Improved Affordability in DoD Acquisitions through Strategic Management of Systemic Cost Risk

by

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ABSTRACT

For almost 70 years, actual costs of Major Defense Acquisition Programs (MDAPs) in the Department of Defense (DoD) have exceeded on average between 20% and 506% of their life cycle cost estimates, which are official expectations of actual program costs prior to completion. Despite numerous DoD acquisition reform efforts and implementation of sophisticated cost estimation techniques, this cost growth continues to exist. Accurate cost estimates are vital to the capital budgeting process for the DoD since they are used to set the affordability cap for each MDAP and across DoD Component weapon system program portfolios. Affordability is defined as the upper limit a DoD Component can allocate for a program without reducing costs or shifting resources between programs. To improve affordability in the DoD, a method that quantifies and adjusts for the persistent cost growth to enhance the accuracy of cost estimates is needed to promote more responsible and sustainable MDAP capital investment decisions.

This thesis presents a simple yet powerful method of quantifying and correcting for systemic cost estimation risk in MDAPs to improve cost estimate accuracy and, consequently, affordability. Cost estimation risk is defined as the difference between estimated and actual MDAP costs (on average a deficit), and it consists of systemic and program-specific components. This dichotomized risk framework is similar to the one used in the Capital Asset Pricing Model (CAPM) in which the growth rate in value of any one of a set of assets comprising a market in equilibrium is proportional to its systemic risk exposure to that market. In the CAPM, systemic risk – aggregated risk from multiple economic factors – pervades the market and is unavoidable, and asset-specific risk is considered unpredictable due to idiosyncratic uncertainties. By analogy, the growth rate in cost estimates for a program belonging to the "market" of MDAPs is assumed proportional to that MDAP's systemic risk exposure to the market. Like in CAPM, systemic cost estimation risk – aggregated risk from 26 systemic factors identified in this thesis – pervades the market for MDAPs, as evidenced by historical cost overruns, and program-specific cost risk is considered unpredictable and best mitigated by program-dedicated professional cost estimators in the DoD and defense industry. From this analogy, the expected growth-beta relationship of CAPM may be adapted to determine for MDAPs the systemic cost risk-adjusted growth rates for the defense commodity classes of aircraft, electronics and software, missiles, ships, space and satellites, and vehicles. These classes are the same used by the Bureau of Economic Analysis to segment defense commodities into distinct price index "baskets" based upon common inflation risks among commodities within each class. Based on this rationale, each MDAP is assumed to share systemic cost risk within its respective class; this risk is measured by beta in the expected growth-beta relationship. Defense commodity class beta values are calculated by linear regression of historical percentage cost estimate changes of member MDAPs with those of all MDAPs, and then averaging these beta values over the appropriate defense commodity class. Next, the expected cost estimate growth rate for any MDAP may be calculated by first estimating the future expected growth rate in all MDAPs using the arithmetic mean of historical annual cost estimate percentage changes, and then scaling this rate by the particular MDAP's systemic cost risk exposure – the defense commodity class beta value for which it is a member. Finally, the Systemic Risk Factor (SRF) for each defense commodity class is calculated from these growth rates and the forecast time horizon, adjusted for compounding effects over relatively longer time horizons, and then applied to current MDAP cost estimates to form systemic risk-adjusted cost estimates to improve affordability.

This method was applied to an empirical retrospective case study using a set of cost data from six MDAPs, one from each commodity class, as a partial validation of the method. The results of this study show an overall 57% enhancement in estimation accuracy when comparing the initial and SRF-adjusted MDAP cost estimates to the final estimates, indicating quantifying and adjusting for systemic cost risk can improve cost estimation accuracy. To show the effectiveness of this method on improving affordability, these six programs were combined to form a hypothetical acquisition portfolio and assessed for affordability over a five year period. While the unadjusted portfolio was *not* affordable four out of five years, the SRF-adjusted portfolio was affordable in all but the last year, illustrating the benefit of adjusting cost estimates for systemic risk. However, the benefits of improved cost estimate accuracy and affordability come at the cost of potentially over-budgeting for priority MDAPs thereby leaving less funds available for other, lower priority programs. Additionally, this method is not shown to be optimal in the sense of minimizing cost estimate errors to maximize affordability. Still, empirical results are promising and warrant further research into the idea of using SRFs to adjust life cycle cost estimates and ultimately improve MDAP affordability for the DoD.

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1. INTRODUCTION

This work is the culmination of a one-and-one-half year United States Air Force (USAF) Fellowship Program intended to broaden and enrich the experience and education of its members through participation in the Massachusetts Institute of Technology's (MIT's) System Design and Management program. Through the pursuit of their fellowship goals, Airmen[1] are expected to intellectually venture outside the bounds of their profession to explore novel and relevant ideas to bring back with them upon completion of their fellowship. It is the spirit of this mission that inspired this exploratory research in applying best business practice to strategic management of systemic weapon system acquisition cost risk. As the USAF, along with her sister services, continues to uneasily settle into an epoch of fiscal uncertainty, a new acquisition cost risk strategy is needed. Motivation for this thesis is drawn from this new and challenging environment.

1.1. EPOCH SHIFT

In general, the Department of Defense (DoD) acquisition enterprise's external environment includes exogenous forces which shift contextual factors. These shifts impart great pressures on an enterprise, eventually triggering internal changes [1]. Such effects change over eras and epochs [1]. Eras are defined as the full lifetime of the current instantiation of the enterprise, while epochs are shorter periods of time characterized by fixed contextual factors and value expectations [2].

In the case of the DoD acquisition enterprise, it is currently enjoying the benefits of the sole superpower status of the United States (US), which began after the end of the Cold War in 1991 and will likely continue for decades. From the perspective of defense acquisition strategy, this Sole Superpower Era began with the Post-Cold War Epoch of threat-based acquisition strategies[2],

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[1] The general term for any USAF member signifying the unifying and traditional culture of the USAF's first mission in the air domain. The USAF has since expanded into the space and cyber domains.

[2] Standard terminology in the Department of Defense is threat-based *planning* acquisition strategy and similarly for capabilities-based *planning* acquisition strategy. This work omits "planning" to save space in graphics.

as formerly Soviet war materiel continued to be the dominant weapons threat even though the nationality of the enemy combatants had changed.

After almost a decade, the US entered the Global War on Terrorism Epoch characterized (with respect to defense acquisition strategy) by the idea of capabilities-based acquisition strategy [3]. The 2001 Quadrennial Defense Review finally acknowledged that the new combatants may be unknown and employ weapon systems different from the formerly Soviet arsenal [3]. As such, the focus shifted from specific-threat weapon systems to the possible capabilities of unknown adversaries [3].

Presently the DoD acquisition enterprise finds itself in the Pivot to Asia Epoch and switching to a new *affordable* capabilities-based acquisition strategy. In his 2012 "Priorities for the 21st Century Defense" strategic guidance, President Barrack Obama called for rebalancing the US military towards the Asia-Pacific region while continuing to provide global security [4]. This change in defense posture has meant a continuation of the capabilities-based acquisition strategy [5]. However, concurrent with this shift in national security posture is a national debt crisis which exerts tremendous forces on the DoD acquisition enterprise, reinvigorating a focus on affordability in acquisition strategy.

Known as "Sequestration," the Budget Control Act requires shedding $487B from defense budgets between 2013 and 2022 [6]. These forced cuts are in addition to $400B of voluntary budget reductions in the DoD negotiated in 2011 over a 10-year period [7]. If budget cuts are planned and known, then the defense acquisition enterprise might devise acquisition strategies to adapt to the new environment. However, future budgets are confounded by large uncertainties in annual budget authorizations and surprise expenses. Secretary of Defense Chuck Hagel warned of cost overruns and the potential for additional budget overages due to the Pivot to Asia during testimony before the Senate Appropriations Committee's defense panel [8]. Rather than accepting the Sequestration cuts of $487B over 10 years, President Obama directed the DoD to plan for only $150B in reductions in the hope that a political solution will be found to end Sequestration [9]. These are just two examples of how the Pivot to Asia Epoch is causing great uncertainty and constraint in defense budgets, and compelling reconsideration of acquisition strategy. Major Defense Acquisition Programs[3] (MDAPs) are most sensitive to the effects of this epoch shift since they include the largest (in dollar value) acquisitions for the DoD.

Figure 1[4] summarizes the era and epochs of the defense acquisition enterprise and graphically depicts the motivation for this work. The Sole Superpower Era encompasses all three epochs. Each epoch contains a different acquisition strategy and the epochs tend to overlap due to the lag in policy promulgation and enterprise-wide implementation. A third strategy, affordable capabilities-based acquisition, may be required to respond to inadequate program funding or funding instability, which is depicted by question marks in the figure.

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[3] MDAPs are defined as Acquisition Category (ACAT) I non-information systems programs with estimated research, development, test, and evaluation costs greater than $365M or expected procurement costs of more than $2.190B [16]. These dollar figures are in fiscal year 2000 constant dollars [16].

[4] Dollar figures are cost estimates for MDAPs in nominal values accessed at [10].

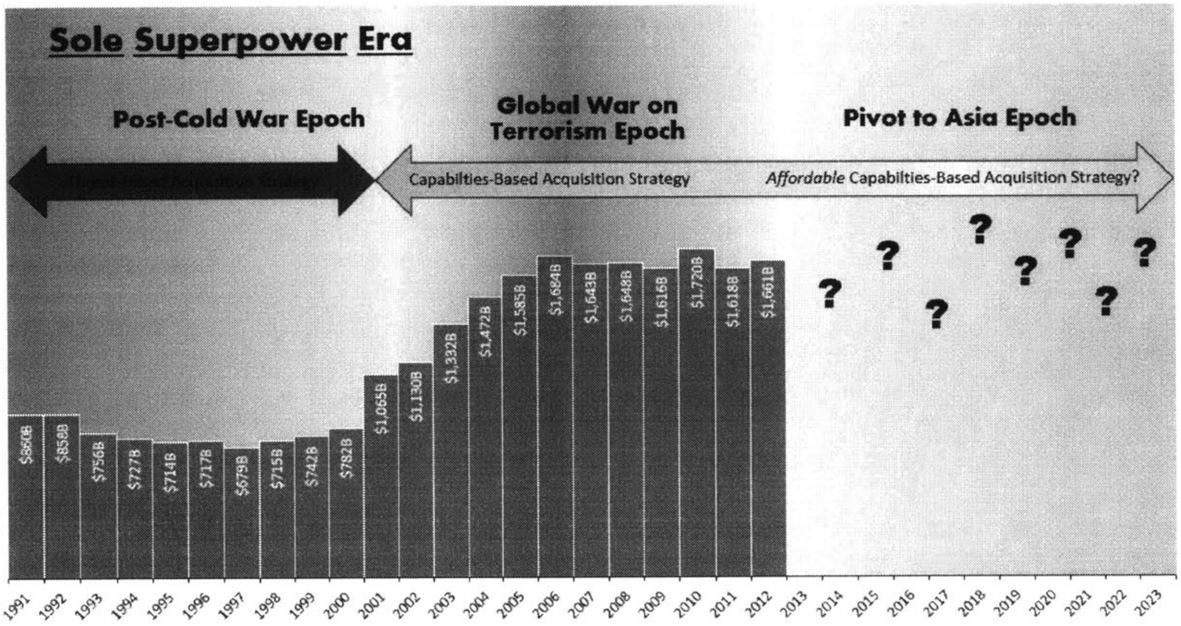

Figure 1: A shift in DoD acquisition strategy, in the context of changing national defense strategy & annual MDAP funding uncertainty.

1.2. AFFORDABILITY IN DoD ACQUISITIONS

Recent DoD guidance [10, 11] has re-emphasized the importance of efficiency and productivity in the DoD acquisition enterprise as an acknowledgement of the shift to the current epoch. Thirty-six initiatives were introduced at the end of 2012 with the goals of obtaining better value for taxpayers and the DoD, which marks a refocused emphasis on affordability in acquisition strategy [11]. The first initiative was to mandate *affordability* as a program requirement (hence the designation of the current epoch's acquisition strategy as affordable capabilities-based acquisition) [11].

In addition to this guidance, the DoD Strategic Management Plan for fiscal years 2014-2015 calls for improved capital budgeting management [12]. The following quote summarizes the need for improved budget management [12]:

> *"The current fiscal environment requires different, more strategic, thinking about how to make budget decisions and achieve the mission within the fiscal targets that are provided without disrupting the mission."*
>
> - The Honorable Elizabeth A. McGrath, Deputy Chief Management Officer

The plan calls for [12]:

- Better *projection*, prioritization, and *planning* of expenditures for the business mission area to drive more informed business decisions that support the mission, *assess risk*, and *focus on cost* as opposed to budget, as a primary measure of performance.
- Continued implementation of 21st century business operating models, processes, and technology to measurably *improve cost effectiveness* with an emphasis on return on investment.
- Instilling a "*cost culture*" which looks beyond budget data to emphasize the use of cost data to develop a true understanding of business expenditures so that leaders can better assess return on investment which results in *better decision making*.
- Institutionalizing an end-to-end business process perspective to include effective use of *investment decision making* (i.e., capital budgeting) and *risk management techniques*.

Each of these initiatives relate to affordability and improved understanding of cost risks, especially for the DoD's most expensive systems developed and procured in MDAPs.

Affordability is defined as "the ability to allocate resources out of a future total [for each DoD Component] budget projection to individual activities" using a time horizon of 30-40 years [10, 11]. Affordability caps for unit production cost and sustainment costs on each acquisition program are set at the DoD Component[5] level for its acquisition portfolio [11]. A budget projection is made for future fiscal years and these data are plotted against aggregate program costs, as illustrated in Figure 2. As seen in this figure, this example DoD Component portfolio becomes unaffordable almost immediately in the second fiscal year (FY), and action must be taken to reduce portfolio cost. Also, most concede that accurate projections are tricky and projections 30-40 years out are all but impossible to guess right. If that weren't enough, the budget uncertainty in the current epoch makes these projections even more tenuous. Rightly assuming that these projections may be incorrect, the consequence of these misjudgments is decreased value to both taxpayers and the DoD.

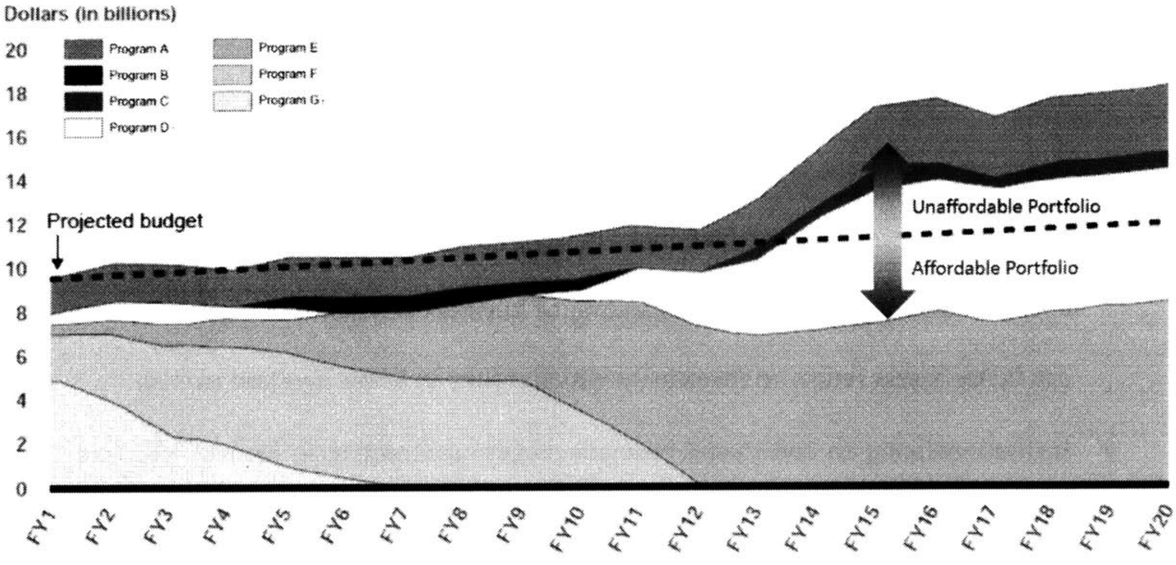

Figure 2: Example DoD Component portfolio Affordability Assessment from [13].

Affordability Assessments are performed for MDAPs at Milestone B and C, as shown in Figure 3 (yellow triangles) [14]. Each Affordability Assessment is a top-down process originating from DoD Component leadership that considers estimates of total obligation authority (TOA) and service acquisition portfolio obligations to set procurement unit and sustainment cost constraints

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[5] The US Air Force, Army, Navy, and Marine Corps.

on individual programs [10]. These constraints set the upper threshold for program costs based on the Component's best estimate of TOA, which will likely fall short of expectations due to systemic cost bias, program-specific cost estimation errors, and the current uncertain fiscal environment, further explained in Sections 2.2 and 3.3. If a program's costs exceed the constraints or if the forecast TOA is overestimated, then a program may either be cancelled or have its production quantity reduced [10]. Other program adjustments are possible as well, such as deferring requirements, but may not produce the affordability savings required.

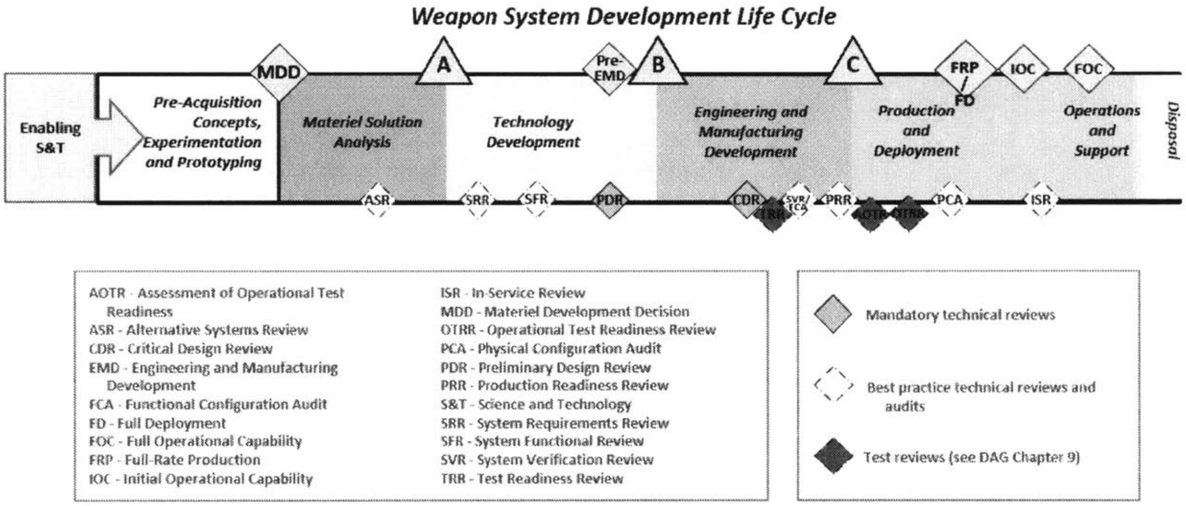

Figure 3: DoD weapon system development life cycle from [10].

One solution to this likely problem is to produce better TOA forecasts so that affordability constraints are not breached. But with forecast horizons measured in decades, this solution option appears infeasible. Instead, improving program cost estimates may prove more attainable useful. Specifically, if cost estimation risk is separated into *systemic* and *program-specific* risks, then reducing these risks could lead to the improved MDAP cost estimates needed for enhanced affordability.

MDAPs have suffered a cost estimating bias of 20% since the mid-1960s (i.e., on average, programs have cost 20% more than originally estimated) [15]. If this bias is not corrected using a pragmatic and holistic method, then affordability will be difficult if not impossible to achieve. Blindly adjusting upward each program cost estimate by 20% is too coarse a remedy, and this approach may cause over-budgeting for some programs – resulting in missed acquisition program opportunities – while continuing to under-budget for those types of programs which have chronically overrun budgets by more than 20%. This issue should be addressed through more realistic capital budgeting planning in the DoD Components to enable a new affordable capabilities-based acquisition strategy to mitigate systemic cost risk.

1.3. THESIS DEVELOPMENT

The sources and causes for the bias presented in the previous section have been researched previously, and many correlations and potential causal factors have been postulated. However, a practical method – one that fits well into the current cost estimation methods and processes so that organizations may readily adopt it - for mitigating this systemic cost estimation risk has not been found. This thesis explores improving MDAP cost estimate realism by quantifying systemic cost risk and estimating cost growth rates to improve forecasted program cost and affordability.

Developing a method to adjust for the systemic cost estimation bias will enable more accurate DoD Component capital budget planning. Returning to Figure 2, one sees that improved MDAP cost estimates could reduce the Component costs to the "Affordable Program" region, which is below the affordability line (projected budget). In this way, strategic management of MDAP systemic cost risk could lead to improved affordability in the DoD, which would result in more predictable budgeting, improved program integrity, and less inter-program funding "cannibalization."

The other source of MDAP cost estimation error, program-specific cost estimation risk, is situation-dependent. Although the general trend in MDAP cost estimates is underestimation of true program costs, cost performance of individual MDAPs have varied around the 20% estimation bias caused by program peculiarities; some programs have even completed under their baseline cost estimate. Because of this peculiar nature, program-specific cost estimation risk is better left to the many cost estimators and cost estimation agencies within the DoD who know the intricacies of their programs best.

1.4. SCOPE & RESEARCH QUESTIONS

This thesis will analyze cost estimate data of 141 MDAPs to quantify systemic cost estimation risk and develop a method to mitigate this risk to produce more realistic MDAP cost estimates. Consequently, more realistic MDAP cost estimates will lead to improved affordability in the DoD. MDAPs from all DoD Components and programs run directly by DoD are included in this study. MDAP cost data from between 1997 and 2012 will be used, as well as the total cost estimates for all MDAPs between 1969 and 2012.

Cost data will be pulled from publicly available Selected Acquisition Reports (SARs). SARs are required annually by statute and contain cost estimates in baseline (i.e., base-year dollars) and then-year dollars for each MDAP [16]. Although published quarterly, the SAR from each December is the only comprehensive release for the year covering all MDAPs (with certain exceptions applicable) [16]. As such, the shortest practical sampling period for revised cost estimate data is one year.

Unlike previous research on this topic, cost data will be left unadjusted for inflation and production quantity adjustments. Cost data controlled for these variables look to observe real changes in cost estimates and assess the performance of MDAP management without the effects of inflation estimate errors and changes in final production quantities. Unadjusted cost data include both the effects of inflation mis-estimation as well as changes in production quantity decided upon by DoD Components, since these effects are of practical importance to capital budgeting and improving affordability.

Cost data will be used to not only quantify the systemic cost estimation risk for MDAPs, but also to develop a method for adjusting annual budgets to account for this risk and improve affordability. The concepts of time value of money in the DoD will be presented so that the MDAP cost growth rates derived from the systemic cost estimation risk can be applied to capital budget planning in the DoD.

Program-specific cost estimation risk will not be covered due to the peculiar nature of this source of risk, as mentioned in the previous section. The United States Government (USG) has developed much expertise in mitigating this source of risk through sophisticated estimation techniques and training. The DoD is expected to continue to hone these skills. These types of specialized methods and training are best left to the experts.

Finally, this thesis will attempt to answer the following research questions:

1. How can the DoD quantify systemic cost risk for MDAPs?
2. How can the quantified systemic cost risk be used to create more realistic MDAP cost estimates?
3. Can strategic management of systemic cost risk lead to improved affordability in the DoD?

1.5. THESIS ORGANIZATION

The remainder of this thesis is organized as follows.

- Section 2 presents results from the literature review accomplished for this thesis.
- Section 3 covers best practices for the DoD for MDAP cost estimation and the many associated factors which cause mis-estimates and program cost overruns.

