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ABSTRACT

A novel approach to technical risk identification and analysis for major weapons systems acquisitions is proposed. It is informed by the limitations of the current risk matrix. The approach is to examine representations of the evolving system design to locate sources of complexity and then inform the program manager as he/she makes technical choices among competing alternatives. Some of the alternatives will create more complexity and therefore more risk. The PM will then be able to balance risk and reward at the point of decision-making, deciding to engage risk at that moment by his/her choices. In addition, we propose to rate or score the contractor + government organizations' abilities to master the complexity they have chosen, so that the PM will know whether there is a match of product complexity with organizational capability.

Future work will add dimensions of interconnections and interdependencies among risks, timing, delay, order of risks, and uncertainty.

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"It is not possible to know exactly how a particular design will perform until it is built. But the product cannot be built until the design is selected. Thus, design is always a matter of decision making under conditions of uncertainty and risk" [(Hazelrigg, 1998), quoted in (Deshmukh, 2010), p. 128].

1. RISK MANAGEMENT IS MANY PROCESSES

Defined in the *DoD Risk Management Guide* (2006, p. 1),

> Risk is a measure of future uncertainties in achieving program performance goals and objectives within defined cost, schedule and performance constraints. Risk can be associated with all aspects of a program (e.g., threat, technology maturity, supplier capability, design maturation, performance against plan,) …. Risk addresses the potential variation in the planned approach and its expected outcome.

Risks have three components:

- A future root cause (yet to happen), which, if eliminated or corrected, would prevent a potential consequence from occurring,
- A probability (or likelihood) assessed at the present time of that future root cause occurring, and
- The consequence (or effect) of that future occurrence.

A future root cause is the most basic reason for the presence of a risk. Accordingly, risks should be tied to future root causes and their effects.

Further risk management is a number of processes:

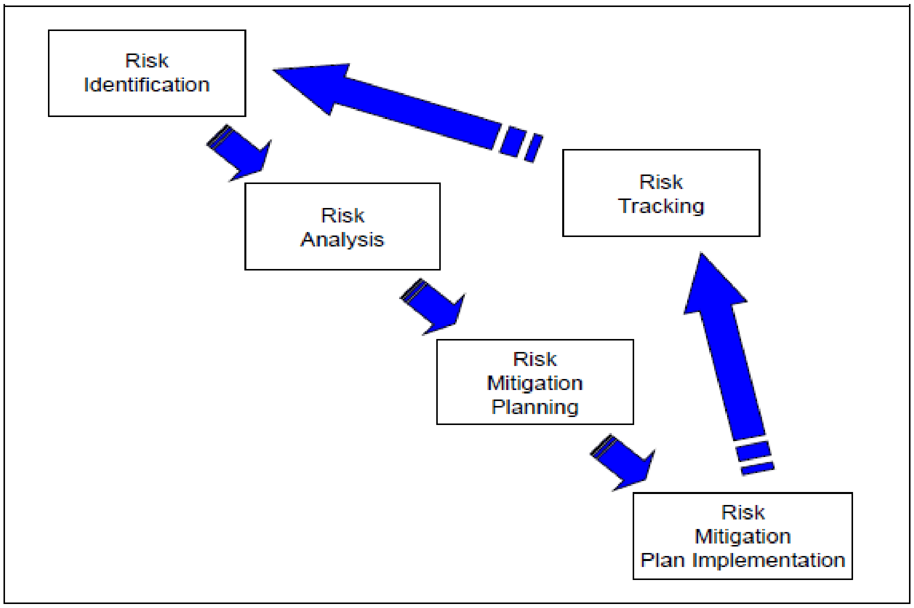

Figure 1. DoD Risk Management Process (from *DoD Risk Management Guide*, 2006, p. 4)

Of these processes, which are the most important to practice, to "get right"? If we want to improve the management of technical risks, on which process(es) should we focus?

Our conjecture is that Risk Identification and Risk Analysis are key because, as in the Figure, everything else depends upon them. So, we are starting there.

2. FORECASTING RISK IS DIFFICULT AND SUBJECTIVE

As listed above, program management needs to collect and identify: future root causes, likelihood, and consequences. This is often, under the best circumstances, by assembling experts and asking them to converge on the three components. It is a group process and based on the extensive practical experience of the expert panel. It is necessarily subjective, based on the memories of the panel members and their analogic reasoning.

Tversky and Kahneman (see, for example, (Kahneman, Slovic, & Tversky, 1982)) are celebrated for their prospect theory, which explains how our biases interfere with our rational appraisals. They explain how our subjective judgments are susceptible to internal and also normative forces that cloud our perceptions and our reasoning. Accordingly, subjective assessments of technical risk are vulnerable to biases.

