractor. Finally, considering using off-board systems (such as sensors from other aircraft that can link information) could also be used to cut down on the total number of sensors procured.

The schedule of the program to reduce concurrency between development and production can also affect the ultimate procurement costs. The B-2, the F-22, and the F-35 program started producing in larger quantities while the development phase was still on-going. This concurrency led to unstable design that caused design changes to be made while the aircraft were in production. Changes on the aircraft and tooling updates were needed to build and assemble the parts. Additionally, a retrofit of the already produced aircraft was required and some early production aircraft could not be retrofitted in an economic way, limiting their usefulness.

The contractor can also make decisions in the design that will affect the production costs. The contractor controlled decisions are:

1. Using standard materials and processes vs new less tested approaches
2. Designing with manufacturing in mind to save labor
3. Using make vs buy decisions to allocate work to the best source
4. Reducing part counts to save in assembly work
5. Choosing to use or modify available engines for integration

When the design uses standard materials and processes that are well understood, the production cost should be less and should help to contain cost growth. Standard materials such as aluminum as compared to more exotic materials such as titanium not only have a lower cost to buy, but require lower cost tools to fabricate parts. Also, given the larger market for standard raw materials guards against dramatic cost fluctuations in the market as titanium experience in the mid-2000s. A comparison of the two aircraft from the Lightweight Fighter competition (the YF-16 that became the F-16 and the YF-17 that became the F/A-18) demonstrates this characteristic. The YF-16 used aluminum as its primary structural material and carried this approach into the production to keep the price of the F-16 down. The YF-17 adopted composite parts, which were cutting edge at the time, causing manufacturing disruptions and early cost problems for the F/A-18 production line.

Designing with manufacturing in mind is a tenant in the concept known as lean manufacturing where the value stream (each step in the product build to delivery) is analyzed for inefficiencies and waste. In the RAND report, *Military Airframe Acquisition Costs,* by Cook & Graser, it documented the functional areas of cost and how they could be affected by implementing lean manufacturing ideas. However, due to the timing of when the report was written as these methods were just beginning to be adopted, they could not conclusively say it was time to adjust cost estimating methods to account for savings due to lean. Additionally, the nature of both the aerospace market and the monopsony effect of the DoD being the main customer of military aircraft, the savings from lean seemed to be diluted.

When the contractor is considering whether to make a part or buy it from a vendor, the decision should be determined based on cost and competency. Unlike the method of spreading the work share based on an artificial split of the costs used in the F-22 example, care should be exercised to determine who can make/build the item for the least cost. Specific, demonstrated competency and labor rates should both be used in the decision. Also, competitors in the same market, such as the cases of the two contractors used on the F-22 radar, splitting the work should be carefully considered.

Reducing parts counts is another design decision that the contractor can control. By using tools such as computer aided design and manufacturing (CAD/CAM) as well as virtual assembly, designers have a much better idea of the process that will be used when fabricating and assembling parts. Fewer parts should mean a smaller inventory to keep up with less labor at the prime for final assembly. However, these benefits could be offset by more complex and expensive parts.

Finally, the contractor has some say in what propulsion technology is used in the aircraft design. Using already designed engines or only slightly modifying an existing engine should help to lower the production costs and reduce risks in integration in the airframe. A good example of this is the use of the modified GE F404 (the GE F414) engine used in the F/A-18E/F. The engine had a long history on the F/A-18 A/B and C/D models and was upgraded in outside efforts (including the failed A-12 program) to be ready for use on the F/A-18E/F. It established a known baseline design at the core of the air vehicle.

INNOVATIVE APPROACHES TO REDUCE O&S COST

Some of the same considerations that save Production costs can also apply to saving Operating & Support costs. Some are controlled by the customer and some are controlled by the contractor.