- Section 4 introduces the concepts of the time value of money in the DoD and systemic risk-adjusted asset valuation.
- Section 5 addresses the three research questions and develops a method to quantify systemic cost risk in MDAPs, calculate systemic risk-adjusted cost growth rates, and adjust budget planning to improve affordability.
- Section 6 presents conclusions and recommendations.

2. LITERATURE REVIEW

A thorough review of the literature was conducted to determine the current state of research in managing systemic cost risks within the DoD and to ensure originality of this work. The topics "defense acquisitions," "decision support systems," "capital asset pricing model defense," "capital budgeting," "DoD affordability," "acquisition cost growth," "DoD cost estimation," and "DoD cost overruns" were entered into search engines for the MIT Barton Libraries, Air and Space Power Journal, Defense Acquisition University, various DoD acquisition policy websites, and the Defense Technical Information Center. Documents produced from these searches were reviewed, and additional information was gathered from the references in these documents. In particular, the Naval Postgraduate School and, to a lesser extent, the Air Force Institute of Technology produced additional current papers on these topics of interest. The Defense Technical Information Center, a web-based repository for defense-related research, contained many of the DoD-funded papers found in the other repositories. It also produced many more works, particularly those produced by Federally Funded Research and Development Centers like MITRE, RAND, and by the Institute for Defense Analysis, and the public policy think-tank the Center for Strategic and International Studies.

2.1. DOD ACQUISITION PROGRAM COST ESTIMATION

Two sources were reviewed for best practices in cost estimations for MDAPs. The first document was produced in 2009 by the Government Accountability Office (GAO) and intended to present best practices for developing and managing capital program costs [13]. The other source, which is characterized in the GAO document as a "good reference," was produced by the Air Force Cost Analysis Agency expands the details on calculating and managing cost risk and uncertainty [17]. Best practices in cost estimation were examined to judge the level of sophistication in MDAP cost estimates in terms of acknowledging and addressing risk and uncertainty, and to discern any procedures which may lead to the systemic bias evident in MDAP cost estimates introduced previously.

In [13], the GAO covers the entire process of gathering data, analyzing historical costs, establishing assumptions and ground rules, generating quality cost estimates, addressing risk and uncertainty in estimates, maintaining and updating cost estimates, and presenting cost estimates to leadership. Seventeen best-practice checklists are presented and real-world case studies of many USG programs are used to support the document's procedures and conclusions [13]. Overall, the procedures outlined in the document are very sophisticated in its treatment of risk and uncertainty. It appears that following these procedures would lead to more realistic MDAP cost estimates; however, despite publication of these advanced best practices, the systemic estimation bias continues.

As an example of the sophistication of the procedures outlined in [13], probability distributions are encouraged to convey risk and uncertainty in point estimates [13]. The development of S-curves and confidence levels are emphasized to enable better capital budgeting decision making [13]. Scenario analysis and, when feasible, Monte Carlo simulations of cost estimate random variables are used to form the S-curves [13].

Besides addressing best-practices for cost estimation, [13] focuses on creating credible cost estimates that overcome historically observed problems with estimates, such as the systemic cost estimate bias. It cites its own work in 1972 entitled "Theory and Practice of Cost Estimating for Major Acquisitions" which included many of the themes repeated in the 2009 work [13]. In 1972, the GAO found that cost estimates were frequently underestimated. GAO identified factors in the cost estimating procedures used during that time causing this phenomenon and offered suggestions to reduce these underestimates [13]. Its conclusion was that rigor and objectivity was lacking in cost estimation procedures and techniques which allowed optimism bias to skew estimates downward [13]. GAO found that despite its 1972 publication, many USG agencies had not adjusted its cost estimation practices to account for the factors previously identified [13]. However, the DoD has refined its cost estimation practices by creating cost analysis agencies in each of its Components as well as at the DoD-level and staffing these agencies with qualified and experienced personnel. One may conclude that despite adoption of these best practices, the historical bias in MDAP cost estimates persists.

One such DoD Component cost analysis organization is the Air Force Cost Analysis Agency. In 2007 it published its cost risk and uncertainty handbook to help analysts and estimators produce more realistic and defendable cost uncertainty analysis [17]. It includes more advanced tools than [13] such as multiple regression techniques and the type of probability distributions selected for Monte Carlo simulation to predict costs for MDAPs [17]. Confidence intervals and statistical significance for cost estimates are also covered [17].

Interestingly, the lognormal distribution is promoted over the normal distribution to describe the uncertainty and risk underlying cost estimates [17]. Two reasons are given. Since estimates cannot be negative and the lognormal distribution is bounded by zero on one side (unlike the normal distribution), the lognormal distribution appears more suitable [17]. More importantly, the handbook acknowledges that the lognormal distribution places more weight on overruns than underruns, as opposed to the normal distribution, which is desirable given the more likely occurrence of an overrun [17]. In this way, the handbook acknowledges the existence of systemic cost estimation bias and supports the conclusion that, despite attempts to eliminate it, the systemic cost estimation bias continues to plague MDAPs.

2.2. COST GROWTH IN DOD ACQUISITION PROGRAMS

Cost overruns in the DoD have been studied in every decade since the 1950s, and data for these analyses go back to 1946 [18]. Many of these studies use MDAP cost estimate data from SARs or databases filled with SAR data. Studies varied in the number of programs evaluated, timeframes used, cost adjustments employed, and determinations of factors contributing to cost overruns and cost estimate bias. In [18] the authors provide a table summarizing these studies; this table has been curtailed and adapted as presented in Table 1. The table has also been appended with data from a more recent cost overrun report, [19].

Several aspects of each study listed in Table 1 differ, but the metric used to quantify cost growth over program's lifetime, the cost growth factor, is the mostly same. It is defined as the ratio between final (actual) costs and cost estimate baselines, either Milestone B or C (see Figure 3) [18]. By subtracting one from the cost growth factor, the percentage change in the program's cost relative to a baseline may be determined. Most studies included only those MDAPs which were completed or had completed 90% of production [18]. The study by Wandland and Wickman considered MDAPs as well as smaller programs [18]. Some studies adjusted cost data to remove inflation and changes in production quantities between baselines – generically called "adjusted" – while others looked at both adjusted and unadjusted data [18]. Different statistical measures were used in the various studies, such as median or mean cost growth factors. Overall program cost overruns in constant-year dollar (i.e., real) figures and percent changes are shown for the Hofbauer et al. study. This study also calculated the geometric average annual growth rate for each of the 104 programs studied [19]. Finally, some studies did not report cost growth factors.

Study Source	Cost Data Sources	Time Horizon	Number of Programs Studied	Cost Growth Measure	Total Program Cost Growth Factor
Tyson, Nelson, Om and Palmer; Wolf	SARs and Program Concept Papers	1960-1987	63 Weapon Systems	Mean Ratio	1.51
Tyson, Harmon, and Utech	SARs and Historical Memoranda	1962-1992	20 Tactical Missiles and 7 Aircraft	Mean Ratio, Median Ratio	1.20 (Aircraft), 1.54 (Missiles)
McNicol	OSD Program Analysis and Evaluation Database	1970-1997	138 Developmental Weapon Systems that Passed Milestone II[6]	Average Percentage Change from Development Cost Estimate	Not Reported
Drezner et al.	SARs	1960-1990	120 Programs with Development Cost Estimate	Average Adjusted Cost Growth Factor	1.20
Unpublished 1959 Draft RAND Report	Weapon System Reports	1946-1959	16 Aircraft and 8 Missiles	Average Adjusted, Unadjusted Cost Growth Factor	3.23 (adjusted), 6.06 (unadjusted)
Asher and Maggelet	Last SAR for Program or December 1983	As of 1983	52 Weapon Systems that had Achieved Initial Operational Capability	Several[7]	Not Reported
Wandland and Wickman	Program Management System Contracts from 5 Air Force Organizations	1980-1990	261 Competed and 251 Sole-Source Contracts	Average Total Cost Growth Factor	1.14 (Competed) 1.24 (Sole-Source)
Arena, Leonard, Murray et al.	Last SAR for Program	1968-2003	46 Completed Programs similar in complexity to those for the Air Force	Average Cost Growth (Mean)	1.46
Hofbauer, Sanders, Ellman et al.	June 2010 SAR	1999-2009 (effective[8])	92 MDAPs with Milestone B cost estimate baselines plus 12 cancelled programs	Total Real Cost Overruns in 2010 constant-year dollars & percentages; Geometric average[9] growth rates	Approx. -\$1B to \$100B, -25% to 50%; Approx. -10% to 10%[10]

Table 1: Summary of DoD weapon system acquisition cost growth studies reviewed.

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[6] Roughly analogous to Milestone B in Figure 3 [18].

[7] These include development cost estimate to initial operational capability; mean cumulative total development cost growth factor; and cumulative total procurement unit cost growth factor at initial operational capability [18].

[8] Since comprehensive SARs are published in December, the June 2010 SAR would not include all data for that year. Instead, the June 2010 SAR could include new MDAPs but not necessarily updates for all MDAPs.

[9] Geometric averages are covered in Section 4.1.4.

[10] Excludes EFV (approximately 21%) and C-130 AMP (approximately 145%) programs [19].

2.2.1. Trends in MDAP Cost Growth

Various studies in Table 1 show completed program cost growth ranging from 14% to 506%. If only MDAPs are considered, then this range becomes 20% to 506%. The systemic cost bias mentioned previously is the 20%[11] value reported by Drezner, et al. in his 1993 publication stretching from 1960-1990. This document included the most MDAPs and reported a cost growth factor, unlike the work by McNicol which covered more programs but did not report the cost growth factor. Arena et al. performed the most comprehensive study in terms of the timeframe; it covered 35 years ending in 2003. The reported cost growth rate was rather larger at 46% than that found by Drezner (20%), but the Arena study focused only on Air Force-relevant programs. In [18], the author cited the works of Drezner et al. and Tyson et al. which showed cost growth measures highest in the 1960s, lower in the early part but higher in the latter part of 1970s, and lower yet again in the 1980s. Even if the exact values of the cost growth factors do not agree, cost growth is clear: since 1946 MDAPs do show a tendency to overrun baseline cost estimates.

Elaborating on this point, Drezner et al. attempted to "gain insight" into the magnitude of weapon system cost growth [15]. The paper acknowledges that precision in cost estimates is unachievable due to uncertainties, and that a systemic bias in estimates could lead to chronic cost overruns or foregone weapon system acquisition programs due to lack of funds from over-budgeting other programs [15]. The authors found such a bias existed and that cost estimates are *systematically underestimated* [15]. On average, MDAP cost growth was about 20% when comparing the final program costs to the Milestone A and B estimates, and cost growth was about 2% at the Milestone C date [15].

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[11] Interestingly, Drezner et al. point out that although MDAP cost growth has remained at about 20% between the 1960s and 1990s, this cost growth value is somewhat less than that experienced in large civilian projects such as energy and chemical plants [15].

On a positive note, although a systemic cost estimation bias is real and pervasive, Arena did note several improvements over time [18]. Based on his review of previous cost growth studies, Arena found cost growth was much lower after the publication of the Packard Initiatives in 1969 [18]. Independent cost estimates, which were introduced in 1973, improved cost estimates baselined at Milestone C or its equivalent[12], but did not improve cost estimates at earlier milestones [18]. Finally, Arena's data showed a recent (as of 2003) improvement is cost growth, but this improvement could not be attributed to acquisition reforms or other deliberate actions by the DoD [18]. Instead, this improvement was attributed to his selection of only finished programs for inclusion in his study, which tended to be shorter in duration than other programs in the sample [18]. Since cost growth increases with time, Arena concluded that the observed improvement was illusory [18]. Additionally, the Hofbauer et al. study found that the geometric average of annual real growth for programs with varying baseline estimate dates was about constant, even for the more recent baselines in 2010 [19]. The Hofbauer et al. finding supports that by Arena [18] and adds modern relevance since the timeframe is more recent.

2.2.2. Factors Affecting MDAP Cost Growth

The literature reviewed cited many factors contributing to MDAP cost growth. The strength of correlations varied and were even contradictory between studies. Factors given include:

- Programs with longer durations had greater overall cost growth [20].
- Programs with earlier baseline estimates had similar geometric average annual cost growth rates [19].
- Electronics programs experienced lower cost growth [20].

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[12] The modern acquisition development lifecycle shown in Figure 3 has gone through several name changes of phases over time.

- MDAP size and DoD Component had *no* impact on cost growth [20].
- MDAP size and DoD Component *did* impact cost growth [15].
- The Army was found to have higher cost growth when considering vehicle and rotary wing programs, and the Air Force experienced higher average cost growth while the Navy[13] programs' average cost growth was lower [15].
- Older programs had higher overall cost growth [18].
- Development schedule growth, program stretch, and development schedule length all affect cost growth [18].
- Contract structure affects cost growth, with fixed-price contract program displaying smaller cost overruns than cost-plus contracts; however, this difference may be due to the nature of the program rather than contract type since less risky programs tend to use fixed-price contracts while cost-plus contracts are used for riskier programs [19].

In [15] the authors concluded that "no dominant explanatory variable" exists for cost growth. However, inflation and production quantity changes appeared as dominant factors in cost overruns [15]. Secondary to these factors, the authors found MDAP size and age did effect cost growth significantly [15]. While MDAP size was not found as a factor impacting cost growth in [18, 20], program age was corroborated as a significant factor in [15].

2.2.3. SAR Data Limitations & Adjustments

Several important limitations exist when using SARs for studying cost growth [20]:

- Data are reported at high levels of aggregation;
- Baseline changes, modifications, and restructuring are not well documented;

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[13] Navy programs analyzed appeared to publish a cost estimate baseline once development was well underway, thereby masking cost growth due to technical immaturity [18]. Because of this deviation, the Navy's cost growth performance appeared better than reality.

- Reporting guidelines and requirements change;
- Weapon system costs are incomplete;
- Certain types of programs (e.g., classified, those below the MDAP cost threshold) are excluded;
- The source and basis of the cost estimate is often ambiguous; and
- Risk reserves (i.e., management's budget reserve) are unidentified but included in the cost estimate.

Still, SARs contain the most consistent set of MDAP cost data available to the DoD [20].

Adjustments to SAR cost data are made depending on the purpose of the study. If its purpose is to characterize the effect on annual budgets, then unadjusted SAR values should be used since these are used to set budgets [18]. If the purpose is to measure performance of a program, then inflation and changes in procurement quantity should be removed from cost estimate data in SARs [18]. Quantity- and inflation-adjusted values are more appropriate when attempting to characterize cost estimate uncertainty, while the unadjusted values were better suited for describing funding uncertainty [20, 15]. These adjustments were made to remove the effects of factors beyond the control of cost estimators [15]. Based on cost growth data from the literature review, it appears that cost growth factors are larger for the unadjusted SAR data. Other adjustments, such as MDAP selection for a desired level of maturity (e.g., programs past Milestone B) are also used, but they mask the impacts on budgeting.

2.3. CAPITAL ASSET PRICING MODEL APPLIED TO DOD ACQUISITION PROGRAMS

The Capital Asset Pricing Model (CAPM) is a private industry best practice that offers many desirable features. One of its more desirable features is its theoretical separation of systemic from asset-specific risk [21]. This attribute is particularly interesting for this thesis which aims to quantify systemic cost estimation risk for MDAPs.

Two works on the CAPM, [22] and [23], were reviewed. In [22] the author identifies the CAPM as useful to the private sector as a valuation tool, but contends it is inappropriate for valuing public sector investments. A simplifying assumption leading to the basic version of the CAPM indeed precludes "governmentally funded assets" [21]. However, this assumption is needed only if one attempts to create an *optimal* (minimized in the mean-variance sense for return and risk) portfolio of assets [21]. If the goal is to use a portion of the CAPM, such as the expected growth-beta relationship, which gauges how returns on an asset vary with its parent market, then this basic assumption does not have to hold.

A review of [23], which is entitled "Applying...the Capital Asset Pricing Model to DoD's Information Technology Investments," proved to be unsatisfying. Despite this promising title, the thesis offered only a definition of the CAPM but did not apply it to defense acquisition programs.

2.4. LITERATURE REVIEW SUMMARY

Literature covering the topics of DoD acquisition program cost estimates, cost growth factors in DoD acquisitions, and the CAPM applied to DoD acquisition programs were reviewed. Despite attempts to eliminate total cost estimate risk and uncertainty through adoption and use of sophisticated cost estimation procedures and tools, a cost estimation bias continues to plague MDAPs. Many factors have been found to contribute to cost growth in MDAPs, however, some of these factors are contradictory across studies. Inflation and production quantity changes appear to be dominant, but most of the studies controlled for these variables to focus on program management performance rather than funding uncertainty. Since this thesis is concerned with systemic cost estimate risk leading to unaffordable MDAPs, SAR data analyzed will include the effects of inflation and quantity changes. Rather than tackling total cost estimate risk as in the best practices in cost estimation, this thesis will leverage CAPM's principal feature which dichotomizes systemic and program-specific risk, and will attempt to quantify the systemic cost estimation risk in the DoD.

3. DoD ACQUISITION PROGRAM COST ESTIMATION

The DoD decision support systems consist of three interrelated processes: the Joint Capabilities Integration and Development System (JCIDS); the Planning, Programming, Budgeting, and Execution Process (PPBE); and the Defense Acquisition System (DAS) [10]. MDAP cost estimation plays a vital role in each of these processes. This section covers cost estimation best practices, as written by the GAO, to help identify causes for poor MDAP cost estimates and to make the point that even with best practices, there is still uncertainty and risk in these estimates. The relationship between affordability and cost estimates is established. The section also discusses acquisition reforms intended to minimize MDAP cost overruns, and shows that these reforms have failed. Finally, the section concludes with the identification of a new approach to help the DoD mitigate cost overruns in MDAPs through strategic management of systemic cost risk.

3.1. DoD DECISION SUPPORT SYSTEMS

Figure 4 shows graphically the three systems which comprise the DoD acquisition enterprise known as the DoD decision support systems. These systems are defined by processes which run continuously and interact to develop weapon system requirements to meet future capability needs, create an acquisition strategy and program to deliver a system to meet these requirements, and budget to provide resources necessary to carry out the acquisition [10]. PPBE is the DoD's strategic planning, program development, and resource allocation process [10]. Its principal outputs are the Future Years Defense Program and Budget Estimate Submission which are used to help meet the needs of the National Security Strategy within funding constraints [10]. JCIDS is a systematic method run by the Chairman of the Joint Chiefs of Staff to identify, assess, and prioritize joint warfighting capability shortfalls and recommend potential materiel and nonmateriel solutions to resolve these shortfalls [10]. JCIDS provides the PPBE process with affordability advice supported by Capabilities-Based Assessments [10]. These assessments are also used by the DAS to deliver militarily useful capabilities in affordable increments [10]. DAS is an event-based process and it is the management structure by which the DoD acquires weapon systems [10].

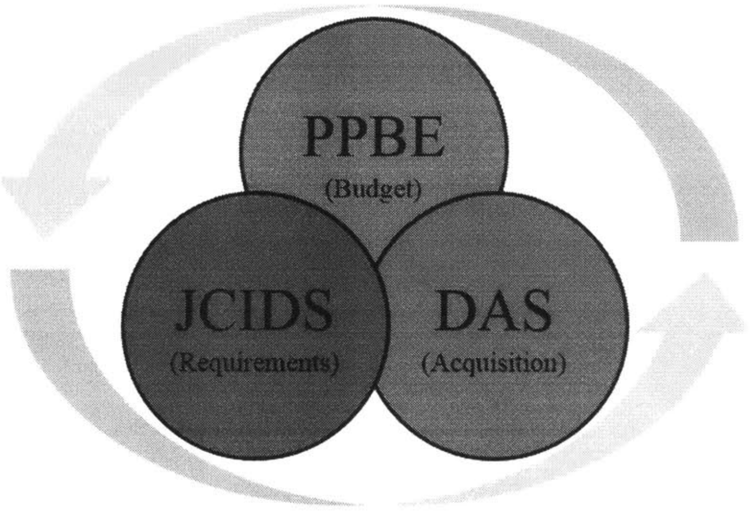

Figure 4: DoD decision support systems (adapted from [10]).

3.2. COST ESTIMATES FOR MDAPs

Life-cycle cost estimates (LCCEs), the formal cost estimates used in the DAS, include estimates for research and development, investment and production, operating and support, and disposal costs [10]. An illustrative example of life-cycle costs is shown in Figure 5. According to [14], formal LCCEs are required at decision points and milestone reviews shown in Figure 6. These estimates are made by the sponsoring DoD Component, which are called (DoD) Component Cost Estimates (CECs), or by an independent organization, which are called Independent Cost Estimates (ICEs) [10]. In general, cost estimates are also made for MDAPs in support of

Affordability Assessments, program cost goals for Acquisition Program Baselines, and estimates of budgetary resources [10].

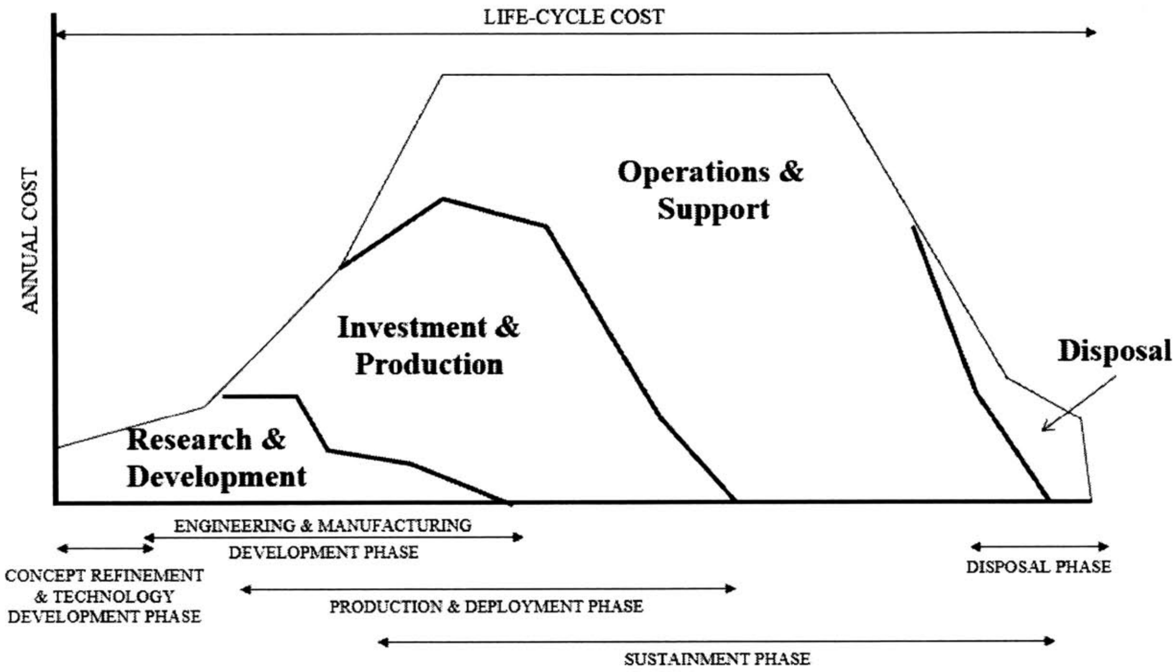

Figure 5: Illustrative example of life-cycle costs (adapted from [10]).