And this mentions nothing about the problem of using analogic reasoning, which is what expert team members often apply. The challenge in analogical reasoning is that the strength of the relevant similarities must outweigh the strength of any significant dissimilarity. But is that what happens when experts get together to evaluate risks? When one expert says, "This is just like Project X, so I can foresee a risk of type A," is the analogy apt? Is it questioned? [Here is a list with examples of errors by analogy: http://www.skepdic.com/falseanalogy.html]

Expert panels, in creating their subjective assessments, are susceptible to both biases and errors in analogical reasoning.

3. RISK IDENTIFICATION IS ALMOST ALWAYS POST HOC

One part of the *Risk Management Guide* states, "Use a proactive, structured risk assessment and analysis activity to identify and analyze root causes, " (p. 5) and others state, "Use the results of prior event-based systems engineering technical reviews to analyze risks potentially associated with the successful completion of an upcoming review," (p. 5) and "During decomposition, risks can be identified based on prior experience, brainstorming, lessons learned from similar programs, and guidance contained in the program office RMP [Risk Management Plan]." p. 7.

Looking backwards to find risks is unassailable, except that it is applied by judgment and analogy and therefore subject to bias and error. For all of the looking backwards, the purpose is to predict the future. Where is the justification of the predictions?

OUR APPROACH AND ITS JUSTIFICATION

SUMMARY

Our approach is to characterize aspects of the technical products being developed in a way that would inform a program manager about to make decisions by weighing alternative technical courses of action. We would score or rank the alternatives based on the relationship that each alternative would incur future risk.

The result of our research would be a scorecard, dash board, or workbench that the program office operates before each major technical decision. The workbench would be fed information about the nature of the product alternatives and based on that would compute the relative attractiveness of each option with respect to incurring future risk.

In addition to examining characteristics of the product, the workbench would also scrutinize the match between the characteristics of the product and the characteristics of the developing organization, as risk can arise relative to an organization's capability to develop a certain product alternative.

As our research progresses, we intend to add capabilities to take into account the order and timing of decisions, their cascade effects, and the impact/influence of uncertainty.

We are taking this approach for a number of reasons:

1. The current method of risk characterization, measurement, and mitigation has not improved even though the Department of Defense has spent tens of millions of dollars on research to improve it. Evidently the research results have not proven useful enough to change the guidance. After all, much of the DoD research investment has been in Bayesian methods, which have been around for almost 200 years and still have not found their way into the published guidance.

2. We have all heard the remark, usually made informally by those who see many major weapons systems acquisitions, that by the time the real issues become visible it is very late and the effects have spread. We seek to identify risky courses of action at the time they are being considered for selection. This is very early in the unfolding of the systems development, hopefully in time to take alternative steps if unaddressed impacts are discovered.

A. OBJECTIVE ASSESSMENT

Our approach does not use any judgment, only objective measures of the product and of the organization's capability to create the product. Accordingly, we hope to circumvent the subjective biases that can be found in the current DoD risk identification and analysis practices.

B. QUANTIFIABLE ASSESSMENT

We seek to compute characteristics about the product alternatives and about organizational capability, so the outputs of our analysis would be quantities that would aid program management in making decisions among competing technical alternatives.

C. AID IN DECISION MAKING

Since our approach is a tool to be used during decision-making, we are not taking a retrospective view per se, but rather trying to give the PM information in order to avoid risk, that is, avoid encountering a state of nature that potentially would have unacceptably high likelihood and consequence.

D. TIME IS A VARIABLE, RISKS ARE INTERCONNECTED

There is no explicit time dimension in the current DoD risk management practice. We, on the other hand, see technical risks as largely interdependent/interconnected, so the order in which the technical decisions are considered matters. Accordingly, as our research progresses we intend to be able to present a program manager with the options during decision-making of understanding the effects of deferring or accelerating certain technical decisions.

In addition, time plays another important role in risk because time delay between cause and effect interferes with our ability to connect the two, our ability to reason about what the root causes are of untoward and/or unexpected program outcomes. Therefore, characterizing the time-dependent (that is, dynamic) flow through the program and technical product structures is crucial to identifying real, latent causes, not just their surface symptoms, such as cost and schedule over-runs.

E. ADVANCES IN RISK MANGEMENT: WHERE TO LOOK

A great deal of work already has been done on improvements to risk identification and risk analysis. For example, the DoD has sponsored:

The Software Engineering Institute's Risk Program for several decades.

University of Virginia's Center for Risk Management of Engineered Systems for several decades.

Research at the Air Force Institute of Technology and Naval Postgraduate School for decades.

Research and application at its FFRDCs, such as MITRE and Aerospace, for decades.