Customer decisions that affect O&S costs include:

1. Concept of Operations (CONOPs) and material solution – manned vs unmanned example

2. Quantity of aircraft and usage (flying hours)
3. Trade of today's technology vs future technology
4. Sustainment strategy (organic vs contractor)

The CONOPS chosen can have a large impact on the future O&S costs. For example the decision to make the aircraft unmanned vs manned can greatly affect O&S. Let's consider the example of the MQ-9 Reaper. Although the lack of a pilot in the cockpit seems to indicate a savings to manpower, each MQ-9 typically has at least three operators flying the aircraft and monitoring the ISR data and managing target intelligence. Also, the MQ-9 requires satellite and data transfer while a manned aircraft could perform the mission (although with reduced intelligence) with minimal satellite linkage. Additionally, the MQ-9 cannot self-deploy and requires transport aircraft to deliver it to the theater of operations. It requires a forward deployed support crew needed for local operations. Finally, the early days of MQ-9 operations were plagued with a high crash rate that tended to damage the aircraft and destroy the relatively expensive sensors.

It is obvious that the quantity of aircraft required will also determine the eventual O&S costs, but also the usage has an effect as well. As the aircraft is used more, the engines and subsystems will require more scheduled maintenance. More usage also will mean more costs for fuel and consumable items. The environment (such as salt water environment for the Navy or desert conditions with fine sand particles) also has an effect on the O&S costs. One study also concluded that the lack of usage (fewer hours in flight) also contributed to cost due to more time that aircraft spent on the ground accumulating corrosion damage due to water condensation.

The decision to go with current technology vs game-changing new technology can also have an effect on O&S costs. For example although stealth is a big advantage in performance while the mission is being carried out, but it can have O&S cost ramifications. Early stealth aircraft required environmental control and difficult repair work to cut through the skin to reach subsystems for repair. Patching the skins after the repair and checking the radar return was a laborious process. Also, stealth aircraft tend to have a clean exterior and require internal weapons bays where heat can build up that affects the aircraft systems and the weapons.

Finally, sustainment strategy also affects the O&S costs. The older aircraft typically used a three level approach: organic, intermediate, and depot. Simple procedures were done by the maintenance crews organically at the flight line. If more work was required to repair a box, there was an intermediate shop that could do some component repair work. If heavy maintenance was required the aircraft or subsystem would be sent back to the depot for repair. This approach required more inventory at all levels of the process. Today, given the complexity of the systems, more maintenance work is done by the contractor who originally designed and built the aircraft. This approach tends to lock in continued dependency on the contractor due to lack of technical data and equipment to perform the repairs by government depots.

Contractor decisions that affect O&S costs:

1. Reliability of subsystems and cost per subsystem
2. Software attributes
3. Engine selection

Subsystems tend to be one of the larger cost drivers in O&S that is directly linked to the contractor design. The reliability of the subsystems not only drives the mission capability rate of the aircraft to perform it's desired mission, but it also affects how often maintenance needs to be done. Unreliable subsystems can cause more maintenance actions, more spares to be necessary, and more overall aircraft to be required as backups for aircraft that can't perform the mission. Also, the costs per subsystem have tended to become higher due to each item becoming more complex. As such, the replacement and repair costs of the subsystems tends to increase.

Software considerations are important factors that the contractor determines at the early part of the design phase and can affect O&S. Obviously the larger the size of the software code, the more software maintenance needs to be funded. During the life of the aircraft modifications and updates become harder as the size of the software increases and the functionality is embedded in the overall software architecture. Finally, the selection of language can have an effect on future support cost. For example, the F-22 used Ada software that never caught on outside the DoD; it has become harder to find qualified software experts who are familiar with the outdated language and can drive up costs.

Engine selection can affect the O&S costs. Commercial engines are often sold at a discount due to the expectation by the contractor that they can more than make up for the discount through future support costs for labor and material items. New design engines used for military only purposes can affect the O&S costs due to limited users demanding the parts required to maintain them. Engines that push the state of the art can also require high cost replacement items due to limited life.