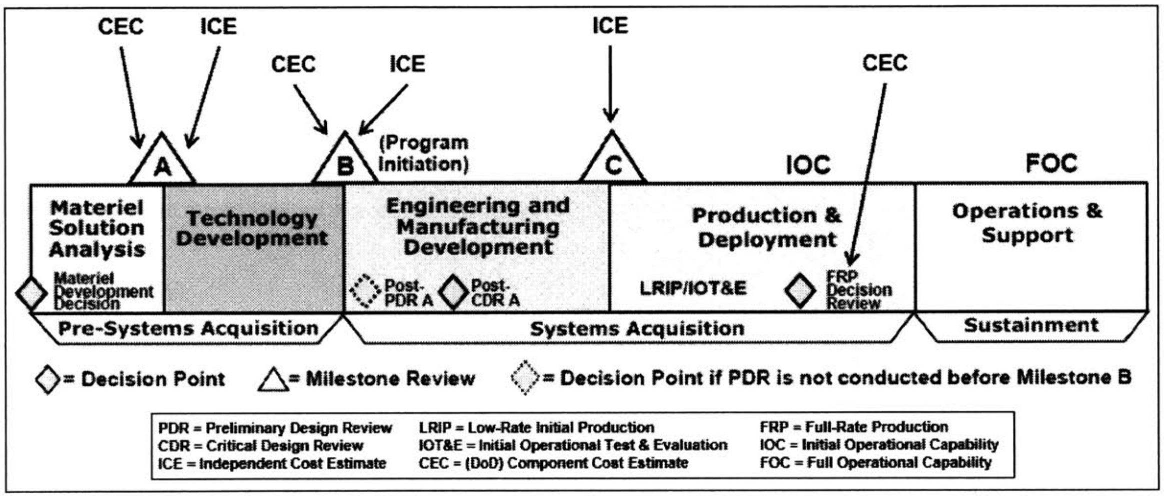

Figure 6: Decision points & milestone reviews requiring LCCEs (adapted from [14]).

3.2.1. Relationship between Affordability & Cost Estimates

Affordability is defined by [10] as:

> *The ability to allocate resources out of a future total budget projection to individual activities. It is determined by Component leadership given priorities, values, and total resource limitations against all competing fiscal demands on the Component. Affordability goals set early cost objectives and highlight the potential need for tradeoffs within a program, and affordability caps set the level beyond which actions must be taken, such as reducing costs.*

Affordability plays a critical role in the decision process for MDAPs. It is a DoD Component leadership responsibility requiring participation from Component-level functional equivalents to each of the three systems shown in Figure 4 [10]. This leadership must consider affordability at all major decision points shown in Figure 6 [10]. Unlike the time horizon for the PPBE process, Affordability Assessments go beyond the time horizon of the Future Years Defense Program [10].

The purpose of Affordability Assessments is to avoid starting or continuing programs that cannot be produced and supported within future budgets assuming a certain acceptable level of cost risk [10]. Affordability Assessments produce DoD Component affordability constraints using a top-down approach in which the Component's top-line budget is used to allocate program funding given all its other fiscal demands [10]. These affordability constraints are then used to develop procurement and sustainment costs which cannot be exceeded by the program; otherwise, it would entail an affordability breach requiring the attention of Component leadership [10]. In contrast, cost estimates are created from a bottom-up approach and forecast whether the program can be completed under the affordability constraints for a given level of risk [10]. Specifically, the difference between the affordability constraint and the MDAP LCCE provides a measure of the level of cost risk inherent in the program [10].

The point of this subsection is that affordability, as defined by the DoD, can be enhanced with improved cost estimates. Ultimately, they will lead to more realistic budgeting and affordability constraints. Some of the specific benefits of improved, more realistic cost estimates include:

- Better decision making and capital investment choices [13];
- Improved budget spending plan which ultimately leads to an increased program probability of success [13]; and
- Less impact on other, lower-priority programs by minimizing shifting of its funding to support higher-priority, struggling programs due to poor cost estimation.

3.2.2. Cost Estimation Best Practices

Cost estimating is defined as "involving collection and analysis of historical data and applying quantitative models, techniques, tools, and databases to predict a program's future cost" [13]. The iterative cost estimating process, as defined by GAO best practices, is shown in Figure 7. Following this process ensures objective, repeatable, and high-quality cost estimates [13]. Not following these steps may lead to poor-quality cost estimates. These 12 steps are discussed next.

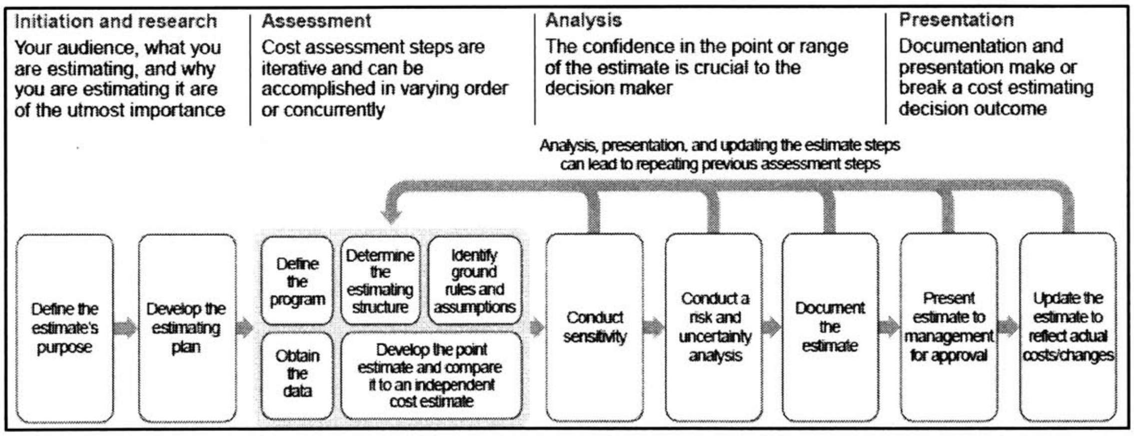

Figure 7: The cost estimating process contained in [13].

3.2.2.1 Step 1: Define the Estimate's Purpose

The first step defines the purpose, overall scope, and required level of detail of the estimate [13]. For MDAPs, the purpose would be to support decision points and milestone reviews as shown in Figure 6. In general, cost estimates support either (and sometimes both) cost analyses, which are really benefit-cost analyses supporting the Analysis of Alternatives in the Materiel Solution Phase shown in Figure 6, or annual budgeting [13]. In the case of cost analyses, the cost estimates are inflated and discounted for the time value of money, while for annual budgeting the cost estimates are inflated only. Typically the LCCE is the scope of the cost estimate per policy and statutory requirements, but program managers may desire only development and procurement costs early in an acquisition effort [13]. The detail included in estimates is influenced by the acquisition stage of the program: as the program progresses, more detailed cost data are available for incorporation into future cost estimates. When lower-level cost data are lacking, parametric estimating tools and causal factor regression may be used to determine cost estimates of program components at a higher level [13]. Additionally, in practice time constraints due to decision point and milestone review deadlines may force estimators to use less detail than desired [13].

3.2.2.2 Step 2: Develop the Estimating Plan

The second step in the cost estimating process, develop the estimating plan, is mostly administrative in nature. It consists of forming the cost estimating team with a broad set of backgrounds, developing the cost estimate schedule so that the process is not rushed, determining the cost estimating approach, and the time horizon for the estimate [13].

3.2.2.3 Step 3: Define the Program

Defining the program characteristics comes next. These characteristics include the technical baseline, program's purpose, system performance characteristics, and all system configurations

[13]. For evolutionary acquisition programs with incremental deliveries of military capabilities, technical baselines should define characteristics of each increment [13]. The technical baseline is an important document; it includes all of the detailed technical, program, and schedule data of the system which will be used to create LCCEs by both DoD Components and independent cost estimators [13]. It is also used to identify specific technical and program cost risks [13]. The technical baseline should be updated prior to decision points and milestone reviews [13]. If it is not, then cost estimates may lose credibility [13]. For the DoD, the technical baseline is the Cost Analysis Requirements Document (CARD) [13]. Program acquisition strategy and schedule are needed also, as well as any interdependencies with other programs, to include legacy systems the new program is planned to replace [13]. Finally, any available production and deployment, and operations and support data are also collected [13]. The amount and quality of data collected in this step directly effects the quality and flexibility (to eventual updates as actual costs are realized) of the cost estimate [13].

3.2.2.4 Step 4: Determine the Estimating Structure

Step four is to determine the estimating structure. This step is where the bottom-up nature of the cost estimate is evident. A work breakdown structure (WBS) and WBS elements are defined and refined continuously at the lowest possible or required level of the program needed for management control [13]. Figure 8 shows an example three-level WBS. The WBS is the cornerstone of every program cost estimate because it describes in detail all the resources and tasks required to complete that program [13]. Best practice is to use a product-oriented WBS since it is defined by deliverables, such as components and subsystems [13]. A product-oriented WBS helps ensure that all costs are included in the program cost element [13]. This type of WBS also provides management with more insight into which portions of a program may have caused cost overruns and allow them to identify root causes more effectively [13]. Once the WBS in created, the estimator then chooses a particular estimation method for each element [13]. Finally, the WBS aids in identifying and monitoring risks for a program [13].

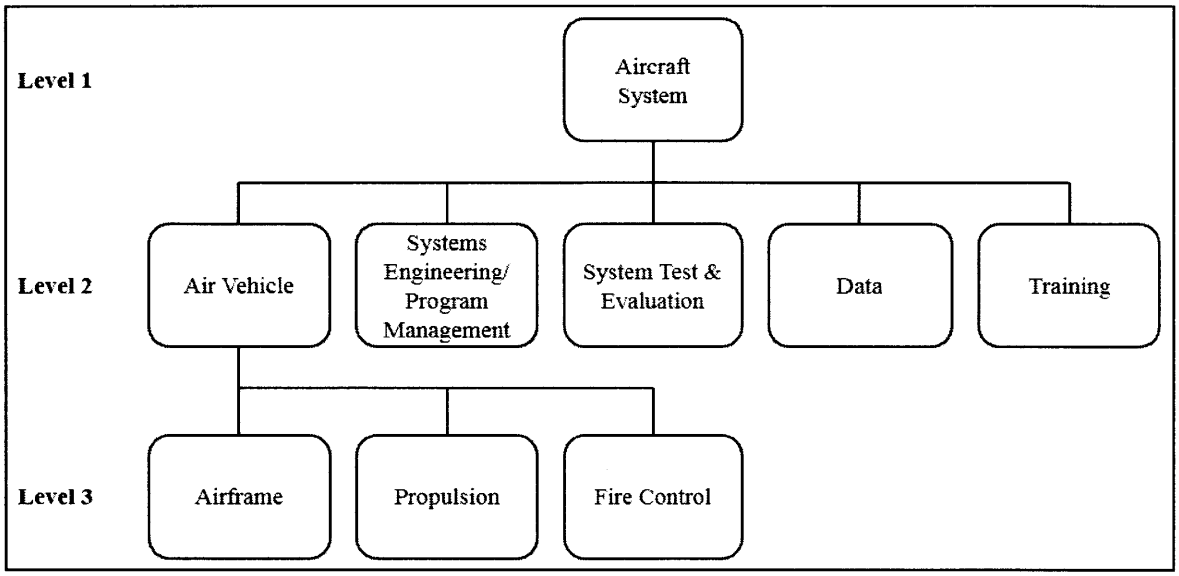

Figure 8: Example WBS for an aircraft. Not all elements shown. Adapted from [13].

3.2.2.5 Step 5: Identify Ground Rules & Assumptions

Next, cost estimators should identify ground rules, which are sets of estimating standards and leadership guidance, and assumptions, to address any unknowns not covered in the ground rules [13]. Ground rules and assumptions can be either global or specific to a WBS element [13]. At a minimum, high-quality cost estimates include the following global ground rules and assumptions[14]: cost limitations, high-level time phasing of funds, defense commodity price indices, general inflation indices, affordability constraints[15], and program base year [13]. Crucially, WBS element-specific ground rules and assumptions carry the most risk and should receive much of the attention of cost estimators in documentation and to check for realism [13].

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[14] List abbreviated to include only those most pertinent to this thesis.

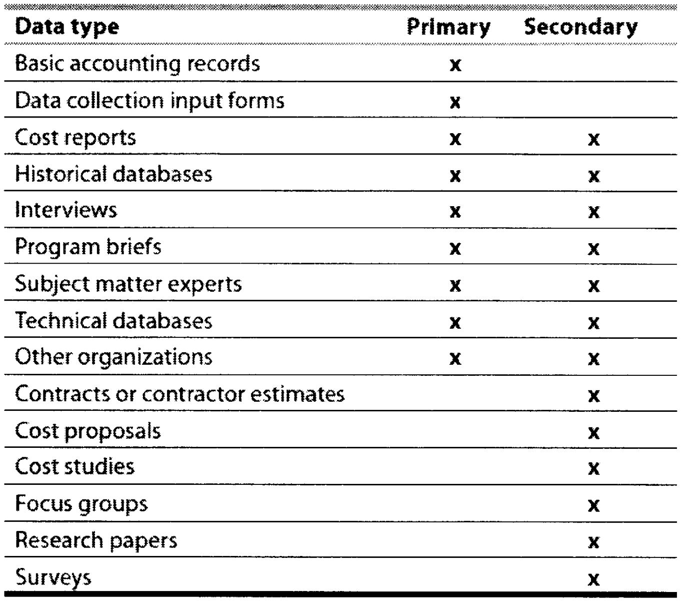
[15] If the program LCCE is over the DoD Component-set affordability constraint, estimators may receive ground rules from leadership to delay program content until a more favorable funding environment is expected [13].

Because cost estimates can be made early in programs well before "metal is bent," assumptions must be made and ground rules set to enable the creation of complete cost estimates [13]. As the program progresses and the CARD and WBS are updated, less assumptions and ground rules are needed to form an estimate [13]. Likewise, the uncertainty around ground rules and assumptions decrease with program progress [13]. For this reason, analysis of MDAP cost growth sometimes selects only those programs beyond Milestone B (see Section 2.2).

3.2.2.6 Step 6: Obtain the Data

Step six is to obtain the data, which forms the foundation of the cost estimate [13]. It is guided by the purpose and scope of the estimate, as well as the CARD, WBS, ground rules, and assumptions [13]. Data types are not just cost-based; they include technical, schedule, and program types as well [13]. The collection process is continual to ensure the most credible cost data are used to form MDAP cost estimates, and contractor quotes, contract data, and actual cost data support the collection process [13]. Data quality can range from an expert's opinion to more accurate cost data generated by causal factor regression models based on statistical analysis of historical cost data [13]. Cost estimates that are based upon historical cost data are seen as more credible [13]. However, the historical data most likely needs to be adjusted to account for differences between the historical program and the current one for which the estimate is made [13]. To check for data quality, often multiple sets of data from related programs are used to see if they converge to a common estimate so that the data provide a high degree of confidence [13]. If there are cost data from many programs related to the program of interest, then cost estimating relationships (CERs) can be made to create parametric cost models [13]. But even the highest quality data can lead to poor cost estimates if the CARD and WBS are inaccurate [13]. Data are collected using many different methods such as: database queries of past, related programs;

engineering build-up estimating analysis; expert interviews; surveys; and focus groups [13]. Obstacles to data collection include barriers to collecting relevant cost data from classified programs (especially space and satellite programs) and proprietary contractor cost data [13]. Figure 9 lists the basic sources of cost data.

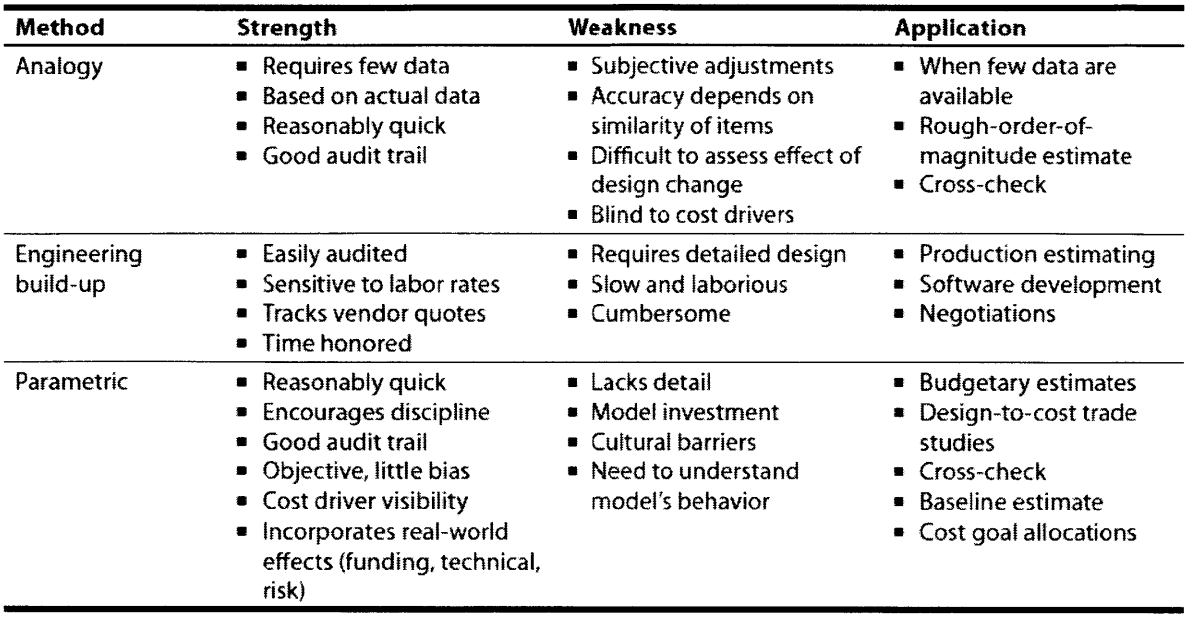


Data type	**Primary**	**Secondary**
Basic accounting records	x	
Data collection input forms	x	
Cost reports	x	x
Historical databases	x	x
Interviews	x	x
Program briefs	x	x
Subject matter experts	x	x
Technical databases	x	x
Other organizations	x	x
Contracts or contractor estimates		x
Cost proposals		x
Cost studies		x
Focus groups		x
Research papers		x
Surveys		x

Figure 9: Basic primary & secondary sources of cost data (from [13]).

3.2.2.7 Step 7: Develop the Point Estimate

The next step is important since it develops the point estimate which is the best "guess" for forecasted MDAP cost [13]. This step consists of the following sub-steps: develop the cost model by estimating each WBS element using the best methodology from the data collected; include all ground rules and assumptions; express costs in constant-year dollars; time-phase costs based on the program schedule; and add the WBS elements to develop the overall point estimate [13]. Once the point estimate is created, it must be validated by determining if errors like double counting or omitted costs are present, compared to the ICE, cross-checked for cost drivers, and updated as more cost data become available [13]. Three cost estimating methods are commonly used; these are shown in Figure 10. Other, less commonly used methods are expert opinion, extrapolation from prototype costs, and learning curves, which are a type of extrapolation [13]. In parametric estimating, cost drivers would be the factors used in regression analysis [13]. Parametric estimation develops CERs, which are the regression equations, and must provide the statistics of the inputs used to develop the CER as well as those for the CER [13]. Typically, the most important CER statistics examined are R^2 and statistical significance [13]. The R^2 value indicates the explanatory power of the cost driver with the CER (independent variable); it ranges between zero and one [13]. Statistical significance is the probability that each of the coefficients relating the cost driver with the CER is zero, so a small probability is desirable [13]. Because of the statistical nature of a parametric estimate, it provides easy integration with running sensitivity analysis and determining statistical confidence levels for this type of cost estimate [13]. Multiple, interrelated CERs may be combined to form parametric cost models [13]. These models are useful in cross-checking cost estimates using other methods [13]. Regardless of which cost estimating method is used on each WBS element, the point estimates for each element could be summed to form the total cost point estimate [13]. However, this total program point estimate may not be interpreted as a most likely estimate due to the uncertainty at each WBS element (more on this subject next). Nevertheless, this point estimate is then updated as the MDAP progresses [13].



Method	Strength	Weakness	Application
Analogy	▪ Requires few data ▪ Based on actual data ▪ Reasonably quick ▪ Good audit trail	▪ Subjective adjustments ▪ Accuracy depends on similarity of items ▪ Difficult to assess effect of design change ▪ Blind to cost drivers	▪ When few data are available ▪ Rough-order-of-magnitude estimate ▪ Cross-check
Engineering build-up	▪ Easily audited ▪ Sensitive to labor rates ▪ Tracks vendor quotes ▪ Time honored	▪ Requires detailed design ▪ Slow and laborious ▪ Cumbersome	▪ Production estimating ▪ Software development ▪ Negotiations
Parametric	▪ Reasonably quick ▪ Encourages discipline ▪ Good audit trail ▪ Objective, little bias ▪ Cost driver visibility ▪ Incorporates real-world effects (funding, technical, risk)	▪ Lacks detail ▪ Model investment ▪ Cultural barriers ▪ Need to understand model's behavior	▪ Budgetary estimates ▪ Design-to-cost trade studies ▪ Cross-check ▪ Baseline estimate ▪ Cost goal allocations

Figure 10: Three commonly used cost estimating methods in the DoD (from [13]).

3.2.2.8 Step 8: Conduct Sensitivity Analysis

Step eight is to conduct sensitivity analysis, which should be performed for all cost estimates since it determines the extent to which the point estimate changes with respect to ground rules and assumptions [13]. Sensitivity analysis is performed by varying one ground rule or assumption at a time while holding the others constant [13]. It may also be performed by changing multiple ground rules and assumptions to describe a likely future scenario [13]. In this case, the sensitivity analysis becomes scenario analysis [13]. The insight gained from sensitivity analysis is invaluable to decision makers as it allows them to gain a sense of how wrong the ground rules and assumptions need to be to yield a certain value for the point estimate [13]. It is at this point where the decision makers' considerable experience can be combined with the output of the sensitivity analysis so that better choices through informed decision making can be realized. Additionally, when considering alternatives' sensitivity analyses, decision makers are better-positioned to select the apparent best solution based on the additional information provided by these analyses [13]. The range for varying ground rules and assumptions needs to be estimated and it must be realistic, well-documented, and supported by leadership. A cost estimator cannot simply vary these parameters arbitrarily; otherwise, the sensitivity analysis loses credibility [13]. Examples of factors varied in sensitivity analysis include: re-scoping the program, productivity gains, configuration changes, inflation rate, technology heritage savings, performance characteristics, labor rates, and procurement contracts [13]. While sensitivity analysis provides a means to identify and quantify the risk associated with ground rules and assumptions, risk and uncertainty analysis provides the same but for the other risks in the cost estimate [13].