While the knowledge created at those institutions has varied, much of it centered on obtaining a more complete list of risks and better estimates of the likelihood and consequence. Evidently the fruits have not been powerful enough to change the written DoD guidance.

One could consult the major defense contractors, as for decades they have been actively managing the risks of developing weapons systems. We approached a few of them informally to ask if they would discuss with us their risk management methods. They responded that they considered their risk management practices to be competition sensitive and determinative of their commercial success and would not share them. We also approached a few industrial firms and received the same answer.

What about firms that deal in risk every day, such as insurance and investment businesses? Here the final report of a previous SERC research topic, valuing flexibility (RT-18), is dispositive (Deshmukh, 2010).

But what is the connection between valuing flexibility and risk? One parallel is that both attempt to characterize future uncertainties. After all, flexibility is about responses to future changes, some unplanned. "Most approaches for valuing flexibility depend on good estimation of uncertainty. However, estimating and characterizing uncertainty, even for foreseeable sources of [change], is difficult, especially in systems involving new technologies." p. 24

Investment advisors often use the technique of Real Options to find the best investment among alternatives, akin to what acquisition program managers must do at multiple points during development. Here are some weaknesses of Real Options in the DoD context (p. 62):

> " Financial options‘ assumptions, such as no arbitrage condition, complete market condition and infinite liquidity, may not hold for the non-financial market.

> "Without checking the assumption of Black-Scholes model, using the Black- Scholes formula does not make sense. For example, the strongest assumption of the model is the fact that uncertainty can be modeled in geometric Brownian motion and as a result the distribution of future status is [a] log-normal distribution. If the future environment cannot be modeled with this stochastic process and distribution, the Black-Scholes model is not valid.
>
> [...]
>
> "Almost all real options related literature assumes the risk-neutral decision maker implicitly or explicitly. This assumption need[s] to be check[ed] in [the] risk management sense."

Further, the report continues, with some overlap with the previous list (p. 64):

> " Real options must be described in terms of specific technologies and the systemic domain in which they are to be developed. Financial analysis alone is insufficient to frame real options. This is quite difficult, when as yet undeveloped technologies are under consideration.
>
> "Financial options are well-defined contracts that are tradable and individually valued, while real options are not: real options have no contract-specified exercise price of time. The usefulness of valuing every potential program alternative that provides flexibility is not clear.
>
> "In military procurement programs, previous experiences associated with the development of similar technologies are not necessarily available. Hence, valuing real options on the basis of so called "comparables" becomes questionable because of the absence of available data.
>
> "Real options are most often path-dependent. Hence, direct applicability of traditional financial options methodologies is not appropriate, as the underlying stochastic differential equations are not necessarily available.
>
> "Real options in military acquisition programs are likely to be highly interdependent. Traditional financial option pricing methods fail here, again, because underlying stochastic differential equations may be unattainable.
>
> "In military procurement programs, there may be no justifiable reason to accept the "no arbitrage assumption". In this case, general option pricing theory breaks down.
>
> "There is typically no quantitative or qualitative reason to believe the real options have uncertainty in price that follow Brownian motion. That is, unlike in financial markets where there exist both quantitative and qualitative analyses that support by weak convergence in measure principles that suggests a limiting Brownian motion price process, there is typically no similar reasoning supporting

> the assumption of Brownian behavior. Hence, the semi-martingale arguments leading to the principal results of general option pricing are not applicable."

And this does not even address what may be the most difficult part of the application of Real Options in the DoD context: the necessity to assess the probability of each state of nature in the unfolding of future events. Investment analysts use historical information to estimate those probabilities, but there is little on which to base estimates of weapons systems development probabilities, especially of new capabilities.

In the end, we cannot rationally defend what some other communities, above, use to manage risk because their assumptions and sources of data match so little of our situation.

CONNECTING TECHNICAL RISK AND TYPES OF COMPLEXITY

A. A FEW DEFINITIONS

The field of complexity is rich and spans over the past half century in various fields of knowledge ranging from biological systems to cyber-physical systems. As it has been discussed by several researchers, an strong correlation can be observed between the complexity of the system and various ranges of failures, including catastrophic failures (Merry, 1995; Cook, 2000, Bar-Yam, 2003).