Note that it can be hard for the customer to consider O&S costs at the early stages of the aircraft design and to create incentives to guide the contractor to provide solutions that reduce O&S costs. Since it typically can take military aircraft five to ten years to just reach the end of development, the O&S costs are not part of the budgeting window considered when decisions are being made on the aircraft acquisition. Also, given that some of the major contributors to O&S costs (such as manpower and fuel) are considered to be outside the control of the contractor, it can be hard to determine a way to provide incentives for O&S when the selection of the aircraft contractor is made.

SUMMARY

Estimating the cost of military aircraft early in the life cycle is a difficult task. This task is made more challenging in that new aircraft tend to push the technology as compared to the aircraft that the DoD already has in inventory and has cost data. A disciplined approach as laid out by the GAO provides a systematic way to construct the estimate. There are advantages and disadvantages of cost estimating techniques that should be considered each time for the program peculiarities. Even with this structure, the cost estimator needs to convey that uncertainty still exists in the cost estimate throughout the life cycle.

Development cost estimating for military aircraft programs can be simplified by thinking of it in terms of the major "chunks": design, build, and test. For the design chunk, airframe costs are typically estimated using either parametric methods, which relate early performance and design aspects to cost, or staffing headcounts and predicted schedule. The propulsion costs that can also be a major cost driver are typically estimated using analogy to earlier programs or using parametric approaches. Software can become another difficult area to estimate and a pacing schedule item. SLOC has typically been used as the measure for scope, but with the advent of agile development, it is becoming more challenging to forecast the costs. The build chunk uses some of the same techniques as production estimating breaking the air vehicle out into its functional cost categories or using production estimates with learning curves run back to development. The test chunk uses scheduled flight test hour and schedules along with metrics for productivity to determine the cost. Test also relates back to both design and build chunks since they influence the test program schedule.

The next phase of the life cycle, production, tends to use similar techniques to the build phase in development and needs to account for specific contractual approaches. The functional categories of the air vehicle are often used but the estimate transitions to using data from the program itself for the build of the test units. The learning curve approach is often used to predict future lot costs with more attention paid to the accounting of labor and material and rates used to calculate cost. The items in addition to air vehicle such as propulsion, ancillary equipment, support equipment, and initial spares use various techniques for costing. Finally, the specific contracting approaches used need to be considered.

For O&S costs, which can be the biggest portion of the life cycle, the OSD CAPE provides a guide for estimating the various parts of that phase. Historical data from related systems is often used to develop analogies with adjustments for the specific program. One thing to note is that decisions made early in the development will have an amplified effect on this largest portion of ownership costs.

There are many contributors to cost that are detailed by looking at the three most recent Air Force military development programs: B-2, F-22, and F-35. Each program had its own challenges it was trying to surmount. The B-2 changed its mission as the contractor staffing was ramping up, delaying the schedule while the spending was peaking. The F-22 used a prototype to demonstrate the design, but needed to be totally redesigned for full scale development and production. It suffered from artificial work splits that gave work to competing contractors and pushed the limits on all aspects of the aircraft. The F-35 struggled the most by designing three aircraft variants in one development program. Concurrency between design and build of the test units and production further exacerbated cost growth.

For production, the cost contributors are associated with associating historical costs from legacy programs to the new program and accurately predicting the quantity to be produced. The three programs mentioned above experienced cost growth partly because they didn’t reflect the older programs in terms of their complexity. As the cost of the program increased, both the B-2 and F-22 were cut in quantities that further exacerbated the cost growth.

There are several innovations that can be used to try to reduce cost growth in each phase of the life cycle. In development, these approaches include limiting design requirements and acquisition approaches. For production and O&S, both the customer and the contractor can make choices that will help to limit cost growth. The customer’s choices relate to the overall program design such as CONOPS and quantities. The contractor’s choices relate to choices in design that can help reduce the recurring production costs and the costs to support the aircraft into the future.

While history provides a good guide for estimating the cost of future aircraft programs, each program will have its own new challenges. It is important to remember the past for approaches that did work and for ones that weren’t successful. A systematic way for developing a cost estimates provides a good avenue for capturing what funding commitments the DoD will have now and into the future.