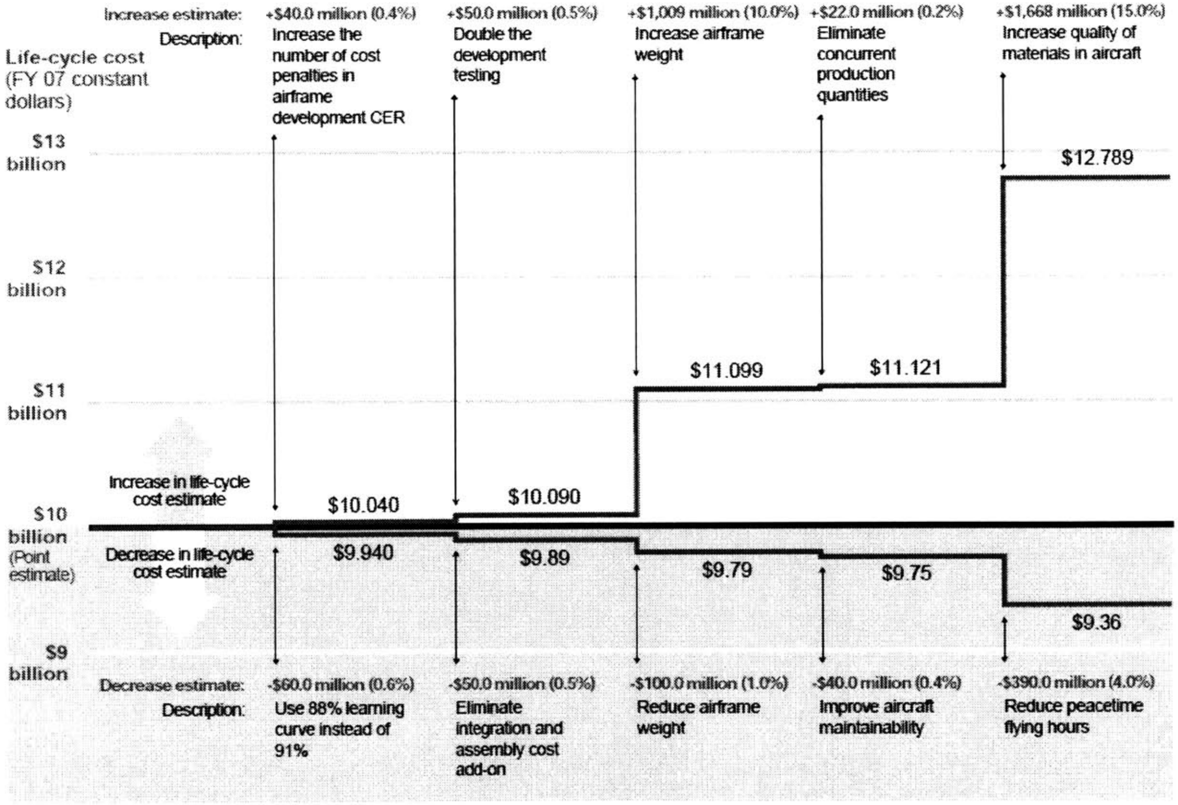


Figure 11: Example sensitivity analysis showing the point, low, & high cost estimate (from [13]).

3.2.2.9 Step 9: Conduct Risk & Uncertainty Analysis

Risk and uncertainty analysis examines the effects of changing many of the risk variables of a cost model in a series of independent simulation runs [13]. For cost estimating statistics, risk is the probability that an unfavorable event will occur, and uncertainty is assessed as one minus the confidence in the estimate as derived from the S-curve (shown later in Figure 12). Uncertainty is also the probability of cost overrun [13]. It recognizes the inevitable errors in forecasting the future and quantifies these errors as risks [13]. Recall that CER-based estimation methods rely on historical cost data to forecast future costs. Since historical data are used, they cannot perfectly represent the expected costs in the future, thus creating a source of uncertainty in cost estimates. Additionally, since cost estimates are the sum of lower-level cost estimates using the WBS, the uncertainties add with each roll-up of cost estimate as one moves up the levels in the WBS. Depending on the correlation between these WBS element cost estimate uncertainties, the cumulative uncertainty in the total cost estimate may be greater than the constituent probabilistic estimates. Due to concurrence between WBS activities and technical interdependencies between WBS elements, it is likely that the risks are correlated[16] so that the cumulative uncertainty at the top level of the WBS is greater than the sum of the lower levels [13]. Rather than summing the most likely estimates from lower levels of the WBS, which typically occurs, best practice is to assign probabilities to the cost estimates at the lower levels and use Monte Carlo simulation for the cost estimate at the top level [13]. This approach can more easily incorporate correlation between elements. An example of this approach is given in Figure 12[17] which shows that using the probability distributions of the lower-level WBS cost estimates can produce an approximation

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[16] A rule of thumb is to assume at least 25% correlation in the absence of data to the contrary [13].

[17] By the Central Limit Theorem, the sum of independent random variables produces a normally distributed random variable, like the bell curve shown in the figure.

of the total system cost estimate distribution[18]. This approximated distribution can then be used to determine the most likely total system cost estimate and allow estimators to select the cost estimate to use for budgeting based on leadership's desired confidence level (from the S-curve).

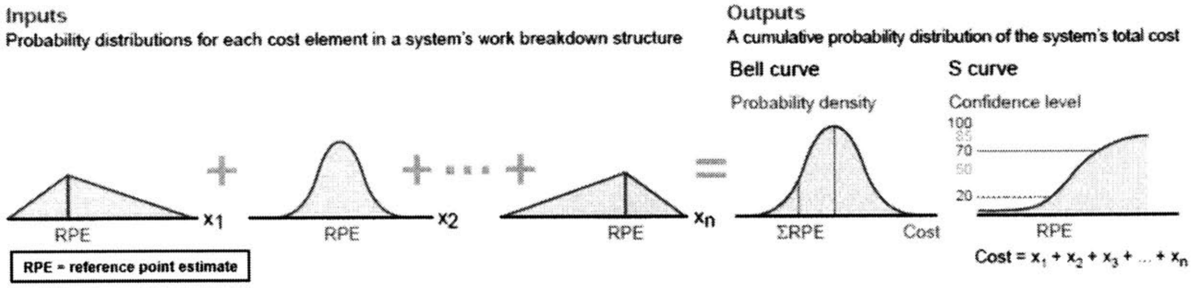

Figure 12: Monte Carlo simulation of the lower-level WBS elements creates an estimate of the total system cost estimate's probability distribution (from [13]). Note that the sum of the reference point estimates from the lower-level estimates does not necessarily produce the most likely total system cost estimate.

Decision makers can "buy-down" risk by funding programs to a cost estimate with a higher confidence level. The funding used is often called "risk dollars" in the cost estimating community for this reason [17]. Referring to Figure 13, leadership may choose to fund the program at a 70% confidence level, which would require additional funding of $271,000 over the $825,000 risk-adjusted primary estimate. Best practice is to fund to at least the 50% confidence level, but recent DoD guidance encourages funding to the 80% confidence level [24]. If a lower confidence level is selected, then justification for selecting the lower level must be documented [24]. The S-curve may also be used to select management contingency reserve in a similar manner [13]. Contingency reserve funds are then allocated to the riskiest lower-level WBS elements in a defendable and consistent manner [13, 17].

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[18] Note that the "+" signs are used symbolically to indicate that the WBS element distributions are *included* in the Monte Carlo simulation and are not intended to imply independence between elements.

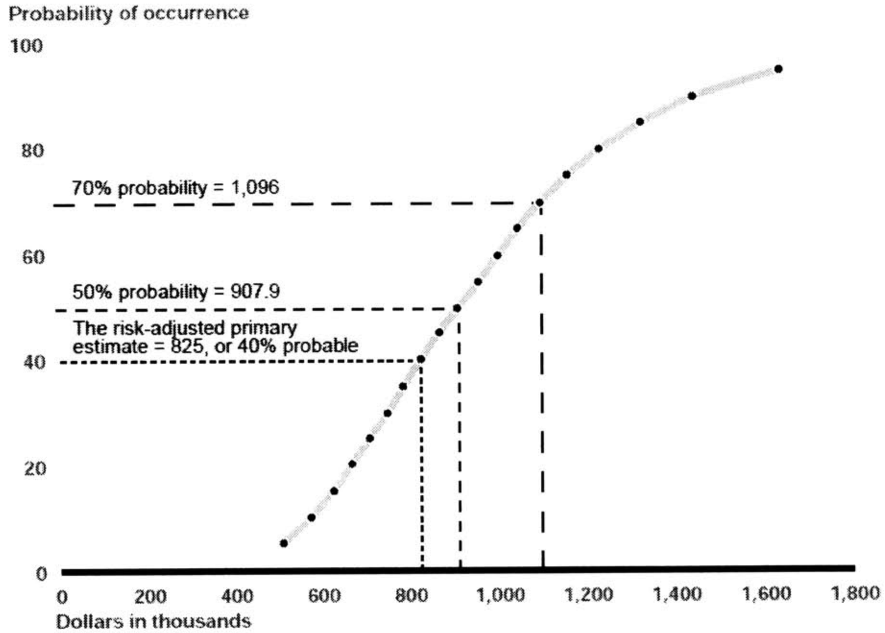

Figure 13: An S-curve used to show levels of confidence in total system cost estimates (from [13]).

Up to this point, the cost estimate has been described as a base-year (constant-year) dollar figure with an associated range to characterize risk and uncertainty. However, MDAPs last many years and need to be budgeted according to the PPBE process on an annual basis, to include adjustments for inflation and defense commodity price indices. As such, the overall cost estimate must be time-phased and converted to then-year dollars [13].

3.2.2.10 Steps 10 - 12: Documenting, Presenting, & Updating the Cost Estimate

The last three steps are the culmination of the previous steps and maintenance of the LCCE to ensure continued accuracy. Documentation and presentation of the estimate will include the main cost drivers, the WBS, confidence level, the underlying data and methods used, as well as additional information required for the target audience [13]. Updating the cost estimate requires program surveillance and continued risk management [13].

3.3. FACTORS AFFECTING POOR COST ESTIMATES & MDAP COST OVERRUNS

Even if the cost estimating best practices described in Section 3.2.2 are followed, inaccurate cost estimates leading to MDAP cost overruns will still occur due the nature of the cost estimation problem. Several studies have found systemic cost underestimation bias for MDAPs leading to cost overruns, as noted in Section 2.2.2. Additionally, in [13] a 2003 DoD study is cited which found that space system acquisitions were biased to produce unrealistically low cost estimates leading to cost overruns of 50% to 100%.

In addition to the factors leading to cost growth listed in Section 2.2.2, many more factors have been shown to influence DoD cost estimates and MDAP cost overruns. The following factors may be added to those covered in that section.

1. Rushed estimates[19] [13]
2. Improperly maintained CARD (i.e., technical baseline) [13]
3. Incomplete or poorly defined system requirements [13]
4. Missed costs due to omissions in the WBS [13]
5. Inaccurate or "massaged" inflation and defense commodity price index assumptions [13]
6. Erroneous or misapplied surrogate cost data from other programs [13]
7. Incorrect cost estimating assumptions, either global or specific to particular WBS elements [13]
8. Unaccounted changes in the defense industrial base (e.g., lower economies of scale) [13]
9. Invalid technology maturity dates [13]
10. Requirements creep and changes [16]

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[19] In [13], a case study example is given in which a DoD program had only a month to complete a cost analysis, which is a benefit-cost analysis (or economic analysis) including a cost estimate and benefit measures for alternative programs. Because of the limited time available to conduct the work, the cost estimate did not follow best practices. Senior decision makers were then left to make the best decision possible with inaccurate LCCEs.

11. Predicting future costs using historical data [13]
12. Ignored cost data outliers [13]
13. Political or budgetary reasons [13]
14. Misrepresented correlation between WBS elements [13]
15. Unplanned[20] funding shortfalls, either across the DoD Component or in a higher-priority program, which cause program delays and cost increases [13].
16. DoD and contractor optimism bias [25]
17. Acquisition strategy [18]
18. Management misbehavior [18]
19. Budget trends [18]
20. Engineering and design issues [16]
21. Schedule issues [16]
22. Quantity changes [16]
23. Revised estimates [16]
24. Economic changes [16]
25. Support costs [16]
26. Production issues [16]

The above list is not exhaustive and surely could be expanded. The point is that mitigating inaccurate cost estimates which lead to MDAP cost overruns is a complex challenge. Even including best practices in cost estimating and myriad acquisition reforms, these factors still prevail, as described in the next section.

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[20] Due to expected shifts in program priority over time, cost estimators could potentially anticipate and plan for funding shortfalls in particular years or set of years to mitigate any realized funding shortfalls [13].

3.4. FAILED ACQUISITION REFORMS INTENDED TO MITIGATE MDAP COST OVERRUNS

From 1960-2009, DoD implemented at least 156 acquisition reform initiatives, 38 of which pertained to weapon system costs [26]. Reform initiatives could be circular, as in the case of competitive prototyping which was required by law in 1987, eliminated in 1996, and then brought back in 2008 [26]. A similar circular trend is fixed-price contracts, which shifts cost risk onto the contractor, that were en vogue in the 1980s, fell out of favor in the 1990s, and then returned in the latter part of the 2000s. In 1983, the Carlucci reform initiatives included budgeting for most likely costs, budgeting for technological risk, budgeting for inflation, and providing more appropriate design-to-cost goals [26]. Parametric cost estimating and cost as an independent variable were formally required as early as 1995 [26]. Price-based acquisition came five years later, bolstering the "cost as an independent variable" initiative [26]. The following year, contractor cost sharing was introduced [26].

One well-known initiative to track cost performance from acquisition reforms (at least in part) in the DoD is the Nunn-McCurdy act introduced in 1982 [16]. This act defined two types of cost breaches [16]. Significant breaches occur when the program acquisition unit cost or the procurement unit cost[21] increases by at least 15% over the current baseline cost estimate or at least 30% over the original baseline cost estimate [16]. Critical breaches occur when either unit cost increases by at least 25% over the current baseline estimate or at least 50% over the original baseline cost estimate [16]. However, as Figure 14 shows, cost overruns of Nunn-McCurdy magnitude continue to plague the DoD.

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[21] The program acquisition unit cost is the total cost of development, procurement, acquisition operations and maintenance, and military construction divided by the number of units procured [27]. Procurement unit cost is the total procurement cost divided by the number of units procured [27].

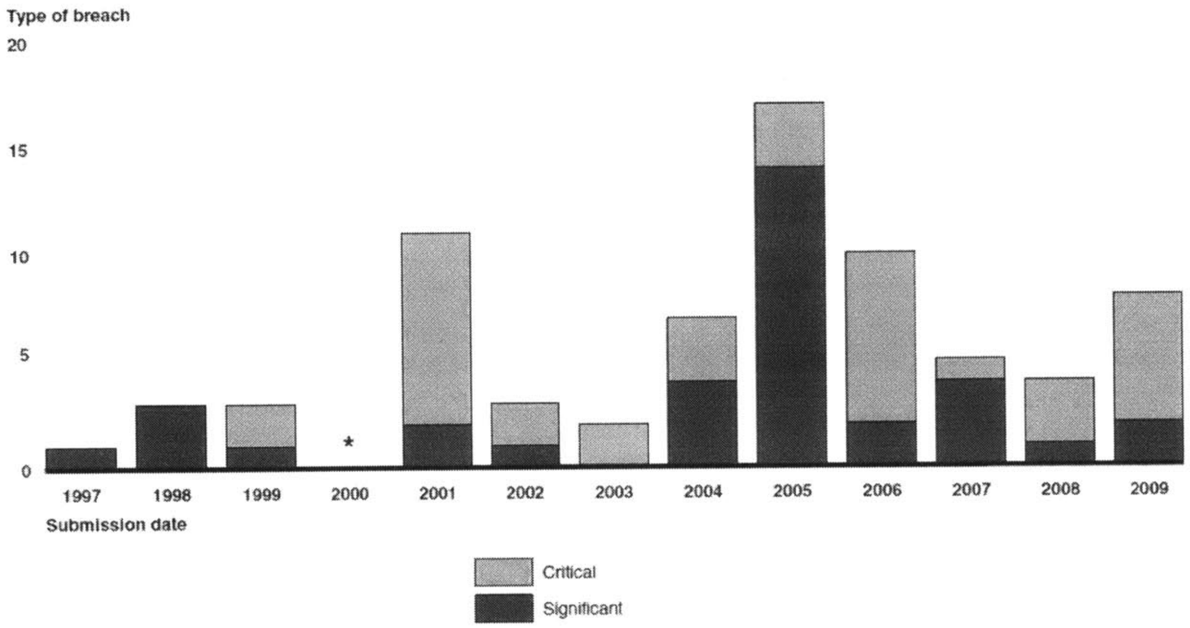

Figure 14: Significant & critical MDAP Nunn-McCurdy breaches between 1997 & 2009 (from [16]).

Even considering those programs that do not breach cost estimate baselines to the extent of triggering a Nunn-McCurdy breach, there is significant evidence of lack of progress with controlling costs in DoD acquisitions. In fiscal year 2008, 96 MDAPs collectively ran $296 billion over budget while in 2010 98 MDAPs overran their budgets by a collective $402 billion [27, 19]. Figure 15 shows that cost growth in MDAPs (programs with cost growth factors[22] greater than one) has occurred between 1968 and 2003. Other studies cited in Section 2.2.1 show this trend existing both before and after this time period. Crucially, there appears to be a persistent systemic bias towards underestimating costs for MDAPs [18].

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[22] See Section 2.2.

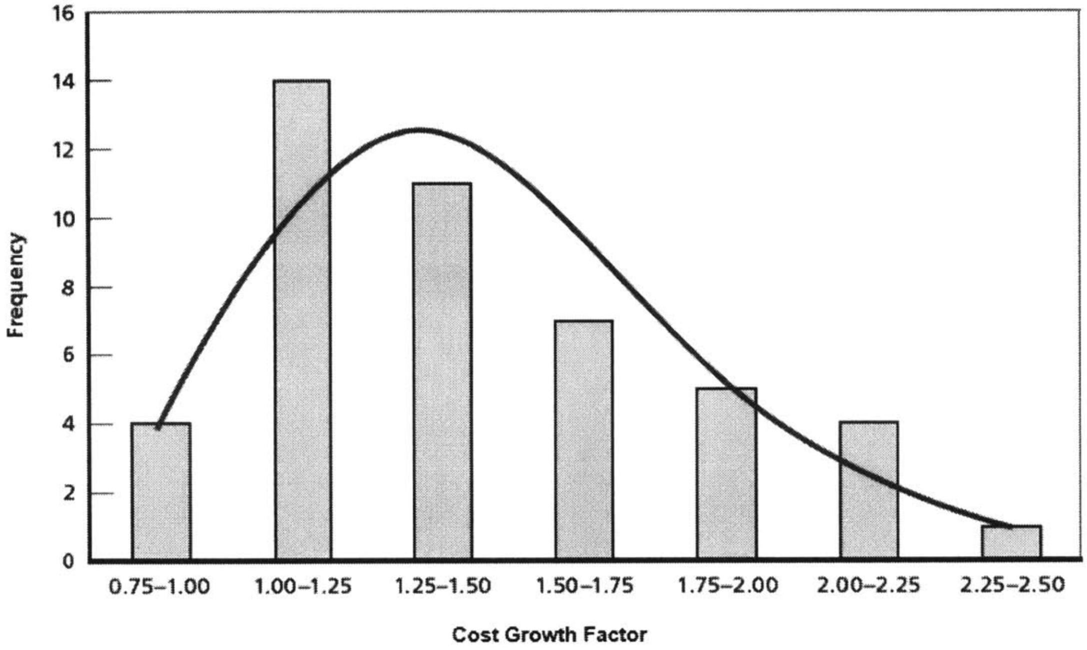

Figure 15: Distribution of cost growth factors in MDAPs from 1968-2003 (from [18]).

3.5. A NEW APPROACH TO MITIGATE MDAP COST OVERRUNS

Considering the many factors which may cause MDAP cost overruns, how can one correct for these to produce a higher-quality cost estimate? It's apparent from Section 3.4 that previous attempts over the past 50 years have not shown much progress in this area. Additionally, it is clear that DoD systemically overruns its MDAP cost estimates through a vast number of factors (see Sections 2.2.2 and 3.3). Causal factor regression tools already in use by cost estimators may help, but it is not obvious how a multi-factor regression could be constructed to provide a better prediction of future program costs. If one lumps all of these factors together into one *systemic cost risk* factor, then the problem of producing better (i.e., adjusted for systemic cost risk) cost estimates becomes tractable.

But on the surface, this approach appears to oversimplify the problem. However, such an approach called the Capital Asset Pricing Model (CAPM), an asset pricing model employed by 73% of corporate managers, has been used since the 1960s to predict asset values using a single-factor regression method [21, 28]. It is used to quantify systemic risk in asset markets, so it may prove useful in quantifying systemic cost risk is the “market” of MDAPs. In fact, the GAO has found that using risk-adjusted estimates is critical to achieving the acquisition program’s objectives [13]. CAPM may provide insight into quantifying systemic risk in MDAP costs that could be used to adjust cost estimates for risk, as suggested by the GAO. This idea will be explored in subsequent sections.

4. THE TIME VALUE OF MONEY & SYSTEMIC RISK-ADJUSTED ASSET VALUATION

This section introduces the concepts of the time value of money (price indices, general inflation rate, discount rates, and growth rates), base-year and then-year dollars (similar to the concepts of present and future value), and valuing assets using the CAPM. It bridges the previous and subsequent sections by explaining the concepts introduced in both. In particular, the concept of time value of money with respect to DoD budgeting is covered in more detail than in the prior section. The CAPM will be used as the basis for calculating systemic risk-adjusted growth rates for defense commodities of MDAPs in the next section.

4.1. TIME VALUE OF MONEY IN THE DOD

Conceptually, the time value of money implies that the value of a dollar today is different from the value of a dollar yesterday, as well as the value of a dollar tomorrow. "Time value of money" is a generic phrase that can mean many things. For instance, from a prospective view, an investor considers the time value of money to be that a dollar in-hand today is worth more than a dollar returned tomorrow, so he will expect compensation for the investment and lost opportunity of use of his dollar. Additionally, there is the risk that the investor may not receive repayment for his investment, so he demands compensation for this risk as well. From a perspective view, an investor may compare the value of the money he received today as a result of the money he invested yesterday and find that he has more or less of it depending on the *growth rate*. If he has more, then his growth rate is positive; if less, then it is negative. The return on investment expected by the investor is considered his opportunity cost of capital because he is giving up other investment opportunities when making his investment selection. From the view of a borrower (borrowing from an investor as a lender), he will incur a cost for the convenience of using an investor's money now with a promise to return the money plus a convenience fee. In this case, the convenience fee is referred to as the cost of capital. This cost of capital is used to *discount* future dollar values to the present. Even if a dollar is "stashed under a mattress" it will eventually be worth less; this concept is closely related to *general inflation rates* and *price indices*, which will be covered in a subsequent section. The DoD acquisition enterprise recognizes these four definitions of the time value of money and teaches these in its acquisition training classes [29].

For DoD acquisitions, the time value of money includes the previous concepts, but adds a unique twist. In the DoD money is not fungible[23] and appropriated for specific purposes. Furthermore, DoD funding expires with time, as shown in Figure 16. For example, research, development, test and evaluation (RDT&E) funding appropriated in fiscal year 2014 expires in fiscal year 2016 and becomes "worthless"[24].

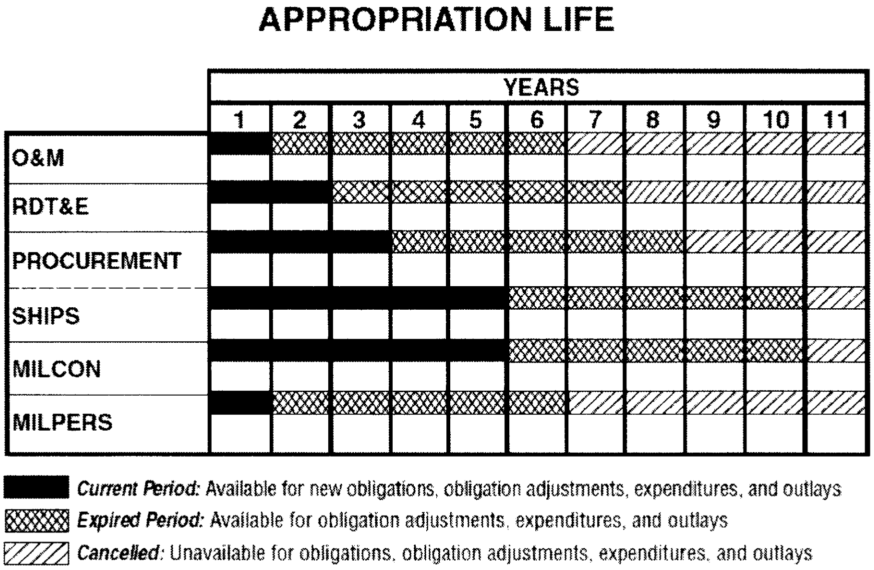

Figure 16: Appropriation life of various types of DoD funding [30].