The term "complexity" has several definitions and various related aspects and characteristics in various domains of knowledge. We adopt the following definition:

Complexity is the potential of the system to exhibit unexpected behavior (Willcox, 2011)

Complex systems exhibit the potential for unexpected behavior with respect to variables of interest. The potential can manifest itself in certain situations and create the actual emergent behavior or stay hidden as a potential. Complex systems have non-linear interactions, circular causality and feedback loops. They may harbor logical paradoxes and strange loops. Small changes in a part of a complex system may lead to emergence and unpredictable behavior in the system (Erdi, 2008). It should be noted that complex systems are very different from complicated systems, and there is a tendency for mistake in using these terms interchangeably. Complicated systems often have many parts, however the interactions between parts and subsystems are often well known and linear, so they do not show emergent or non-linear behavior. In contrast, complex system may or may not have many parts, however, at least one non-linear behavior of feedback loop exists in the structure of the system that drives emergence and unknown unknowns in the system.

The increased complexity is often associated with increased fragility and vulnerability of the system. By harboring an increased potential for unknown unknowns and emergent behavior, the probability of known interactions that lead to performance and behavior in a complex system decreases, which in turn leads to a more fragile and vulnerable system. That is, the presence of complexity in a system, even a little complexity, can swamp the behavior of the familiar, linear interactions.

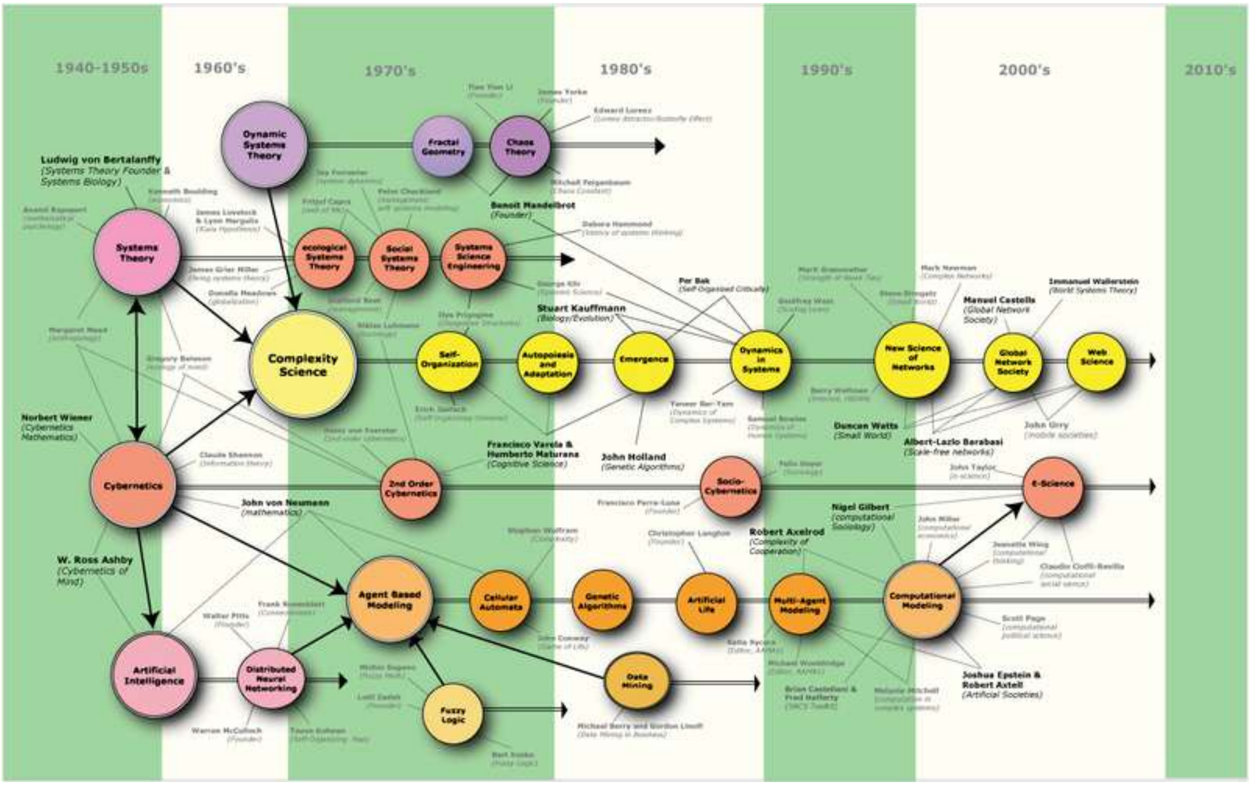

Figure 2. Map of the leading scholars and areas of research in the complexity sciences (http://en.wikipedia.org/wiki/Complexity).

As can be seen (but may not be able to read!) from this figure, there are many threads of research and many definitions of complexity. Our job is to pick and choose among the relevant threads of research which can contribute to the understanding of complexity at various milestones of acquisition programs, and identify the ones most applicable to characterizing technical risk.