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[23] That is, funds are assigned for specific uses and have no value if used for other-than-specified purposes without proper approval.

[24] From a specific DoD program perspective, even though these funds are available for another five years to reconcile any obligation, expenditure, or outlay adjustments from the current period, no *new* obligations may be made.

From these varying concepts, we see that the time value of money is somewhat open to interpretation. What is important is that, whichever concept of time value of money is used, it must be reasonable for the intended application. The DoD acquisition enterprise does not borrow to pay for programs; this task is performed by the US Treasury which issues bills, notes, and bonds. The Treasury then makes interest payments to holders of these financial instruments and these payments represent the cost of capital for the USG. When the DoD acquisition enterprise invests in the development, production, operation, and sustainment of a weapon system, it does so expecting to fulfill an unmet military capability gap. Thus, unlike for-profit organizations, the DoD expects non-monetary benefits from its capital investments. As such, in terms of money, the investment return is always negative since the weapon system developer is paid compensation for its services and products.

The DoD acquisition enterprise has the opportunity to invest in one weapon system over another, so the time value of money for defense acquisitions may be seen as an opportunity cost of capital rather than a cost of capital. This opportunity cost of capital can be used as a systemic risk-adjusted discount rate when valuing defense acquisition programs. However, DoD guidance, such as [31], states that the discount rate to be used for cost analysis (i.e., benefit-cost analysis or economic analysis) is the cost of capital for the USG. So, even though for-profit companies use systemic risk-adjusted discount rates to determine their cost of capital, this practice will not translate well (if at all) to the DoD.

Additionally, the defense acquisition enterprise must contend with and adjust for the specific loss of buying power (i.e., another form of the time value of money) through general inflation and price indices based on defense commodity classes or types. These adjustments are used in the PPBE process.

The time value of money is calculated using discount rates, the general inflation rate, price indices, and growth rates. For the DoD acquisition enterprise, discount rates and inflation are prescribed by OMB, while price indices for defense commodities are published by the Bureau of Economic Analysis (BEA) [32, 33]. The general inflation rate and price indices are used for budgeting weapon system acquisition programs, while discount rates are used for cost analyses (i.e., benefit-cost analyses). Importantly, discount rates are not used to determine time-phasing of funding through budget planning; only inflation and prices indices are used to convert dollars between base-years (i.e., dollars in constant-year purchasing power) and then-years (i.e., inflated and price-adjusted to reflect changes in purchasing power). Growth rates are used to analyze MDAP cost performance.

4.1.1. General Inflation Rate

General inflation accounts for the loss of purchasing power over time due to the general rise of prices in the economy at-large [29]. Past inflation rates are published by the Bureau of Labor Statistics, but future inflation rates are unknown [21]. For the DoD, the current year's inflation rate may be inferred from the published real and nominal discount rates[25] contained in OMB Circular A-94 [33]. These rates are published each January in Appendix C of the circular, and the difference between the nominal and real rate for a given maturity yields the expected inflation rate for the year. However, beyond the current year, the inflation rate is, in actuality, unknown, but the OSD Comptroller sets the official inflation rates to be used in preparing budgets [32]. Also, OMB publishes expected general inflation rates for five years into the future [32]. Interestingly, according to OMB, the inflation index used may include the full, partial, or no anticipated inflation

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[25] These are really the US Treasury bill, note, and bond rates, both real and nominal, for specified maturities.

based on the US gross domestic product (GDP) (also called the GDP deflator) [32, 33]. However, a DoD Component that ignores inflation is exacerbating MDAP cost overruns.

General inflation is used to convert between real – representing changes in buying power of money – and nominal – representing the total change in the value of money – dollars [21]. In terms of rates, the following equation is used to convert between a real rate, r_{real}, and a nominal rate, r_{nom}, using an assumed or mandated value for inflation, i [21].

$$r_{nom} = r_{real} + i + ir_{real}$$

(Eq 1)

When inflation is positive (which is typically the case), one sees that the nominal rate is larger than the real rate.

Given the importance of inflation projections for setting program budgets in the DoD, one may consider the effects of poor inflation projections on MDAP cost estimation. Section 2.2.1 noted a perpetual bias in underestimating MDAP costs which leads to program cost overruns. If inflation projections by OMB were always skewed low (i.e., below the realized inflation), then one might expect this reason to be the cause of the cost estimate bias and program overruns. However, [32] found that between 1991 and 2009, the inflation projections actually overestimated inflation by 0.8% on average, and that years with overestimates tended to have larger errors than those years with underestimates. These findings imply that program cost estimates time-phased for budgeting would be larger than if the forecast inflation rates were known perfectly. As such, inflation projections by OMB seem to have actually reduced the cost estimate bias in MDAPs over this time period.

4.1.2. Defense Commodity Price Indices

Price indices, like general inflation rates, measure the changes in purchasing power over time. For price indices, particular fixed "baskets of goods" are used to represent these changes in purchasing power [32]. The baskets are fixed in the sense that quality is fixed over time, such as with a basket of fruit (thus the reason for the use of the term "basket"). However, some price indices attempt to relax the "fixed" requirement on the basket and remove the effect of quality improvement over time from the index [32]. Components of the basket are assumed to share the same risk of inflation. For defense commodities, the defense commodity price index is set by BEA and covers the following categories of defense commodities: *Aircraft*, *Electronics and Software*, *Missiles*, *Ships*, *Space and Satellites*, and *Vehicles* [34]. These indices are corrected for quality improvements over time [32].

To give the reader an idea of the magnitude of these price indices and how they compare to one another, a graph showing these indices (all except space and satellites) is shown in Figure 17. Notice that the inflation rate, shown as the GDP Deflator trace, has the second largest gain over the time horizon of the chart. Also, notice that the price index for Aircraft remains about constant since, although Aircraft are more expensive in 2009 than 1985, the improvements in quality (such as stealth) make the relative increase in price extremely small. Similar reasoning applies to Missiles and Electronics and Software which have price indices that have dropped since 1985 due to great improvements in quality such as the introduction of smart munitions. Using this same line of reasoning, one can see that the quality of Ships and Vehicles have not improved as much as the other commodities leading to higher price indices for these defense commodities. Figure 17 also serves as visual support for the conclusion in [32] that DoD should not use the GDP Deflator uniformly across all defense acquisition programs in analysis reports of real price changes to Congress since it is a poor proxy for the actual change in buying power for defense commodities.

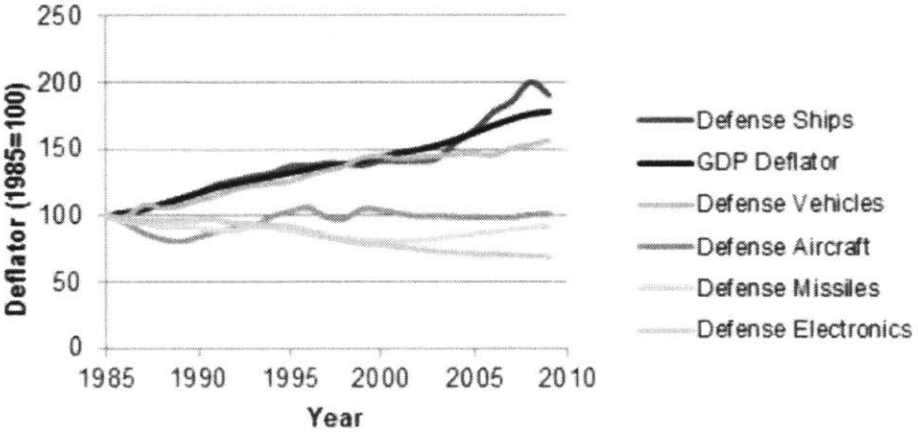

Figure 17: Inflation (GDP Deflator) & defense commodity price indices over time [32].

4.1.3. Discount Rates

Costs and benefits should be discounted in DoD cost analyses [10, 31]. Cost analysis is performed during the Analysis of Alternatives process under the JCIDS shown in Figure 4, but it is not used in the PPBE process [10]. Since alternatives are judged mostly based on filling capability gaps when new threats are anticipated, the discounted monetary costs of alternatives, which have similar forecast program timelines, are less crucial than in for-profit organizations which may have programs spanning various durations to improve profits.

When considering the discount rate as the cost of capital, the USG and for-profit companies differ in how the cost of capital is used and its importance. As noted previously, the USG's cost of capital is the interest it pays on US Treasury instruments since tax revenues do not pay for new weapon systems[26]. Since US Treasury instruments are considered "risk free," the rates do not depend on the underlying risk in the use of the borrowed funds. For-profit companies mostly fund their programs with debt and equity capital. Investors providing the capital require a return measured by the weighted average cost of capital, a rate that is used to discount cash flows

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[26] Mr. Erskine Bowles, co-chairman of President Obama's National Commission on Fiscal Responsibility and Reform, stated that tax revenue pays for Medicare, Medicaid, and Social Security [49]. Other USG expenditures, such as DoD acquisition programs, are funded with borrowing [49].

generated by the investment programs. Since investors risk losing their investment, the weighted average cost of capital is larger than the cost of capital for the USG, and it is dependent on what types of programs the capital funds, unlike for the USG.

More tellingly, for-profit companies derive monetary benefits from programs, and these benefits are highly sensitive to the discount rate since it compounds with time (again, discount rates apply only when performing benefit-cost analyses). A program that yields profits far into the future is less beneficial than one that provides the same profits sooner due to the discount rate. Even though benefits in DoD cost analyses must be discounted, these benefits are often non-monetary so the "discount rate" applied is often subjectively based on the anticipated need date, if at all.

For these reasons, the discount rate plays a less significant role in DoD acquisition programs than in for-profit organizations.

4.1.4. Growth Rates

Growth rates are similar to inflation rates and price indices in that, when positive, they increase the numerical value of an asset over time (unlike discount rates). When cost overruns in MDAPs occur, they do so because the present baseline cost estimate (or, for completed programs, actual program cost) is larger than the previous one. Growth may occur over more than two baseline cost estimates as well. In the case of SARs, one can measure the annual cost growth of a program over time, and calculate the average growth rate in two ways.

The two methods of calculating the average growth rate from a time series of growth rates are the arithmetic and geometric averages [21]. The arithmetic average provides a good forecast for the expected growth in the next time period [21]. It is calculated by summing the per-period growth rates and then dividing by the number of samples [21]. The geometric average provides the equivalent per-period growth rate required to provide the same overall growth from the component per-period growth rates [21]. It provides a measure of per-period growth of a dollar over time, and it is inherently assumed to be backward-looking.

Choosing between the two averaging methods depends on the purpose. If a forecast of expected growth rate is needed, then the arithmetic average should be used [22]. If one needs to quantify past performance in terms of growth rate, then the geometric average is best [21].

4.2. BASE-YEAR & THEN-YEAR DOLLARS

An important aspect in understanding the PPBE process and MDAP cost estimates is the difference between base-year (also called constant-year) and then-year dollars. MDAP cost estimates are made in base-year dollars, but then need to be time-phased in then-year dollars to create an annual budget [13]. The difference between the two types of dollars is analogous to that for real and nominal dollars in which real dollars are nominal dollars adjusted for inflation. Base-year dollars are equivalent to real dollars, while then-year dollars are considered nominal dollars [29].

To convert between base-year and then-year dollars (and vice versa) requires only a simple calculation involving the compounding or discounting factor. Assuming then-year dollars are in the future relative to the base year, as is the case most times, then the base-year dollars are equivalent to present value while the then-year dollars are taken as the future value. In this case, (Eq 2) may be used to convert between the present value (base-year dollars) and future value (then-year dollars).

$$PV_{BY} = \frac{FV_{TY}}{(1 + r_{nom})^p} = DF_p \times FV_{TY}$$

(Eq 2)

In (Eq 2), PV_{BY} is the present value in the base-year, FV_{TY} is the future value in the then-year, r_{nom} is the nominal discounting rate[27] including *both* the effects of general inflation and any applicable price indices, and DF_p is the discount factor over the number of periods p [29]. The inverse of the discount factor is the compounding factor. In this case, the nominal discounting rate r_{nom} is seen as a growth rate g_{nom}, but the numerical values are typically the same.

The discounting and compounding effect of (Eq 2) sometimes leads to under-valuing present values and over-valuing future values. This is because the estimate of the rate may be taken from an arithmetic average over much shorter time periods than p leading to greater upward errors in the rate than negative variation resulting in a positive bias [21]. Because of this phenomenon, for larger values of p, the present value or future value calculated from the equation may become unreasonable since the sum of one plus the rate increases exponentially. One may use judgment to determine if the values produced by (Eq 2) seem unreasonable and apply a correction, if necessary.

4.3. CAPITAL ASSET PRICING MODEL

The CAPM was introduced by Sharpe in his 1964 classic paper and it is used by 73% of corporate managers [28, 21]. He argued that when prices of assets within a market are in equilibrium there exists a consistent linear relationship between their expected returns and systemic risk [28]. This equilibrium condition requires that all risky assets in a market should offer the same reward-risk ratio [21]. The linear relationship may be estimated from historical returns using linear regression, and the scatter about the line-of-best-fit represents the *total risk* of

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[27] Not to be confused with the cost of capital or weighted cost of capital used to discount future cash flows in cost analyses. In (Eq 2) this rate is assumed to include both the general inflation rate and any applicable price index corrections.

the asset's returns [28]. However, a portion of the scatter about this line is due to the causal relationship between the market return and that of the risky asset [28].

This causal relationship is captured by the slope of the regression line, β, and it describes the sensitivity of the asset to *systemic risk*, one of two components of the asset's total risk [28, 21]. The other component of risk, the *asset-specific risk*, represents the remaining portion of the asset's total risk, which is idiosyncratic and unpredictable [28]. The components of risk can be measured precisely from the R^2 statistic produced by the regression analysis: R^2 is the portion of risk associated with the system (i.e., macro-economic activity), and $1 - R^2$ is asset-specific risk. The β term can be used to predict the expected return of a risky asset due to the forecasted expected return for the market over the same time horizon [28]. Since forecasts for expected market returns are typically more accurate than those for individual risky assets due to aggregated forecasts[28], this approach provides a favorable method of calculating expected returns for individual assets.

Figure 18 displays an example of the CAPM linear regression for Yahoo!. The combined monthly returns from the NYSE, AMEX, and NASDAQ markets between May 1996 and August 1997 are plotted against the x-axis; these markets represent the overall market return in CAPM. The monthly returns of Yahoo! over the same time horizon are plotted against the y-axis. The resulting scatter plot is shown in the figure as open circles. Performing a linear regression on the data produces the CAPM parameter β value of 3.73. The portion of Yahoo!'s total risk attributed to the market (i.e., systemic risk) is the R^2 value, 25%. In words, these values mean that Yahoo! delivers returns 3.73 times those of market, and that 25% of the stock's total return risk can be explained by market movements. The remaining 75% of the stock's total return risk is the asset-specific risk and is unpredictable. For a tech stock, these values are expected.

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[28] Such aggregation produces more accurate forecasts if the constituents of the aggregate are not perfectly correlated.

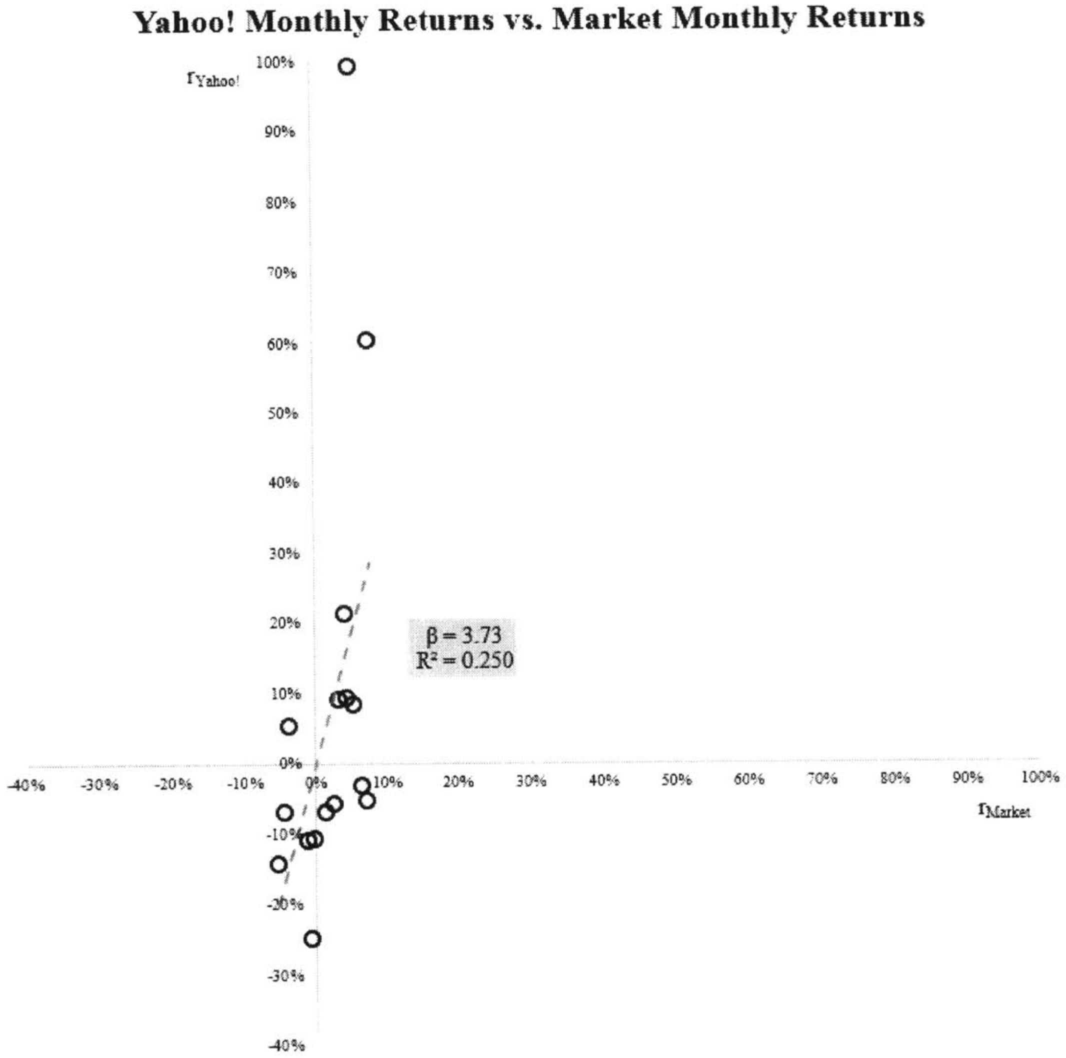

Figure 18: Example CAPM linear regression for Yahoo!.

4.3.1. The Expected Growth-Beta Relationship

The CAPM is most useful to practitioners when expressed in the expected growth-beta relationship [21]:

$$E\{r_{asset\ j}\} = r_{risk-free} + \beta_{asset\ j} \times E\{r_{Market} - r_{risk-free}\}$$

(Eq 3)

where $E\{r_{asset\,j}\}$ is the expected future return rate of risky asset j, $r_{risk\text{-}free}$ is the "risk-free" return rate, $\beta_{asset\,j}$ measures the sensitivity of the asset's return with that of the market, and $E\{r_{Market}$-$r_{risk\text{-}}$

$_{free}\}$ is the expected future risk premium (to the market). In words, the equation states that the expected growth rate of a risky asset is the sum of the "risk-free" return rate and a market risk premium scaled by the asset's relative systemic risk to the market (the beta term). The relationship is derived directly from the equilibrium condition that all risky assets, including the market as an asset, should provide the same return for a given level of risk [21]. In practice, the expected future return of the market is based on the arithmetic average of historical returns and the assumption that future returns will be similar[29], so the expectation operator associated with the market return may be replaced with an historical arithmetic average. The "risk-free" return rate is assumed to be the rate of a comparable-length (for the desired investment time period) US Treasury investment since the USG has not and is not expected to default on its debt obligations because of its power to tax and control the money supply[30] [21]. As before, beta is found through a linear regression[31] of the historical asset return with the market return[32].

It is important to note that beta estimates for individual risky assets will always include a large margin for error [35]. As such, managers usually estimate betas for individual stocks within an industry, and then average these estimates to form an industry beta [35]. It is appropriate when one expects similar risks within an industry. This aggregate estimate tends to cancel-out estimate errors for individual assets [35].

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[29] Of course, this statement brings to mind the standard warning included in all advertisements for investment products: "Past performance is no guarantee of future returns."

[30] This statement is not entirely true. The last time the USG defaulted on its debt was 1979 in which a Congressional vote to raise the government's debt ceiling and pay its debt holders occurred too late to avoid sending out payment checks in time to meet scheduled payments [42]. In this case, only $120M USG debt was affected [42].

[31] The y-intercept is forced to zero based on an assumption in CAPM.

[32] Note that the risk premium, $E\{r_{Market} - r_{risk-free}\}$, is not used in the regression, since time series data for market returns are readily available and the risk premium may be found following the regression. Instead, the nominal market returns are used.

4.3.2. Limitations of the CAPM

The simplicity and power of the CAPM comes at the price of several theoretical and empirical shortcomings [21]. Assumptions which underpin CAPM include a hypothesized simple and unrealistic view of the world which does not exist [21]. Expected market returns are assumed normally distributed so that the variance fully characterizes investment risk [21]. When the expected market return is zero, then the assets expected return is only the risk-free rate. Stated differently, the intercept of the regression in the expected growth-beta relationship is forced to be zero[33]. Notice in (Eq 3) the need for the *expected* risk premium[34], which is not observable. Only time-series historical returns are observable, and these are used instead to estimate this expected return [21]. By dichotomizing risk into only two classes, CAPM oversimplifies the sources of real-world uncertainty [21]. Finally, market equilibrium is assumed in the derivation of the expected growth-beta equation, but this may not hold true in reality [21].

The use of time-series historical data to estimate expected returns leaves CAPM open to selection bias. For example, the expected risk premium in (Eq 3) could be approximated by two different historical values. One could choose the long-term historical risk premium measured between 1926 and 2009 of 7.9%, or one could choose the value 5.1% from a more recent sample including data between 1968 and 2009 [21]. Since the risk premium is scaled by beta, this choice of timeframe could lead to large changes in expected return. Thus CAPM could be applied correctly using either larger or smaller values of the risk premium estimate dependent on one's agenda.

Empirical measures limit the credibility of CAPM to purists in several other ways. There exists historical evidence of non-zero intercepts which are ignored in CAPM [21]. The t-statistic

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[33] The $r_{risk-free}$ term is added *after* regression is performed.

[34] See Footnote 32.

for the beta term, which is used to establish the statistical significance of a non-zero beta value, is ignored as beta must not equal zero if the asset being priced is drawn from the market its returns are regressed against. If it did, then the risky asset in (Eq 3) would simply be the risk-free asset. Finally, small departures from the theoretical equilibrium condition of the same equation can lead to huge discrepancies in the output of the expected growth-beta relationship [21].

Still, despite these empirical failings, the CAPM enjoys widespread use by practitioners in the US and many other developed countries [21]. Intuitively, CAPM allows one to quantify systemic risk relevant to the pricing of assets. Its simplicity and ability to be integrated with normal spreadsheets and financial analysis performed by many organizations, including the DoD, is perhaps its most appealing aspect. In fact, from the practitioner's perspective, the expected growth-beta relationship of CAPM may be viewed[35] as a single-factor ordinary least squares regression with the intercept set to zero and without need of ensuring the R^2 value is arbitrarily large (e.g., 90%). In these ways, it's even simpler than ordinary least squares regression performed by cost estimators in the DoD.

The power of splitting estimation risk into systemic and program-specific components is another strongly appealing feature of CAPM. It is this characteristic of CAPM that makes it a model worth consideration in tackling the challenge of managing systemic cost risk in MDAPs to improve affordability. CAPM may be able to quantify and mitigate the persistent systemic bias in MDAP cost estimates, leaving program-specific cost estimation risk to cost estimators specialized in particular programs.

The true test of value in applying the expected growth-beta relationship to MDAPs is to perform an empirical case study to determine if this relationship can be used to improve

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[35] See Footnote 33.

affordability in the DoD. The remainder of this thesis develops this relationship for MDAPs and presents the results of an empirical test using actual historical program cost data.

5. SYSTEMIC RISK-ADJUSTED COST GROWTH RATES FOR DOD ACQUISITION PROGRAMS

Applying the expected growth-beta expression borrowed from CAPM to MDAPs allows one to determine the effect of systemic cost risk on the cost estimates of MDAPs. It does so by assuming errors in program cost estimates are linearly related to errors in cost estimates for all MDAPs, and that a causal relationship exists between the two quantities through the 26 systemic risk factors listed in Section 3.3. Linear regression is performed to determine the slope of the line-of-best-fit. This value, called the program systemic cost risk beta, captures the extent to which the program's cost estimate changes vary with those for all MDAPs. Program systemic cost risk beta estimates are averaged over the defense commodity types Aircraft, Electronics and Software, Missiles, Ships, Space and Satellites, and Vehicles and then combined with the historical MDAP cost growth arithmetic average to forecast systemic risk-adjusted program cost estimates into the future. Next, Systemic Risk Factors are calculated using an ad hoc compounding effect reduction method and applied to capital budgeting of MDAPs to improve affordability in the DoD. Finally, a historical set of six MDAPs representing each of the defense commodity classes are used to illustrate this new approach to improving affordability.

5.1. EXPECTED GROWTH-BETA EXPRESSION FOR MDAP COST ESTIMATES

The expression in (Eq 3) was derived for determining the expected return on a risky asset in a market whose prices had achieved equilibrium and for which there exists an asset providing a risk-free return [28]. It is assumed that the cost estimate representing the value of the acquisition program is static (i.e., in equilibrium) at least until the next estimate is required. Since there is no such thing as a risk-free asset for MDAPs[36], (Eq 3) becomes

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[36] Recalling the discussion in Section 4.1 on the appropriation life of DoD funding, the DoD cannot choose to hold funds in a risk-free account for use at a later time since these funds will expire.

$$E\{g_{program\ j}\} = E\{g_{commodity\ k}\} = \beta_{commodity\ k} \times E\{g_{MDAPs}\}$$

(Eq 4)

where $E\{g_{program\ j}\}$ is the expected nominal growth rate of the cost estimate of $program\ j$ which is equal to $E\{g_{commodity\ k}\}$ since MDAPs within a particular commodity class are assumed to share the same system cost risk and beta values are aggregated across programs within a defense commodity type to improve the beta estimate; $\beta_{commodity\ k}$ is the averaged beta estimates for individual programs within the defense commodity type (of which $program\ j$ is a member); and the last term is the expected value of percent changes in nominal cost estimates of all MDAPs. Recall that since estimates of beta for individual assets always include large errors, best practice is to average these across an industry with similar risks as the errors tend to cancel each other [35]. As in the CAPM, the line-of-best-fit is determined by performing a linear regression between the program of interest's historical cost estimate changes and those for all MDAPs. These historical data are found in SARs which are published quarterly for some programs but annually for all MDAPs [36]. If one has a good forecast of anticipated cost estimate changes for all MDAPs over a time horizon of interest, then this value would be used for the last term in (Eq 4) instead of the historical arithmetic average.

The results of a linear regression of annual cost estimate changes between the AIM-9X Block I program and the average annual cost estimate changes of MDAPs between 1970 and 2012 are shown in Figure 19. The beta value 0.09 indicates extremely low sensitivity to overall changes in MDAP cost estimates. Approximately 11% of the AIM-9X Block I's cost estimate changes were attributable to that for all MDAPs (i.e., the pervasive systemic bias described in Section 2.2.1); it represents a measure of the systemic cost risk associated with this particular program. Given that the AIM-9X incorporated advanced technologies such as off-boresight cueing and an improved infrared seeker, one would expect much of the difference in cost estimates to be attributed to program-specific cost risk rather than systemic cost risk. Recall from Section 4.3 that the program-specific cost risk, which for AIM-9X is approximately 89% of the total cost risk, is idiosyncratic and unpredictable.

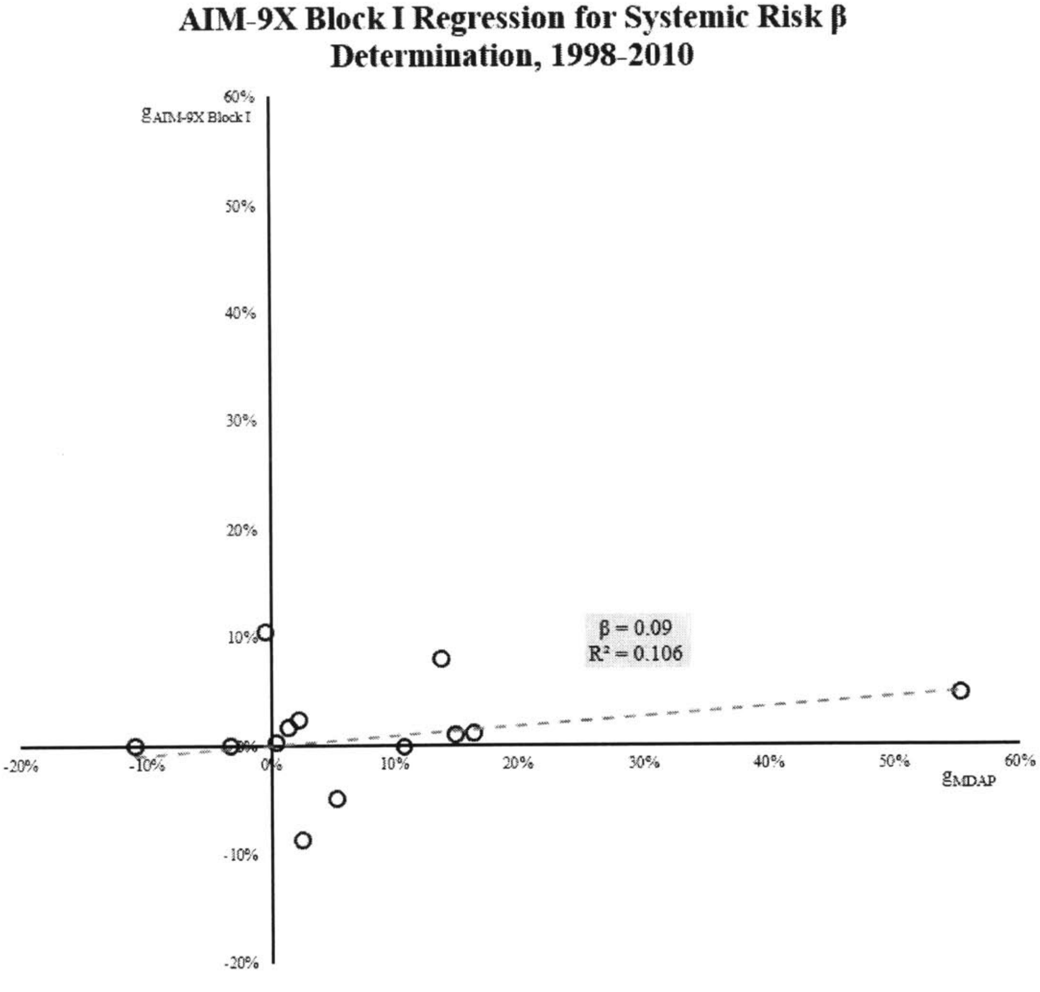

Figure 19: Linear regression analysis of the AIM-9X Block I program annual cost estimate percent changes from SARs.

5.2. RETRIEVING COST ESTIMATE DATA FROM SARS

Cost estimates for MDAPs are found in the quarterly and annually updated SARs which list the latest cost estimates for these programs [37]. Using the CAPM analogy, each cost estimate may be viewed as the market price of the corresponding program and "asset returns" may be formed by taking the percentage difference between two successive cost estimates for the same program. Similarly, "market returns" may be calculated as the percent difference of all MDAP cost estimates between two SAR reporting periods. Care must be taken to include only nominal values, which in the DoD are referred to as "then-year" dollars. In this way, errors in estimating inflation and defense commodity price indices can be included to create a truly systemic risk determination to be used later for budgeting.

In practice, not all MDAPs are updated quarterly and some of these programs last only a few SAR reporting cycles[37]. These infrequency and short existence problems make estimating the beta parameter from (Eq 4) less precise. Since linear regression of the MDAP cost estimate changes are used to estimate beta, less data may lead to worse estimates. However, there are many programs that survive through multiple SAR reporting cycles whose beta estimates may be made with multiple data points. Additionally, omitting those short-lived programs may hide systemic risk as these programs may have been terminated due to poor performance. Finally, as noted previously, by aggregating multiple programs under each defense commodity type one can partially mitigate the issue of precision due to limited data points.

Additional concerns with SAR cost estimate data were noted in Section 2.2.3 and will not be repeated here.

5.3. PROCEDURE FOR CALCULATING SYSTEMIC RISK-ADJUSTED COST ESTIMATE GROWTH RATES FOR MDAPS

Calculating the values of parameters in (Eq 4) is quite straightforward after several assumptions. First, as mentioned previously, only nominal values of MDAP cost estimates in the

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[37] However, all MDAP cost estimates are updated in the annual December version of the SAR.

SARs are used. Recall that nominal values include the effect of inflation and price index corrections, and that the intent is to ultimately capture systemic cost risk for defense commodities. Second, the author relied on his experience in the defense community to identify programs by commodity types and assumed his categorization was accurate. In total, cost estimate data for 141 programs (listed in Appendix E – Beta Calculation Spreadsheets) were collected between the years 1997 and 2012, and of this total, only four of the 141 programs could not be categorized using one of the six defense commodity classes. These four programs were not included in the analysis. Additionally, the NMD and THAAD programs managed by DoD were excluded due to lack of data samples and wild swings in cost estimates which were not representative of the remaining 137 MDAPs analyzed.

With these assumptions in place, the quantities in (Eq 4) are calculated using the following steps. This process is also shown in Figure 20 on the next page.

1. Download MDAP then-year cost estimates contained in SARs at [37] covering the desired time horizon.
2. Categorize each MDAP using one of the six defense commodity types.
3. Sum all MDAP nominal cost estimates (across all commodity types) for each year over the desired time horizon.
4. Calculate period-over-period (e.g., year-over-year) percentage changes for each MDAP cost estimate as well as the period-over-period percentage change for all MDAPs.
5. Perform linear regression on the per-period percent change of cost estimates for each MDAP with the per-period percent change of the total cost estimates for all MDAPs over the desired time horizon to calculate program beta estimates.

6. Average beta estimates over each MDAP in a particular defense commodity type to form one estimate of beta for each defense commodity ($\boldsymbol{\beta_{commodity\ k}}$);
7. Average the total cost estimates per-period percent changes for all MDAPs over *all* (i.e., one may use a longer history of MDAP percent changes than the desired analysis time horizon) available SARs ($\boldsymbol{E\{g_{MDAPs}\}}$);
8. Calculate the systemic risk-adjusted cost estimate nominal growth rate for $program\ j$ ($\boldsymbol{E\{g_{program\ j}\}} = \boldsymbol{E\{g_{commodity\ k}\}}$).

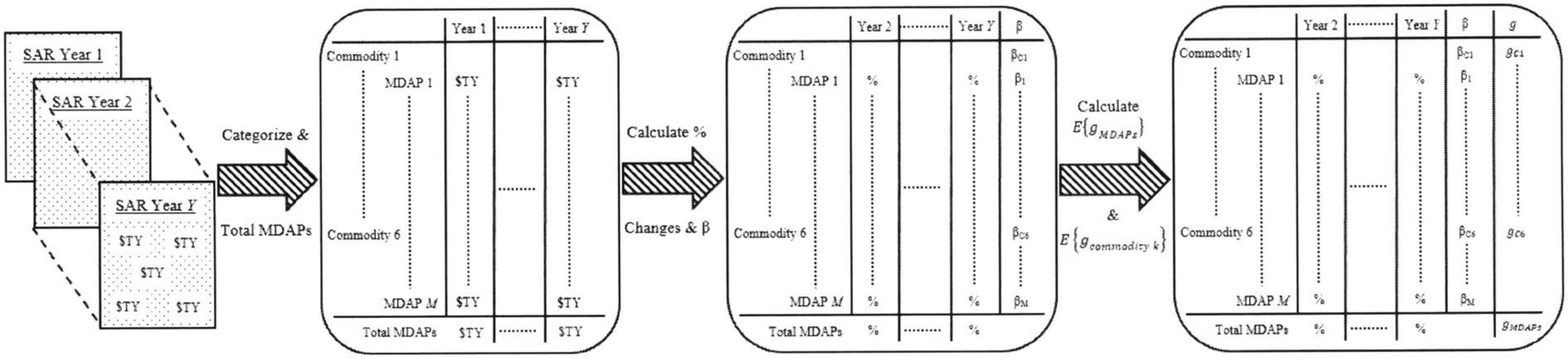

Figure 20: Graphical representation of the eight-step procedure for calculating systemic risk-adjusted cost estimate growth rates for MDAPs. "C#" subscripts are used as shorthand for "Commodity #."

5.4. CALCULATION OF BETA VALUES & SYSTEMIC RISK-ADJUSTED COST ESTIMATE GROWTH RATES

Using the general procedure from the previous section, risk-adjusted nominal cost estimate growth rates for the six defense commodities were calculated. The desired time horizon was set to 1997 through 2012, and annual SAR cost estimates were used as the quarterly SARs did not contain updates for all programs. The expected percentage change in all MDAPs was calculated using an expanded set of SAR data covering 1970 to 2012. Annual SAR cost estimate changes between 1970 and 2012 are shown in Appendix D – MDAP Nominal Annual Cost Change, 1970-2012. Details of the beta calculation are found in Appendix E – Beta Calculation Spreadsheets[38]. Results of the spreadsheet calculations are shown in Table 2.

Defense Commodity Type	β
Aircraft	1.01
Electronics & Software	0.59
Missiles	0.46
Ships	0.68
Space & Satellites	0.35
Vehicles	4.85

Table 2: Beta estimates for each defense commodity type.

Using (Eq 4) and an arithmetic average annual MDAP cost estimate growth rate of 7.4% calculated from Step 7 (again using data from 1970 to 2012) in the previous section, cost estimate growth rates for each defense commodity type were calculated as shown in Table 3.

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[38] Blackened cells appear in the beta calculation spreadsheets to cover automated calculations where there were no SAR data available (i.e., divide by zero errors) or where the program had transitioned to operations and sustainment, and were no longer reported in SARs (i.e., -100 percent changes). These cells were blackened for clarity and the values were not used in beta calculations.

Defense Commodity Type	g
Aircraft	7.45%
Electronics & Software	4.38%
Missiles	3.42%
Ships	5.02%
Space & Satellites	2.56%
Vehicles	35.85%

Table 3: Systemic risk-adjusted cost estimate growth rates for each defense commodity type.

These values will be interpreted in Section 5.5. An ad hoc method to adjust budgeting for MDAPs using these values will be presented in Sections 5.6 and 5.7. The output of this method may be used by decision makers to improve MDAP cost estimates. The results in Table 3 will be applied to six completed programs as a partial validation of this approach to correct cost estimates based on systemic risk adjustments in Section 5.6.

5.5. INTERPRETATION OF BETA VALUES & SYSTEMIC RISK-ADJUSTED COST ESTIMATE GROWTH RATES

The values in Table 2 and Table 3 need to be interpreted to have meaning. Beginning with Table 2, we can divide the defense commodities into two groups: those with beta values greater than one, and those with beta values less than one. Aircraft and Vehicles fall into the first grouping. Since their beta values are greater than one, which represents the level of commodity cost changes with respect to those of all MDAPs, Aircraft and Vehicle acquisition programs are riskier than the average MDAP in terms of systemic cost risk. Notice that vehicle acquisition programs are almost *five* times riskier in terms of cost performance than the average of all MDAPs – does this value make sense? Considering the value was based on cost estimates of all Vehicle programs in the DoD and that the majority are run by the Army with noted problems with Vehicle acquisition programs in the past decade (see [38] as just one example), this value, although high, seems to be reasonable[39]. Additionally, [18] found that Army weapon systems had higher cost growth than those for the Air Force or Navy. Considering the Aircraft beta value, this value seems low. However, since 33 Aircraft programs were analyzed and of these 15 were for lower-risk modernization of existing platforms, this value of beta is not unreasonable.

Focusing on the grouping with beta values below one, representing systemic cost risk below that of the average MDAP, Space and Satellites seem to have an unreasonably low beta value. Given the documented existence of cost overruns and delays with space acquisition programs (see [39], for example) one would expect this value to be larger than one. One explanation is the small sample size in which only 12 of the 137 programs are categorized as Space and Satellites. Additionally, eight of these 12 programs are considered modernization which assumes less cost risk than new development work. The Navy generally performs better than the other services in managing costs on acquisition programs (see [15], for example), and about half of the Ship commodity type programs are for modernization, which have less risk than new development work, so its beta value is not too unreasonable. Beta values for Missiles and Electronics and Software seem reasonable since these systems are generally less complex than Aircraft. In particular, Electronics and Software programs tend to have lower cost growth compared with the other commodity types [18].

In general, since quarterly SAR updates were not available for all MDAPs, at most 15[40] samples of changes in cost estimates were available for each program. If quarterly reporting were available for all programs, this number would quadruple the number of samples available and

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[39] A dramatized version of the Army's woes with Vehicle acquisition programs is found in the 1998 dark comedy *The Pentagon Wars*. In this film, the Army's Bradley Fighting Vehicle program was plagued by years of cost overruns and delays due to requirements creep, and an Air Force acquisitions officer was appointed to investigate the program's poor performance.

[40] Since 16 SARs from 1997 through 2012 were considered, and since year-over-year percent changes were needed to calculate the model values, at most 15 data points could be available for analysis.

provide higher precision in estimating beta values. Still, the resulting beta values in Table 2 seem reasonable with the noted exceptions and especially considering that they were averaged across many programs in each defense commodity type.

With the exception of the systemic risk-adjusted growth rate for Vehicles, the annual growth rates for other commodity types are within the bounds presented in Table 1 from [19]. This cross-check is reassuring and lends credibility to the growth rate results.

5.6. SYSTEMIC RISK FACTORS & METHOD VALIDATION

Six completed programs representing each of the six defense commodity types were used to partially validate the methods described in the previous sections. These programs were: C-17A (Aircraft type), AESA (Electronics and Software type), AIM-9X Block I (Missiles type), SSGN (Ships type), Minuteman III PRP (Space & Satellites type), and STRYKER (Vehicles type).

Initially, the growth rates were applied directly to the earliest available cost estimate which included all life cycle costs through direct compounding using the future value formula in (Eq 2). However, as noted in Section 4.2, compounding over long periods of time may lead to overly large future values. As a result, an ad hoc adjustment was made to (Eq 2):

$$Future\ Cost\ Estimate_t = Current\ Estimate_{t_o} \times \left(1 + g_{program\ j}\right)^{(t-t_o)/n} \qquad \text{(Eq 5)}$$

where $\left(1 + g_{program\ j}\right)^{(t-t_o)/n}$ is the **Systemic Risk Factor (SRF)** adjusted for compounding time effects using the integer n defined in Table 4. These values for the integer n were determined empirically using one program from each of the six defense commodity types.

$t - t_o$ [years]	n
1 to 4	1
5 to 9	2
Over 10	4

Table 4: SRF adjustment to correct for compounding effects.

Table 5 shows the results of the partial validation. It shows the cost estimate values for each program including the initial year, final SAR year, and difference in cost estimates between the initial and final years. It also shows results of applying (Eq 4) and (Eq 5) to each of the six programs of interest. The last column in Table 5 shows the percent improvement in program cost estimate between the initial and final SAR dates. In all cases except for the Minuteman III PRP program, the cost estimates were improved by including the SRF to account for systemic cost risk. Overall, a 57% enhancement in estimation accuracy was achieved when comparing the initial and SRF-adjusted MDAP cost estimates to the final estimates, indicating quantifying and adjusting for systemic cost risk can improve cost estimation accuracy.

MDAP	Defense Commodity Type	Initial SAR Estimate (Yr/$M)	Final SAR Estimate (Yr/$M)	SAR Estimate Difference ($M) (smaller is better)	% Difference (smaller is better)	$t - t_o$ & n	SRF-Adjusted Final Estimate ($M)	SRF-Adjusted SAR Estimate Difference ($M) (closer to zero is better)	SRF-Adjusted % Difference (closer to zero is better)	Improvement (larger positive value is better)
C-17A	Aircraft	1997 / $41,185.7	2009 / $69,570.8	$28,385.1	68.9%	10 & 4	$49,209.0	$20,281.0	49.2%	**29%**
AESA	Electronics & Software	2001 / $500.3	2005 / $579.9	$79.6	15.9%	4 & 1	$594.0	$(14.1)	-2.8%	**82%**
AIM-9X Block I	Missiles	1997 / $3,250.9	2010 / $3,754.6	$503.7	15.5%	13 & 4	$3,626.8	$127.8	3.9%	**75%**
SSGN	Ships	2002 / $3,898.5	2007 / $4,108.5	$210.0	5.4%	5 & 2	$4,208.1	$(99.6)	-2.6%	**53%**
Minuteman III PRP	Space & Satellites	1997 / $2,546.0	2009 / $2,601.8	$55.8	2.2%	11 & 4	$2,729.2	$(127.4)	-5.0%	**-128%**
STRYKER	Vehicles	2001 / $7,039.4	2011 / $16,280.0	$9,240.6	131.3%	10 & 4	$15,142.8	$1,137.2	16.2%	**88%**

Table 5: SAR cost estimates & adjustment for systemic cost risk improvements for the six historical programs evaluated for validation.

Recall from Section 2.2.1 that researchers had found and quantified systemic cost estimation bias in MDAPs. The method employed in this section goes beyond simply quantifying this bias by calculating the SRF and applying it to cost estimates to improve their accuracy. This method leverages the idea of dichotomized risk in CAPM and applies it to cost estimation of MDAPs by separating systemic cost risk from program-specific cost risk (program-specific cost risk is left to cost estimators with specialized knowledge of the particular MDAP of interest). Taking this approach allows one to accept a low R^2 value for the line-of-best-fit calculated using linear regression since CAPM seeks to quantify the relationship between a risky asset's return and the systemic risk of the market. Similarly, one can accept the low R^2 value for linear regression applied to MDAPs since program-specific cost risk is assumed to be dominant over systemic risk due to the technologically challenging goals of DoD weapon system programs.

5.7. APPLICATION TO AFFORDABILITY IN DOD ACQUISITIONS

Now that systemic cost risk has been quantified and a method developed to adjust MDAP cost estimates based on this systemic risk, the next step is to apply these results to improving affordability in the DoD. Recall from Sections 1.2 and 3.2.1 that affordability is "the ability to allocate resources out of a future total [for each DoD Component] *budget projection* to individual activities." It is perhaps best understood graphically in the hypothetical Affordability Assessment of Figure 2 which shows the future expected annual budgets of a DoD Component and its portfolio of program cost estimates over time. Unfortunately, the method produced thus far tells one only about the expected effect of systemic cost risk on the *total* MDAP cost estimate at some time in the future. For the PPBE process, this information alone is inadequate since knowledge of how this systemic effect impacts *annual* budgets is required, not total program cost estimates.