At this early juncture, we can say only that we have not focused on the following areas in the diagram because we think they are not relevant to acquisition programs:

Artificial intelligence (distributed neural networking)

Agent-based modeling (cellular automata, genetic algorithms, artificial life, multi-agent modeling

Case-based modeling

New science of networks

Global network society

Fractal geometry

Synergetics/macroscopic modeling

Ecological systems theory

Fuzzy logic

We are selectively making our way through the remainder to assess suitability to characterize technical risk based on what the government sees during the acquisition life cycle. Certain areas, such as emergence, are potent metaphors, but there is a connotation among complexity researchers that emergence is a property that cannot be sensed by looking at components, so for the moment we are not investigating emergence further.

We are looking closely at these kinds of complexity, in particular:

- *Structural* – The arrangement of pieces and parts that has loops, circuits, so that feedback is possible.
- *Dynamic* – The behavior of a system that unfolds as it executes. Here we look for delays and non-linearities.
- *Interface, interconnection* – How parts communicate and touch each other and whether that connection is across a barrier, whether there is a tight or loose connection, whether information is hidden inside the components, and whether the parts are of different "kinds."

B. HOW COMPLEXITY MANIFESTS AS TECHNICAL RISK

B.1 MECHANISMS AND EXAMPLES

One example of risk is interconnecting inhomogeneous elements. The term is meant broadly, as it could refer to trying to connect two systems that had never been connected before, even though each of them was mature in itself. The poster-child for this type of risk is DIVAD, the M247 Sergeant York "self-propelled anti-aircraft gun" (en.wikipedia.org/wiki/DIVAD). Due to the urgent need for the capability, a decision was made by the Army to select a design that joined three commercial off the shelf systems: an Army M48 Patton tank chassis, a radar, and a cannon.

The three particular commercially off the shelf systems selected by the vendor had never been connected and the computer control system at the heart had not yet been developed. In the end, the tank was too slow to protect the ground vehicles it was intended to. The radar, while off the shelf, was off the shelf for an airplane! Airplane radars work internally by detecting movement. Clearly, a tank in the field was not (always) in motion and nor were its targets. The physical layout of the radar with respect to the cannon had the cannon sometimes getting into the radar's line of sight. The tank's turret moved too slowly to track realistic air targets because, after all, it was never meant to. The list went on. And the program, comprised of commercial off the shelf systems, was cancelled.

How would our analysis have identified these risks? By looking for inhomogeneous interfaces.

A second type of complexity comes from feedback and delay. Feedback itself is a structural characteristic: it is a loop somewhere in the product being developed or in the organization creating the product. And the loop can amplify or dampen the signal passing through it, distorting the original (think of the child's game of "telephone"). And the transit may be delayed at points, which creates difficulty for us humans to reason about what causes the effects, the surface symptoms, that we see.

The field of system dynamics is awash in examples of loops and delays, and there is even something of a cottage industry in one particular example, the Beer Game[1], in which a single instance of a change in a single signal causes the humans operating the game to respond in a way that causes oscillation that appears to be unable to be dampened. All of this due to the (underlying) structure of the system, illustrating that structure produces behavior.

The example below comes from a book on business management (Beer, 1979), written to create interest in cybernetics. In this example are trying to construct a system that has even an output around the value 0, given an input single in the form of a regular sine wave:

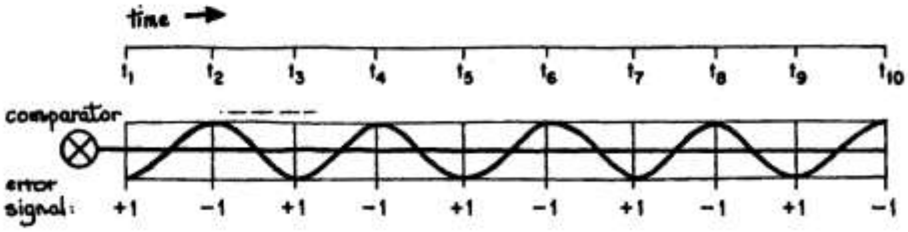

Figure 3. An output varying regularly about a mean value that is its target, showing the corrections at appear necessary at each time epoch when the measurement is made. (Beer, 1979), p. 60

The approach is to generate a -1 when we see a +1 and generate a +1 when we see a -1. Here is what happens, according to that rule:

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[1] http://www.systemdynamics.org/products/the-beer-game/