Essentially, the new systemic risk-adjusted program estimate must be time-phased for budgeting (as covered briefly in Section 3.2.2.7).

Without inside knowledge of how funding was time-phased for MDAPs, one may use instead the percentage of the total MDAP cost estimate allocated to each year in the budget. A baseline year may be selected and the SAR cost estimate for the desired MDAPs can be retrieved from [37]. Future program annual budget data for a given baseline year may be downloaded from the Defense Acquisition Management Information Retrieval (DAMIR)[41]. Dividing the annual budget projections made in a baseline year by that year's MDAP cost estimate (from the SAR) produces the percent allocation of total program cost for those budget projection years. The percent allocation for each forecast budget year may then be multiplied by the SRF-adjusted MDAP cost estimate to produce the systemic cost risk-adjusted budget forecast.

The steps in the previous paragraph augment the method defined in Sections 5.4 and 5.6 for generating SRF-adjusted MDAP cost estimates to conduct an Affordability Assessment of the six programs listed in Table 5. The same graphical approach to affordability shown in Figure 2 will be used along with the following assumptions:

1. All of the six programs fall under one DoD Component so that the affordability definition may be applied;
2. 2002 is the year of the Affordability Assessment (i.e., budgets and costs in 2002 are known perfectly);
3. The 2002 Affordability Assessment will be used as the forecast to set the annual budgets through 2007 (i.e., the forecast costs in 2002 form the budget for 2002 through 2007);

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[41] DAMIR is restricted to DoD employees and contractors with approved access, and budget data from this repository are For Official Use Only. However, data may be masked by scaling it such that the original figures cannot be discerned.

4. n is set to 2 (see Table 4) for (Eq 5) since the MDAP cost estimate is adjusted for systemic cost risk and projected from 2002 to 2007; and
5. Annual budget data will be scaled to mask the true values since these are "For Official Use Only."

Figure 21 shows the results of the Affordability Assessment of the six MDAPs using both the unadjusted and SRF-adjusted cost forecasts plotted against the actual program costs. All dollar figures have been scaled to mask true values of actual costs pulled from DAMIR. Forecast costs are equivalent to the budgets set in 2002. In terms of affordability, the SRF-adjusted budget appears to outperform the baseline budget, which ignores systemic cost risk. In particular, the SRF-adjusted budget appears affordable in four of the five years, while the unadjusted budget is *un*affordable in four of the five years.

However, there are two undesirable effects of the SRF-adjusted budget. Firstly, the SRF-adjusted portfolio costs are unaffordable in 2007 by 8%. Secondly, the SRF-adjusted budget overestimates constituent MDAP costs by as much as 34% in the early years. This second effect could lead to other programs going unfunded due to excess funding being applied to the portfolio of six MDAPs. Both effects are partially caused by the compounding issue discussed in Section 4.2 despite the ad hoc correction made in Section 5.6. Other factors causing these effects include assuming that SRF-adjusted dollars would be budgeted according to the baseline percentage annual allocations, and program-specific cost risk which is, by design, not accounted for in the SRF.

It is interesting to note that if the fourth assumption (i.e., n set to 2) is changed to set n to 1, then the SRF-adjusted budget is affordable for all five years. However, peak over-budgeting becomes 87% instead of 34%, further decreasing funding for other programs.

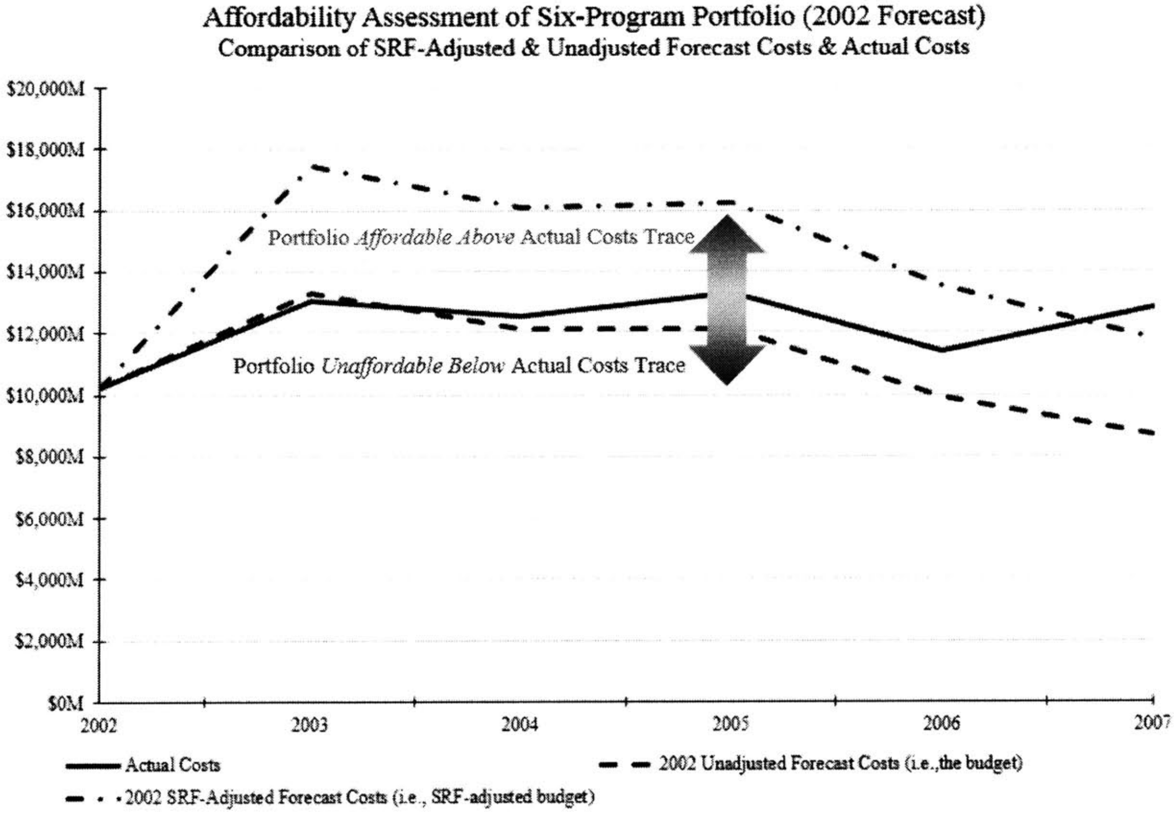

Figure 21: Affordability Assessment of six historical MDAPs in a hypothetical portfolio.

Still, since the budget may be altered after each year by DoD Component leadership and funds budgeted in one year may span multiple years (see Figure 16), active management of budgeting could augment this method to improve affordability further. Component leadership may be informed of a significant program issue, such as unfavorable test results requiring redesign, and require a new program cost estimate. Budgets for the remainder of the forecast period could then be adjusted based on this new data. Program managers could also retain funds from over-budgeting in prior years as additional management reserve until the funds expire. Both of these management options would complement the SRF-adjusted budgeting method and improve affordability by shifting funds between years of funding overages and underages.

5.8. SUMMARY

An approach to improve affordability for DoD Components through quantification of, and capital budgeting adjustment to, systemic cost risk for MDAPs was presented in this section. The approach first used a modified version of the expected growth-beta relationship borrowed from CAPM to calculate systemic cost risk-adjusted growth rates for MDAPs based on defense commodity type using SAR cost data and (Eq 4). Next, the SRF was used to project MDAP cost estimates to a future time by adjusting for the appropriate systemic cost risk. This projection was made using (Eq 5) which also applies an ad hoc adjustment to mitigate the effects of compounding over relatively long periods of time.

A partial validation of the approach was made using six historical MDAPs over the period of 2002 to 2007 so that actual costs at program completion could be used as truth data. The selected MDAPs represented each of the six defense commodity types of Aircraft, Electronics and Software, Missiles, Ships, Space and Satellites, and Vehicles. A hypothetical Affordability Assessment using scaled actual cost data (since the data are "For Official Use Only") was performed to compare the affordability of the systemic cost risk-adjusted portfolio budget with that of standard practice in the DoD. Results from the systemic cost-risk adjusted approach demonstrated improved affordability for the portfolio analyzed.

6. CONCLUSIONS & RECOMMENDATIONS

The research and methods presented in this thesis were targeted at quantifying systemic cost estimation risk in MDAPs and improving affordability for DoD Components. Despite adding increasingly sophisticated cost estimation tools (see Section 3) and previous attempts at acquisition reforms (see Section 3.4), little progress has been made in improving MDAP cost estimates. Methods presented are relatively simple in nature when compared to other sophisticated cost estimation techniques (see Section 3.2), and this simplicity makes it appealing for adoption by senior decision makers[42] with broad scope of responsibilities. This section summarizes the motivation, goals, findings, contributions, recommendations, and limitations of the ideas presented in this thesis. It also includes potential future research on these ideas.

6.1. RESTATEMENT OF MOTIVATION & RESEARCH QUESTIONS

Affordability in DoD acquisitions has been an emphasis recently, and with growing fiscal problems in the USG, this emphasis will only be amplified in the coming years. An epoch shift describing this emphasis was presented in Section 1 to support this assertion.

For almost 70 years a negative cost estimation bias (i.e., estimated costs are systemically less than realized costs) has persisted in defense acquisition programs. This thesis aims to address this systemic bias and improve affordability in MDAPs by answering three research questions.

1. How can the DoD quantify systemic cost risk for MDAPs?

By applying a modified form of the expected growth-beta relationship of CAPM to historical MDAP cost estimate data, one may quantify the systemic risk portion of cost estimation risk for MDAPs through determining the beta term in (Eq 4) (see Sections 4.3 and 5).

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[42] Simplicity is critical in obtaining senior leadership buy-in, as pointed out in [40, 35].

2. How can the quantified systemic cost risk be used to create more realistic MDAP cost estimates?

Quantifying systemic cost risk for MDAPs based on their respective defense commodity type allows one to calculate the expected cost estimate growth for each commodity type (and for any program within a commodity class assuming common systemic risks) using the aggregate forecast for cost estimate growth for *all* MDAPs and the expected growth-beta relationship of (Eq 4). Applying an ad hoc method which accounts for the compounding effect of growth rates on long-term forecasts enables one to find the SRF and calculate the SRF-adjusted MDAP cost estimate which accounts for systemic cost estimation risk (see Section 5).

3. Can strategic management of systemic cost risk lead to improved affordability in the DoD?

Applying the methods of this thesis to a historic case study of representative MDAPs from each of the six defense commodity types does show an improvement in affordability as depicted in Figure 21 (see also Section 5.7).

6.2. FINDINGS & CONTRIBUTIONS

Applying CAPM, which dichotomizes risk into systemic and asset-specific contributions, to MDAP cost estimates is the central contribution of this thesis. Previous studies have found a systemic bias in MDAP costs and cost estimates; however, no known attempts to quantify *and* mitigate this effect have been made previously. CAPM provides a means to both quantify and correct for systemic cost risk in MDAP cost estimates. Recall that program-specific risk is idiosyncratic and unpredictable based on CAPM assumptions. As such, program-specific cost risk is left to those best-equipped to mitigate this risk – the cost estimators assigned to specific MDAPs who are intimately familiar with their programs.

CAPM provides direct answers to the first two research questions, and underlies the third question. The expected growth-beta relationship of CAPM is useful in defining the sensitivity of MDAPs in each of the six defense commodity classes to systemic cost estimation risk for all MDAPs based on each commodity type's systemic risk exposure. The beta term in (Eq 4) quantifies this systemic cost estimation risk and responds to research question 1. By grouping MDAPs into the six defense commodity types and assuming that MDAPs within each commodity type group shares similar systemic cost estimation risk, estimates of beta can be improved and the components of (Eq 4) can be estimated from SAR data and used to generate the expected systemic risk-adjusted growth rate for a particular MDAP of interest. Then, the systemic risk-adjusted MDAP cost estimate can be calculated using (Eq 5) depending on the time horizon desired by decision makers. In this way, one can answer research question 2 and produce more realistic (in the sense that systemic cost risk is accounted for) MDAP cost estimates.

With the first two research questions answered, a method to strategically manage systemic cost risk can be devised to respond to the third research question. This method would facilitate improving affordability in the DoD by adjusting annual budgets according to more realistic MDAP cost estimates. A simple method to adjust annual budgets based on the original (i.e., without the systemic cost risk adjustment) annual allocation of program funds was presented in Section 5.7. This method was found to improve affordability of MDAPs in the DoD when applied to a hypothetical portfolio of actual completed MDAPs using representative cost data.

6.3. RECOMMENDATIONS

DoD should consider adopting the methods described in this thesis to improve affordability in MDAPs for each Component. Current DoD practices for capital budgeting for MDAPs could be augmented with this method in the PPBE process. In this role, these methods are tools for cost estimators, cost analysts, program managers, and senior acquisition decision makers that may be used to improve MDAP cost estimates and enhance affordability for DoD Components. These methods and tools would not replace critical decision making in capital budgeting, and care must be taken to understand the limitations presented in this thesis.

Department-wide assumptions should be set above the DoD Component level to ensure fairness in quantifying systemic cost risk for MDAPs. These assumptions should include:

- The set of historical total MDAP cost data to calculate $E\{g_{MDAPs}\}$ in (Eq 4);
- The categorization of defense commodities (i.e., it may be desirable to use a finer level of groupings, such as separating space from satellites in the Space and Satellites category set by BEA); and
- The level of maturity of MDAP cost estimates (e.g., include only those programs which have successfully completed Milestone B).

Finally, if any of the assumptions listed above are different from those in this thesis, then the ad hoc method of calculating SRF-adjusted cost estimates in (Eq 5) may need to be adjusted by reassessing the values of n.

6.4. LIMITATIONS

The principal limitation of this work is that CAPM was created for investment portfolio selection using economic and financial theory, not measuring systemic cost risk in DoD acquisition programs. It assumes that the y-intercept of the regression line used to determine beta, a way to quantify systemic risk in terms of overall expected market returns, is zero. This assumption is contrary to linear regression estimation practice when the statistical significance of a zero intercept is low. However, CAPM is indeed a method to quantify systemic risk, which makes it suitable for application in this thesis.

The methods presented in this thesis do not claim optimality with respect to minimizing cost estimate errors or MDAP cost overruns. Use of the methods in this thesis may not completely eliminate MDAP cost overruns and affordability breaches, since it considers only systemic cost estimation risk and not program-specific cost estimation risk. Additionally, use of these methods may lead to over-budgeting priority programs, leaving fewer resources available to fund other, lower priority programs. In particular, the ad hoc method of (Eq 5) to reduce the effect of compounding over longer time periods is not claimed to be optimal[43]. Other methods may work better, such as simply using the arithmetic average cost overrun rate presented in other studies.

Finally, all models are inexact and can never truly capture reality with complete accuracy and precision. *Practical* models are even less exact. But besides precision and accuracy, the way in which a model is used is important as well. The models and methods presented in this thesis are relatively low fidelity, focused more on practicality and as an initial attempt to quantify systemic cost risk. Still, empirical results show improved affordability for MDAPs based on representative historical cost data. To date, there is no known method to adjust MDAP cost estimates to mitigate the bias documented in MDAP cost estimates, with the only related method being increasing the confidence level used to set cost estimate baselines for funding.

6.5. POSSIBILITIES FOR FUTURE RESEARCH

This thesis represents a first step towards addressing the persistent bias in MDAP cost estimates and cost overruns, which have plagued the DoD for almost 70 years. Future research on the ideas presented in this thesis could benefit the DoD and provide improved affordability beyond that which was demonstrated in this thesis. Specific areas of future research include:

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[43] The methods of this thesis were shown effective in application to an historical case study and not in general. In this way, these methods were not shown to be optimal in a general sense or according to any objective function which minimizes cost estimation errors.

- Including multiple systemic factors by applying a multi-factor regression model, such as a variant of the Arbitrage Pricing Theory model [21];
- Re-defining defense commodity categories;
- Empirically determining values for n that produce more accurate MDAP cost estimates;
- Selecting different time frames for calculating $E\{g_{MDAPs}\}$ (e.g., using data no earlier than 1998 marking the transition to Evolutionary Acquisition as the preferred acquisition strategy of the DoD);
- Using a non-linear regression model instead of the linear model in CAPM;
- Using different SAR data conditioning and selection of programs to include in analysis; and
- Defining system cost risk-adjusted growth rates for MDAPs in difference stages of the acquisition lifecycle.

In finance, the development of CAPM in the 1960s was a major event for asset pricing. However, it took almost 30 years for CAPM to become used widely. Shortly thereafter, modifications to CAPM were created to include other systemic factors besides market risk to improve explanatory power. It is this author's hope that future research in the area of this thesis will follow a similar path, although at a much faster pace.

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APPENDIX A – SUMMARY OF EQUATIONS & METHODS

This appendix is intended to conveniently present the pertinent equations and methods of this thesis in one location.

First, (Eq 4) is the equivalent expected growth-beta relationship of CAPM applied to MDAPs. It is

$$E\{g_{program\ j}\} = E\{g_{commodity\ k}\} = \beta_{commodity\ k} \times E\{g_{MDAPs}\}$$

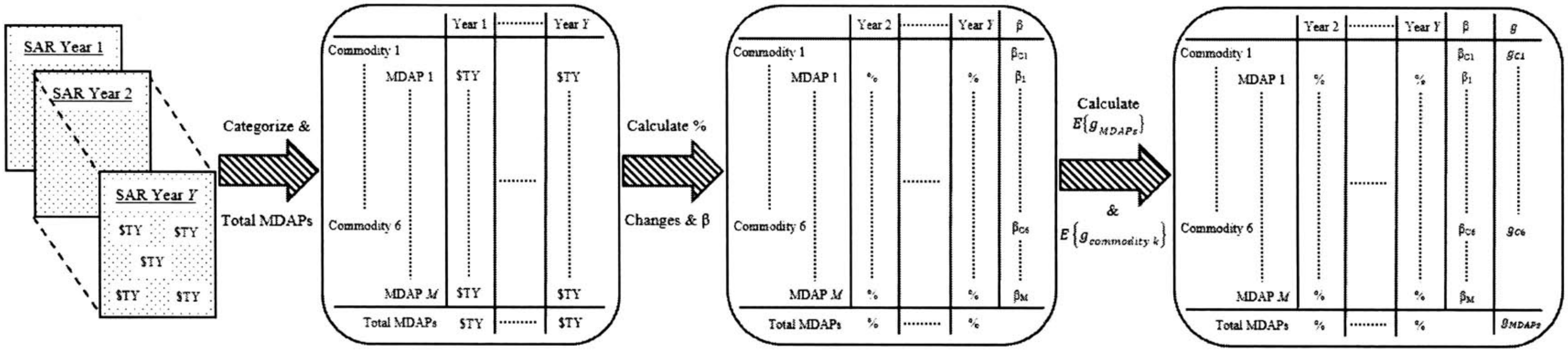
where $E\{g_{program\ j}\}$ is the expected nominal growth rate of the cost estimate of $program\ j$ which is equal to $E\{g_{commodity\ k}\}$ since beta values are aggregated across programs within a defense commodity type to improve the beta estimate which results in the implication that program systemic cost estimation risks within a commodity type are the same; $\beta_{commodity\ k}$ is the averaged beta estimates for individual programs within the defense commodity type (of which $program\ j$ is a member); and the last term is the expected value of percent changes in nominal cost estimates of all MDAPs.

Next, (Eq 5) relates the current cost estimate for an MDAP to its systemic cost risk-adjusted value at some time in the future:

$$Future\ Cost\ Estimate_t = Current\ Estimate_{t_o} \times \left(1 + g_{program\ j}\right)^{(t-t_o)/n}$$

where $\left(1 + g_{program\ j}\right)^{(t-t_o)/n}$ is the Systemic Risk Factor adjusted for compounding time effects using the integer n, as described in Table 4.

The method for arriving at the systemic cost estimation risk-adjusted MDAP cost estimate uses both of these equations. More specifically, (Eq 4) is used in a regression analysis in a spreadsheet to calculate the systemic cost estimation risk betas for each commodity type and the systemic risk-adjusted cost estimate growth rates for each program using the eight-step procedure in the flow chart depicted in Figure 20 and reproduced next.


SAR Year 1
SAR Year 2
SAR Year Y
$TY
Categorize &
Total MDAPs
Year 1
Year Y
Commodity 1
MDAP 1
Commodity 6
MDAP M
Total MDAPs
Calculate %
Changes & β
Year 2
β
%
β_{C1}
β_1
β_{C6}
β_M
Calculate
$E\{g_{MDAPs}\}$
&
$E\{g_{commodity\ k}\}$
g
g_{C1}
g_{C6}
g_{MDAPs}

APPENDIX B – LIST OF ABBREVIATIONS

Abbreviation	Meaning
ACAT	Acquisition Category
BEA	Bureau of Economic Analysis
CAPM	Capital Asset Pricing Model
CARD	Cost Analysis Requirements Description
CEC	(DoD) Component Cost Estimate
CER	cost estimating relationship
DAMIR	Defense Acquisition Management Information Retrieval
DAS	Defense Acquisition System
DCAPE	Director of Cost Assessment and Program Evaluation
DCF	discounted cash-flow
DoD	Department of Defense
FY	fiscal year
g	return or growth rate
GAO	(United States) Government Accountability Office
GDP	gross domestic product
ICE	Independent Cost Estimate
JCIDS	Joint Capabilities Integration and Development System
k	discount rate
LCCE	Life-Cycle Cost Estimate
MDAP	Major Defense Acquisition Program
MIT	Massachusetts Institute of Technology
OMB	Office of Budget and Management
PI	price index
PPBE	Planning, Programming, Budgeting, and Execution
PV	present value
RC	research question
RDT&E	research, development, test and evaluation
SAR	Selected Acquisition Report
SRF	Systemic Risk Factor
TOA	Total Obligation Authority
US	United States
USAF	United States Air Force
USG	United States Government
WBS	work breakdown structure

APPENDIX C – LIST OF DEFINITIONS

Term	Definition
affordability	The difference between the forecast total obligation authority of a DoD component & its estimated investments over the same time horizon. Affordability is the ability to allocate resources out of a future total budget projection to individual activities. It is determined by Component leadership given priorities, values, and total resource limitations against all competing fiscal demands on the Component. Affordability goals set early cost objectives and highlight the potential need for tradeoffs within a program, and affordability caps set the level beyond which actions must be taken, such as reducing costs.
program-specific cost risk	The cost risk peculiar to a particular program or project. Also known as development risk, technological risk, and diversifiable risk. This type of risk is unpredictable.
systemic cost risk	The cost risk associated with a particular market of assets. Also known as programmatic risk, financial risk, market risk, and non-diversifiable risk. This type of risk is predictable using beta.
Systemic Risk Factor	The compounding factor adjusted for compounding length of time used to estimate the systemic-risk-adjusted MDAP cost estimate at some future date. The factor includes the product of the beta factor for the appropriate defense commodity and the average historical cost estimate change. SRF = (1+g_nom)^(t-t_o)/n
DoD Component	The United States Air Force, Army, Navy, and Marine Corps are the four military components in the DoD.