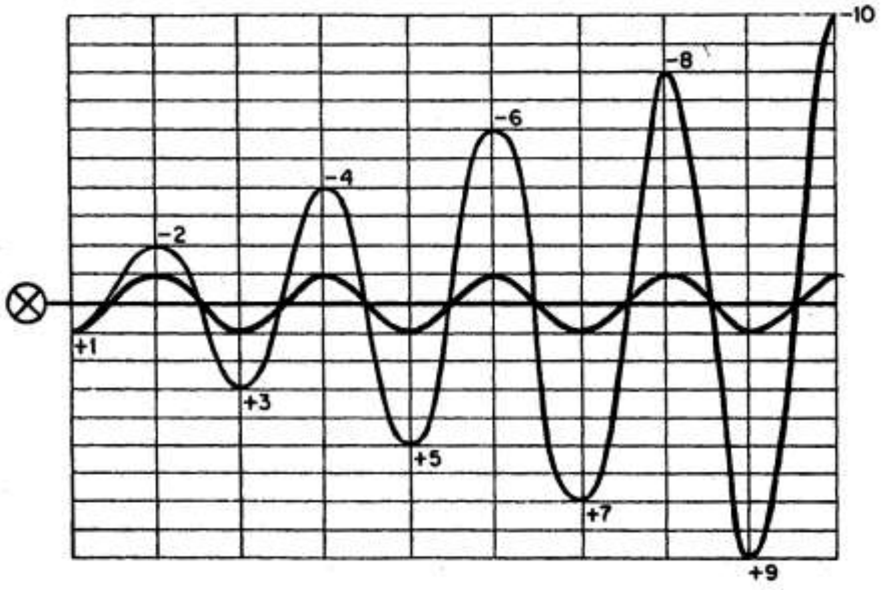


Figure 4. Explosive behavior induced by the direct application of error corrections to a system that has reversed it input states by the time the correction is applied. (Beer, 1979), p. 60

As seen, the system is "exploding." Why? Because the signal we generate to correct for the input is just one phase late, so instead of subtracting when it sees a +1, there is a slight delay and the negative signal we generate supplements an already negative signal, making it even more negative.

The important points are: this is common and is the result of the structure of the system, both static and dynamic. Our methods of risk identification and analysis would try to identify such connections and delay.

B.2 RISK AND COMPLEXITY CORRELATION

Risk can be defined as “a measure of future uncertainties in achieving program performance goals and objectives within defined cost, schedule and performance constraints.”{US Department of Defense (Office of the Undersecretary of Defense (Acquisition, 2006 #1, p. 1}.

For complex defense acquisition programs, often various types of risks exist that manifest themselves at different times throughout the acquisition process, including system development. These risks can be technical, programmatic or strategic in nature and can result in substantial cost overruns, delays, performance issues, reduced adaptability to changing requirements or even total cancellation of a project. One of the challenges with assessing risk using the traditional risk reporting matrices (See Figure 5) for complex systems acquisition is that neither the likelihood nor the true consequence of a risk can be objectively established. For one, there is substantial uncertainty around the interactions among different components of a system as well as uncertainties about how effectively various kinds of risks can be managed across a multiplicity of interfaces.

In this research we are proposing a fundamentally different approach to risk management, one that looks at how complexities within the technical and organizational realms result in uncertainties that can ultimately lead to risks in the system. The premise of this research is that in the realm of technical project risk, it is the complexity of the system combined with the experience/know-how of the contractors that determines system uncertainties and the resulting risks.

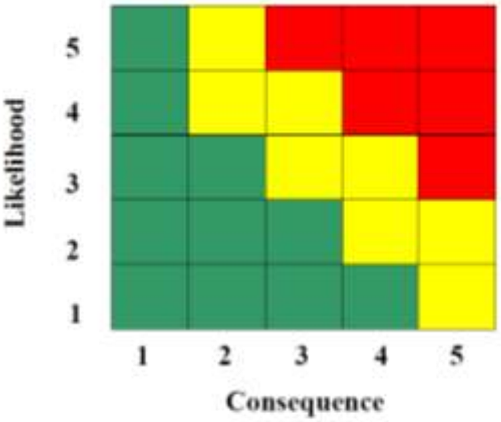


Figure 5. Traditional Risk Reporting Matrix {US Department of Defense (Office of the Undersecretary of Defense (Acquisition, 2006 #1}

The objective of this research is to link technical complexity with uncertainty and risk across different stages of the acquisition process, and dynamically quantifying and updating risk elements for decision-making on project continuation, modification or retirement.

Complexity may be the root cause of many unforeseen risks. Program/project complexity per se can generate negative consequences that may often take the project management team by surprise. Common and advanced methods of risk modeling, including, for example, Bayesian Networks, cannot predict the sort of emerging risks that manifest continuous ripple effects that unfold one after the other almost for the entire duration of the complex projects. This type of intimidating effect of complexity is not something one would like to have for the entire program duration, or perhaps at any time during the program, as the effect is one of being out of control, or, indeed, in the control of something unknown. Often the complexity manifests in risk and risk creates more complexity. This is known as complexity-uncertainty death spiral. In several case studies in our previous research, we have observed that the increase in structural complexity increases the risk and therefore occurrence of the minor undesired event (Efatmaneshnik and Nilchiani, 2012)(Nilchiani and Heydari, 2012). The unfolding of the first risk oftentimes affects the structure of the system in a manner that increases the structural complexity. The incremental increase in structural complexity again can contribute to the next risk to unfold and the spiral escalation can continue. We model this process by hybrid techniques and seek techniques that tackle the root cause of hidden risks that manifest in the form of a set of continuously mysterious (no clear root cause) risks. There is a very intricate relationship between structural complexity and fragility of complex Systems of Systems that can be the result of an escalation of overall system sensitivity, sometimes in a very short time period (Figure 6).

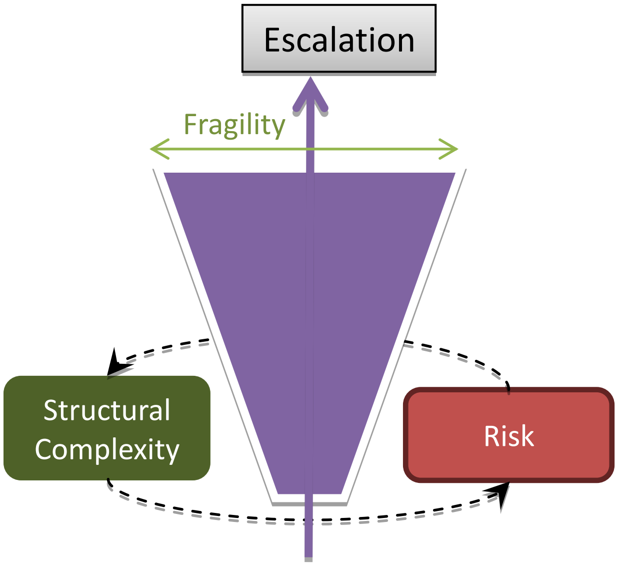


Figure 6. The Complexity-Risk spiral. Insignificant uncertainties and risks in combination with structural complexity escalate into a fragile situation and to a point of no return at which failure is certain.

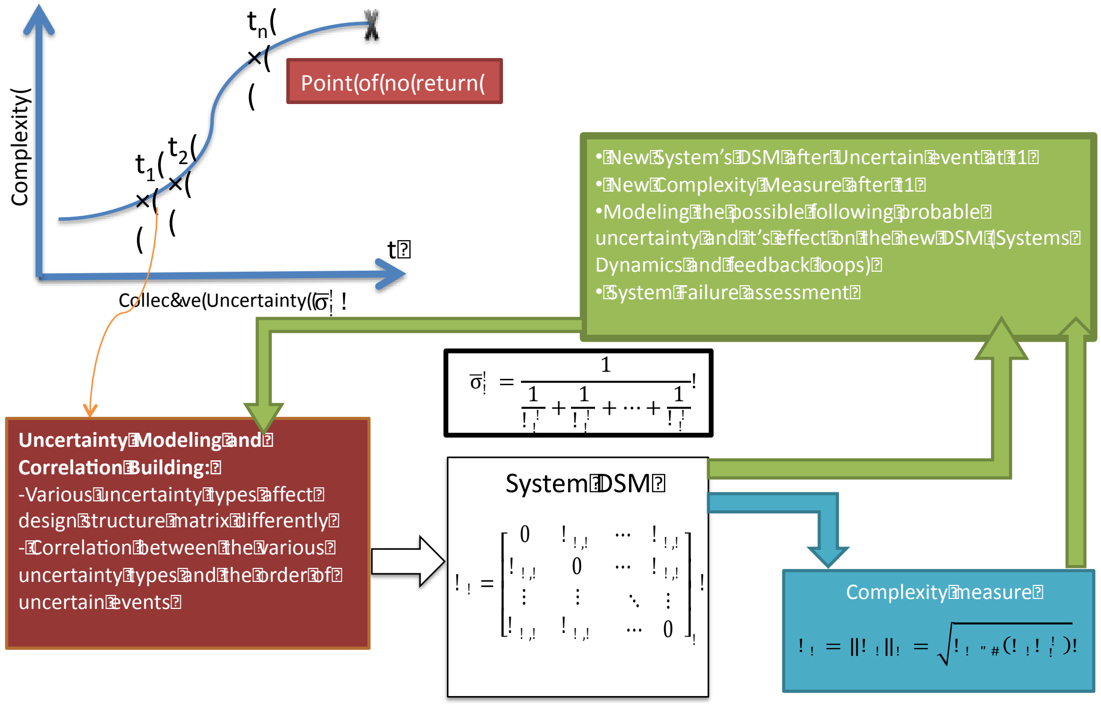


Figure 7. Structural complexity and risk (uncertainty) correlation in the DARPA F6 program.