APPENDIX D – MDAP NOMINAL ANNUAL COST CHANGE, 1970-2012

Year	YoY SAR Change, Nominal
1970	5.38%
1971	9.69%
1972	-1.45%
1973	13.22%
1974	16.98%
1975	2.49%
1976	28.67%
1977	3.78%
1978	13.53%
1979	10.01%
1980	21.11%
1981	46.64%
1982	18.67%
1983	38.89%
1984	0.14%
1985	-2.46%
1986	7.56%
1987	-3.85%
1988	8.10%
1989	3.08%
1990	2.59%
1991	-0.62%
1992	-0.32%
1993	-11.83%
1994	-3.83%
1995	-1.75%
1996	0.34%
1997	-5.34%
1998	5.40%
1999	3.78%
2000	5.41%
2001	36.11%
2002	6.07%
2003	17.91%
2004	10.52%
2005	7.64%
2006	6.26%
2007	-2.43%
2008	0.32%
2009	-1.95%
2010	6.43%
2011	-5.96%
2012	2.69%
Average:	7.4%

APPENDIX E – BETA CALCULATION SPREADSHEETS

Component	Program	Defense Commodity	12/1998	12/1999	09/2000	12/2001	12/2002	12/2003	12/2004	12/2005	12/2006	12/2007	09/2008	12/2009	12/2010	12/2011	12/2012	β
AF	C-130J	Aircraft	138.5%	-7.9%	0.0%	495.1%	5.3%	-0.6%	-62.0%	22.3%	6.0%	49.0%	0.0%	26.2%	-1.3%	4.9%	-1.1%	6.86
AF	C-17A	Aircraft	9.1%	-0.1%	0.0%	31.5%	2.3%	-0.3%	-1.6%	0.6%	4.9%	-0.2%	0.0%	11.7%				0.50
AF	C-27J	Aircraft												-50.8%	13.9%			-3.41
AF	C-5 RERP	Aircraft					-0.1%	-0.6%	8.4%	0.1%	2.6%	-1.8%	-30.9%	-2.9%	-0.3%	-0.1%	-0.5%	0.43
AF	F-22	Aircraft	-1.7%	-1.3%	0.0%	12.6%	3.0%	-0.1%	-14.5%	2.1%	4.3%	-1.2%	0.0%	3.4%	0.9%			0.16
AF	HC/MC-130 Recap	Aircraft														-0.4%	5.7%	-0.15
AF	MQ-9 Reaper	Aircraft													5.6%	4.7%	1.8%	-0.41
AF	RQ-4A/B Global Hawk	Aircraft					-15.1%	8.0%	4.5%	19.0%	25.4%	-0.6%	0.0%	40.7%	1.7%	-32.8%	-3.8%	1.32
Army	AH-64E New Build	Aircraft														-8.4%	15.2%	1.04
Army	AH-64E Remanufacture	Aircraft										0.1%	0.0%	29.9%	1.8%	0.6%	15.0%	1.17
Army	ARH	Aircraft									49.6%	17.6%	-91.5%					5.09
Army	BLACK HAWK (UH-60A/L)	Aircraft	10.6%	-3.8%														1.37
Army	CH-47F	Aircraft		1.8%	0.0%	117.9%	6.9%	0.1%	72.0%	3.6%	5.1%	-0.7%	0.0%	2.1%	5.9%	-1.3%	0.9%	1.84
Army	COMANCHE	Aircraft	-4.6%	0.6%	485.9%	-0.5%	-20.0%	2.6%										-0.49
Army	LONGBOW APACHE	Aircraft	-7.2%	0.7%	0.0%	1.1%	2.9%	0.0%	-0.7%	4.0%	17.3%	1.3%	0.0%	17.2%	0.3%			0.13
Army	LUH	Aircraft										11.1%	0.0%	-4.1%	0.1%	-0.1%	-9.7%	-0.12
Army	MQ-1C Gray Eagle	Aircraft													0.8%	-9.8%	3.0%	1.54
Army	UH-60M Black Hawk	Aircraft					8.8%	3.8%	40.1%	14.0%	0.3%	0.9%	0.0%	-1.5%	15.4%	5.6%	-11.0%	0.52
DoD	F-35	Aircraft	4.6%	-0.8%	0.0%	877.0%	-11.8%	22.6%	4.8%	7.7%	8.5%	-0.3%	0.0%	9.8%	15.6%	4.3%	-1.1%	12.11
Navy	AV-8B REMANUFACTURE	Aircraft	2.0%	0.4%	-0.2%	2.2%	0.1%											0.04
Navy	CH-53K	Aircraft									0.1%	-1.0%	0.0%	36.4%	0.9%	3.4%	7.1%	0.85
Navy	E-2C REPRODUCTION	Aircraft	-6.6%	2.0%	0.0%	22.5%	10.8%	-0.7%	1.0%	0.1%	0.2%							0.33
Navy	EA-18G	Aircraft							2.0%	4.5%	-7.5%	3.4%	0.0%	33.5%	-3.0%	-1.3%	18.3%	0.52
Navy	F/A-18E/F	Aircraft	2.0%	0.0%	-0.3%	4.2%	4.0%	-13.6%	0.3%	0.1%	5.4%	-0.1%	0.0%	3.8%	6.0%	0.0%	-1.8%	0.04
Navy	H-1 Upgrades	Aircraft	6.2%	2.4%	0.0%	67.1%	7.8%	1.6%	17.2%	0.1%	8.6%	0.2%	0.0%	38.9%	4.9%	1.0%	-0.9%	1.14
Navy	KC-130J	Aircraft														5.9%	0.0%	-1.14
Navy	MH-60R	Aircraft	-3.3%	17.3%	0.0%	61.4%	7.1%	4.9%	6.0%	1.9%	2.7%	3.7%	0.0%	17.3%	1.1%	-1.0%	-5.6%	0.95
Navy	MH-60S	Aircraft		36.0%	-0.1%	24.5%	12.0%	-1.0%	29.3%	0.0%	2.4%	-0.8%	0.0%	1.7%	-0.4%	0.3%	-1.0%	0.45
Navy	MQ-4C Triton	Aircraft													-1.8%	0.9%	2.6%	-0.37
Navy	P-8A	Aircraft								0.7%	1.7%	0.6%	0.0%	3.9%	0.2%	0.7%	1.5%	0.13
Navy	V-22	Aircraft	-3.0%	5.2%	0.0%	21.3%	4.4%	-0.5%	5.1%	0.0%	8.2%	-0.8%	0.0%	-2.4%	0.7%	0.4%	2.9%	0.32
Navy	VH-71	Aircraft									-6.1%	9.9%						-0.39
Navy	VTUAV	Aircraft										2.7%	0.0%	21.6%	8.2%	1.1%	10.0%	0.89
AF	ABL	Electronics & Software	12.5%	30.6%														4.18
AF	AWACS RSIP (E-3)	Electronics & Software	1.7%	7.0%	0.0%	3.3%	-0.3%	0.2%										0.06
AF	B-1B CMUP	Electronics & Software		11.7%	-31.8%	-3.0%	-33.8%	-37.4%	-2.0%									-0.21
AF	B-2 EHF Inc 1	Electronics & Software											0.0%	-9.2%	-0.3%	-6.9%	-2.5%	-0.41
AF	B-2 RMP	Electronics & Software								-1.1%	-3.9%	8.5%	0.0%	3.3%	-3.2%	-0.8%		-0.02
AF	C-130 AMP	Electronics & Software					-0.7%	0.9%	-3.0%	10.9%	21.2%	-3.0%	0.0%	9.5%	1.6%	-65.9%		0.79
AF	C-5 AMP	Electronics & Software										-0.4%	0.0%	-14.2%	-4.7%			0.85
AF	FAB-T	Electronics & Software										14.4%	0.0%	9.9%	15.8%	1.9%	-0.6%	0.50
AF	GBS	Electronics & Software	6.0%	14.7%	-2.1%	25.5%	14.6%	-6.9%	9.7%	-1.6%	15.0%	-5.8%	0.0%	26.2%	2.0%	3.2%	3.4%	0.51
AF	JPATS	Electronics & Software	-2.4%	1.8%	0.0%	26.5%	1.5%	1.2%	1.6%	0.1%	5.4%	0.0%	0.0%	-1.4%	-3.4%	1.3%	-0.7%	0.38
AF	JSTARS	Electronics & Software	0.2%	2.9%	0.0%	12.0%	0.3%	-0.1%										0.20
AF	LAIRCM	Electronics & Software											0.0%	13.5%	-0.5%			0.59
AF	MP-RTIP	Electronics & Software							-3.4%	3.1%	-20.6%	-1.1%	0.0%	1.8%	3.6%	1.0%		-0.47
AF	MPS	Electronics & Software								6.3%	-11.1%	-0.4%						-0.76
AF	NAS	Electronics & Software	0.6%	27.6%	0.0%	10.8%	30.9%	-3.7%	5.5%	-3.5%	2.4%	1.9%	0.0%	-1.0%	2.5%	-2.5%	-2.0%	0.19

Component	Program	Defense Commodity	12/1998	12/1999	09/2000	12/2001	12/2002	12/2003	12/2004	12/2005	12/2006	12/2007	09/2008	12/2009	12/2010	12/2011	12/2012	β
Army	AMF JTRS	Electronics & Software													-0.7%	-53.0%	-11.1%	8.83
Army	ATIRCM/CMWS	Electronics & Software	21.9%	-10.1%	0.0%	7.0%	36.9%	-15.5%	43.0%	18.6%	1.3%	-15.0%	0.0%	-6.3%	2.3%			0.16
Army	CGS (JSTARS GSM)	Electronics & Software	-1.6%	0.5%	28.1%	-56.8%												-1.04
Army	FBCB2	Electronics & Software			0.0%	9.4%	-6.5%	-39.9%	13.9%	35.8%	9.8%	25.5%	10.6%	3.2%	-0.8%			0.02
Army	JTN	Electronics & Software						4.0%	34.5%	35.2%	17.8%	-6.8%	0.0%	-1.2%	2.5%	0.2%	4.6%	0.70
Army	JTRS HMS	Electronics & Software								5.5%	1.6%	-71.4%	0.0%	55.6%	10.9%	60.1%	9.5%	0.84
Army	SINCGARS	Electronics & Software	1.0%	1.1%														0.23
Army	SMART-T	Electronics & Software	12.4%	-3.9%	0.0%	5.4%	25.4%											0.13
Army	WIN-T	Electronics & Software							3.6%	9.9%	15.5%							0.78
Army	WIN-T INC 1	Electronics & Software											0.0%	-0.6%	12.2%	-1.9%		0.08
Army	WIN-T INC 2	Electronics & Software											0.0%	29.1%	27.1%	1.7%	-20.5%	1.39
Army	WIN-T INC 3	Electronics & Software													0.6%	-10.0%	23.8%	0.90
DoD	JTRS GMR	Electronics & Software						8.0%	5.4%	-5.5%	-0.6%	1.0%	0.0%	-6.8%	1.5%	91.5%		0.58
Navy	ADS (AN/WQR-3)	Electronics & Software									-62.6%	0.0%						-4.17
Navy	AESA	Electronics & Software					9.2%	9.7%	-0.5%	-2.8%								0.43
Navy	CEC	Electronics & Software	0.5%	7.1%	0.0%	10.1%	7.9%	-3.2%	2.2%	-0.8%	-0.9%	1.8%	0.0%	0.3%	2.0%	3.0%	-1.6%	0.13
Navy	COBRA JUDY REPLACEMENT	Electronics & Software							0.4%	1.5%	1.1%	7.2%	0.0%	5.1%	0.1%	0.0%		0.14
Navy	E-2D AHE	Electronics & Software							4.1%	1.0%	11.2%	-0.3%	0.0%	8.5%	-2.4%	12.3%	-1.4%	0.38
Navy	IDECM	Electronics & Software												4.3%	5.5%	2.3%	6.9%	0.24
Navy	JHSV	Electronics & Software													0.1%	-44.6%	-0.2%	7.18
Navy	JPALS Inc 1A	Electronics & Software													-0.3%	1.2%	10.7%	-0.55
Navy	MIDS	Electronics & Software	-5.8%	9.5%	0.0%	9.5%	6.5%	7.1%	12.6%	2.9%	2.6%	7.9%	0.0%	10.4%	1.6%	13.1%	10.8%	0.22
Navy	NMT	Electronics & Software										-1.4%	0.0%	-1.6%	-7.6%	-0.6%	0.1%	-0.11
Navy	SSDS	Electronics & Software								-22.1%	6.6%	-44.9%						0.40
Navy	SSN 21 / AN/BSY-2	Electronics & Software	1.8%	-1.9%														0.15
Navy	T-45TS	Electronics & Software	23.8%	-23.7%	0.0%	6.2%	13.3%	0.2%	7.6%	0.6%	-0.2%	0.0%						0.14
Navy	T-AKE	Electronics & Software					-9.8%	1.6%	2.3%	-0.2%	0.9%	23.5%	0.0%	20.5%	-0.4%			0.37
AF	AMRAAM	Missiles	-0.3%	-0.2%	0.0%	0.5%	3.2%	0.4%	22.5%	0.1%	12.2%	0.6%	0.0%	43.0%	-3.8%	-1.3%	-0.4%	0.26
AF	JASSM	Missiles	233.1%	4.8%	0.0%	48.5%	29.8%	-1.3%	16.1%	5.8%	18.0%	4.6%	0.0%	27.1%	4.2%	-9.1%	0.2%	1.18
AF	JDAM	Missiles	5.5%	1.4%	0.0%	47.2%	48.9%	-7.9%	3.3%	-6.2%	3.2%	-0.8%	0.0%	9.4%	1.8%	5.9%	3.8%	0.68
AF	SDB I	Missiles							-0.4%	-12.7%	-6.1%	-0.5%						-0.26
AF	SDB II	Missiles														-19.1%	-0.6%	3.70
Army	ATACMS-APAM	Missiles	-0.6%	-4.0%														-0.38
Army	ATACMS-BAT	Missiles	20.0%	-4.9%	0.0%	9.5%	-62.7%											0.17
Army	GMLRS/GMLRS AW	Missiles	26.5%	-0.9%	0.0%	153.5%	-4.6%	3.5%	11.6%	17.3%	-57.8%	-11.3%	0.0%	0.8%	-0.6%	6.4%	4.4%	1.94
Army	HIMARS	Missiles						7.6%	0.7%	-28.6%	-37.4%	-1.9%	0.0%	-0.3%	-1.5%	-1.1%		-0.43
Army	IAMD	Missiles													9.1%	5.9%	-4.8%	-0.14
Army	JAVELIN	Missiles	7.2%	-7.5%	0.0%	10.5%	-5.0%	1.8%	3.5%	5.2%	1.3%	9.4%						0.18
Army	JLENS	Missiles									0.4%	1.8%	0.0%	7.5%	5.9%	-69.3%	1.0%	0.83
Army	LONGBOW HELLFIRE	Missiles	-2.1%	0.6%	0.0%	4.0%	-1.8%	-2.6%	0.0%									0.05
Army	PAC-3	Missiles	1.8%	1.3%	0.0%	-10.4%	7.1%	0.7%	-6.2%	-28.7%	-0.1%	0.0%	0.0%	9.4%	7.2%	7.9%	1.9%	-0.12
Army	Patriot/MEADS CAP	Missiles								2.0%	-1.2%	-0.9%	0.0%	3.1%	-59.2%	3.1%	-0.9%	-0.22
Army	SADARM	Missiles	7.9%	-71.2%	0.0%	0.0%												-0.04
DoD	BMDS	Missiles					33.2%	5.1%	31.8%	-1.4%	20.2%	-0.4%	0.0%	13.4%	4.2%	3.1%	4.7%	0.99
DoD	NAVY AREA TBMD	Missiles	11.0%	1.5%	0.0%													1.37

Component	Program	Defense Commodity	12/1998	12/1999	09/2000	12/2001	12/2002	12/2003	12/2004	12/2005	12/2006	12/2007	09/2008	12/2009	12/2010	12/2011	12/2012	β
Navy	AGM-88E AARGM	Missiles							1.7%	-0.1%	8.7%	1.1%	0.0%	8.3%	3.1%	5.1%	0.4%	0.36
Navy	AIM-9X BLOCK I	Missiles	-4.9%	-8.7%	0.0%	4.8%	1.7%	1.1%	-0.1%	10.4%	1.0%	0.2%	0.0%	8.0%	2.4%	-60.8%		0.09
Navy	JSOW	Missiles	-20.4%	-18.5%	0.0%	19.2%	-29.9%	-10.8%	8.0%	-0.7%	-2.8%	-0.5%	0.0%	10.7%	4.7%	-1.2%	0.0%	0.22
Navy	SM 2 (BLKS I-IV)	Missiles	1.1%	-0.1%	0.0%	4.8%	7.7%	0.0%	-91.9%									-0.20
Navy	SM-6	Missiles								1.9%	-2.2%	-0.1%	0.0%	10.8%	1.5%	-3.4%	51.2%	0.15
Navy	Tactical Tomahawk	Missiles		-1.6%	0.0%	18.4%	36.4%	11.2%	28.0%	-1.4%	9.4%	-3.6%	0.0%	57.4%	-0.2%	4.5%	-1.1%	0.61
Navy	Trident II Missile	Missiles	-0.3%	-0.6%	0.0%	38.1%	-0.7%	0.1%	-0.9%	2.3%	2.4%	-0.2%	0.0%	1.9%	2.7%	-0.1%	2.2%	0.53
Navy	ASDS	Ships							-38.6%	-38.6%								-3.41
Navy	CVN 68	Ships	3.6%	-41.0%	0.0%	2.8%	1.2%	-46.4%	15.2%	-0.5%	-1.2%	0.3%	0.0%	0.1%				-0.14
Navy	CVN 78	Ships				6.8%	-5.1%	-0.8%	898.8%	-0.3%	-2.4%	0.3%	0.0%	15.5%	-0.6%	5.5%	1.4%	2.54
Navy	DDG 1000	Ships		63.6%	0.0%	107.1%	-4.0%	-0.6%	-21.8%	353.7%	-1.5%	-19.8%	0.0%	-31.6%	5.7%	0.7%	0.9%	1.29
Navy	DDG 51	Ships	0.2%	3.4%	0.0%	18.3%	-4.9%	0.1%	-0.1%	-0.2%	0.2%	0.0%	0.0%	28.1%	10.0%	-1.2%	4.5%	0.35
Navy	LCS	Ships								29.6%	13.9%	46.9%	0.0%	31.0%	903.0%	0.0%	-9.3%	4.75
Navy	LHA 6	Ships									-0.5%	9.4%	0.0%	102.7%	65.9%	0.7%	-0.7%	2.76
Navy	LHD 1	Ships	-0.2%	31.0%	0.0%	-4.7%	1.2%	0.5%	0.7%									-0.05
Navy	LPD 17	Ships	-0.9%	8.3%	0.0%	43.7%	1.5%	-0.2%	-22.2%	3.0%	8.9%	4.8%	0.0%	31.0%	0.3%	-0.1%	0.1%	0.68
Navy	RMS	Ships										9.8%	0.0%	-15.7%	10.9%	0.0%	0.0%	-0.55
Navy	SSGN	Ships						2.9%	1.4%	0.8%	0.0%	0.3%						0.10
Navy	SSN 774	Ships	2.3%	0.8%	0.0%	11.8%	11.4%	1.7%	12.9%	2.0%	-2.9%	-1.1%	0.0%	-0.6%	1.8%	0.2%	-1.5%	0.20
Navy	STRATEGIC SEALIFT	Ships	0.0%	5.5%	0.0%													0.30
AF	AEHF	Space & Satellites			0.0%	133.1%	-11.6%	2.3%	21.2%	-0.9%	6.4%	14.6%	35.0%	25.3%	8.6%	25.5%	-21.1%	1.88
AF	EELV	Space & Satellites	1065.8%	-0.6%	0.0%	6.6%	10.3%	59.5%	-1.8%	0.4%	12.0%	0.0%	0.0%	0.0%	0.0%	0.0%	97.8%	1.74
AF	GPS III	Space & Satellites												5.1%	3.4%	-4.2%	2.0%	0.44
AF	MILSTAR	Space & Satellites	-3.1%	0.4%														-0.45
AF	MINUTEMAN III GRP	Space & Satellites	13.7%	-3.3%	0.0%	6.4%	0.9%	-1.1%	-0.7%	-0.3%	-0.4%	-0.3%						0.10
AF	MINUTEMAN III PRP	Space & Satellites	-14.5%	-1.6%	0.0%	6.0%	0.3%	1.9%	9.5%	0.1%	3.0%	-0.7%	0.0%	0.0%				0.11
AF	NAVSTAR GPS	Space & Satellites	2.3%	9.2%	0.0%	-44.7%	-32.7%	0.5%	10.3%	2.8%	-1.2%	8.7%	0.0%	0.1%	-6.4%	1.5%	0.1%	-0.59
AF	NPOESS	Space & Satellites	-1.1%	8.4%	0.0%	0.4%	22.7%	-3.1%	6.6%	103.1%	-19.2%	-0.2%	0.0%	-47.9%	25.7%	-57.1%		-0.14
AF	SBIRS High	Space & Satellites	18.4%	105.6%	0.0%	-18.0%	27.6%	0.3%	11.4%	5.7%	-2.7%	17.0%	0.0%	30.8%	16.3%	22.7%	-18.4%	-0.03
AF	SBSS BLOCK 10	Space & Satellites											0.0%	7.0%	4.1%			0.34
AF	TITAN IV	Space & Satellites	-6.7%	2.6%	0.0%	-3.0%												-0.06
AF	WGS	Space & Satellites					76.1%	0.8%	18.1%	7.7%	-1.8%	0.3%	0.0%	76.5%	2.0%	10.2%	-1.2%	1.35
Navy	MUOS	Space & Satellites								0.0%	7.4%	4.8%	0.0%	3.1%	0.6%	1.5%	1.4%	0.26
Navy	NESP (Navy EHF Sat Pgm)	Space & Satellites	-7.8%	0.2%	0.0%	-4.6%	3.5%	-0.4%	0.1%									-0.08
Army	ABRAMS UPGRADE	Vehicles	7.3%	23.3%	0.0%	-8.8%	-18.3%	4.8%										-0.10
Army	BRADLEY UPGRADE	Vehicles	-21.5%	7.8%	0.0%	-3.1%	-34.5%	-2.6%	-0.7%	233.9%	3.3%	4.4%	0.0%	-8.2%				-0.13
Army	Crusader	Vehicles	-1.8%	48.1%	0.0%													2.44
Army	Excalibur	Vehicles						-17.8%	-42.9%	1.9%	0.4%	7.0%	0.0%	0.2%	-30.7%	-2.0%	1.3%	-0.84
Army	FCS	Vehicles							6.8%	66.5%	-1.6%	-1.6%						0.05
Army	FMTV	Vehicles	16.8%	-3.2%	0.0%	1.6%	6.6%	-5.5%	-0.9%	-3.3%	19.2%	-0.6%	0.0%	-0.2%	-9.2%	-10.5%	-0.4%	0.10
Army	LAND WARRIOR	Vehicles						332.9%	5.0%	-68.7%	-83.4%							7.06
Army	STRYKER	Vehicles			0.0%	1870.0%	3.4%	20.6%	20.2%	9.2%	15.6%	19.5%	0.0%	-3.2%	12.4%	-4.7%		25.87
Navy	EFV	Vehicles	0.0%	11.6%	0.0%	824.7%	10.2%	-0.2%	18.6%	0.3%	-5.7%	33.2%	0.0%	-1.9%	-78.6%			11.29
Navy	JOINT MRAP	Vehicles											0.0%	61.9%	12.7%			2.80
Army	TMC		61.7%	24.7%	0.0%	-49.5%	28.5%	-52.0%	16.4%									-0.86
DoD	Chem Demil-ACWA									-5.7%	72.4%	0.5%	0.0%	4.5%	28.2%	-0.8%	0.3%	2.15
DoD	CHEM DEMIL-CMA			-9.6%	0.0%	79.8%	0.5%	2.3%	6.3%	0.6%	2.6%	2.6%	0.0%	-6.1%	-5.1%	1.7%		1.10
DoD	CHEM DEMIL-CMA NEWPORT									0.2%	-0.4%							-0.02
	All Cross-SAR YoY Changes	From Same Cross-SAR	5.3%	2.5%	-3.3%	55.3%	1.4%	16.5%	10.8%	-0.5%	15.0%	0.4%	-10.9%	13.9%	2.3%	-5.0%	-1.0%	1.00