Figure 7 shows an example of the structural complexity metrics that we defined and used for the DARPA F6 program on fractionated space systems (Nilchiani, 2012). Fractionated space systems are a network of satellites in orbit that can consist of different number of heterogeneous satellites with various architectures flying in formation. Our research has shown a direct correlation between an increase in structural complexity and how fast a failure or risk in a network of these satellites propagates (such as a security attack on one of the satellites in the network). Figure 8 shows some of the results of the F6 simulation that connects the complexity measure of the system to the mean time to failure for various architectures of the fractionated space systems.

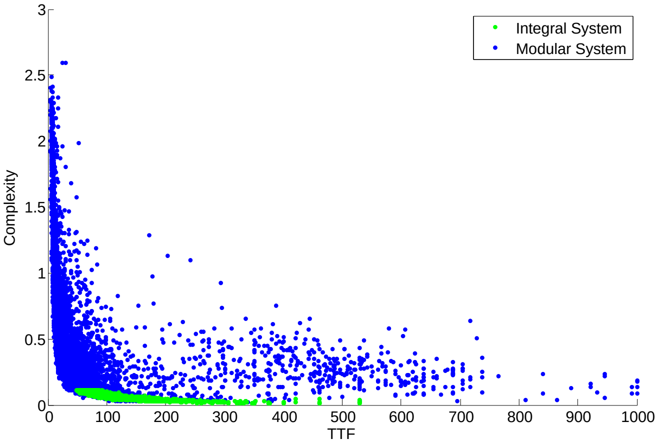


Figure 8. F6 Simulation results showing that increased structural complexity leads to shorter time to failure in the system.

According to some of our initial studies (Salado and Nilchiani, 2012; Efatmaneshnik and Nilchiani, 2012), the results of implementing some risk mitigation plans can create ripple effects through a project or system, increase the complexity of the system and therefore lead to making the program more vulnerable to known risks as well as the hidden uncertainties. Moreover, the existence of a minimum of only three interrelated risks with significant correlation can lead to a ripple effect that can remain hidden up until the last moment, when the negative consequences become fully developed and surface, overwhelming the system. Uncovering these types of hidden cause and effect relationships requires thorough structural monitoring of the system requirements and design as early as possible to uncover all the dependencies with a very high level analysis.

Additionally, as systems demonstrate more functional complexity, they can perform more sophisticated missions. However, the increased functional complexity can also produce an increased structural complexity for systems, which in turn increases risks of failures. While more complex functionalities are more likely to deliver higher values, structural complexity per se is not a positive attribute. More complex functions can require that structurally complex structures, which one after the other can act in unpredicted ways. In essence, functional complexity is the driving force behind complexification. Yet structural complexity is a cost on the system, because it increases the possibility of dramatic response to uncertainties, or fragility (Figure 9).

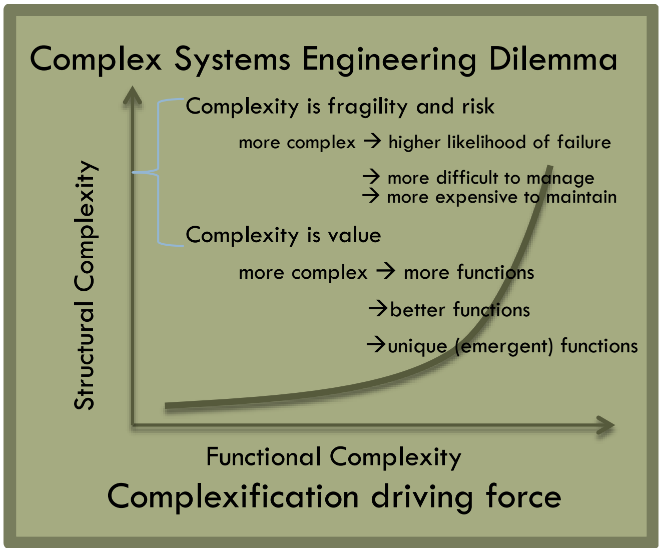


Figure 9. Logical relationship between structural and functional complexity

C. DERIVING PROJECT RISK FROM TECHNICAL COMPLEXITY AND CONTRACTOR ORGANIZATIONAL CAPABILITIES

A modified risk cube that looks at the causal relationships among technical systems complexity and organizational capability in dealing with technical and strategic complexity is presented in the complexity-uncertainty-risk environment cube of Figure 10.

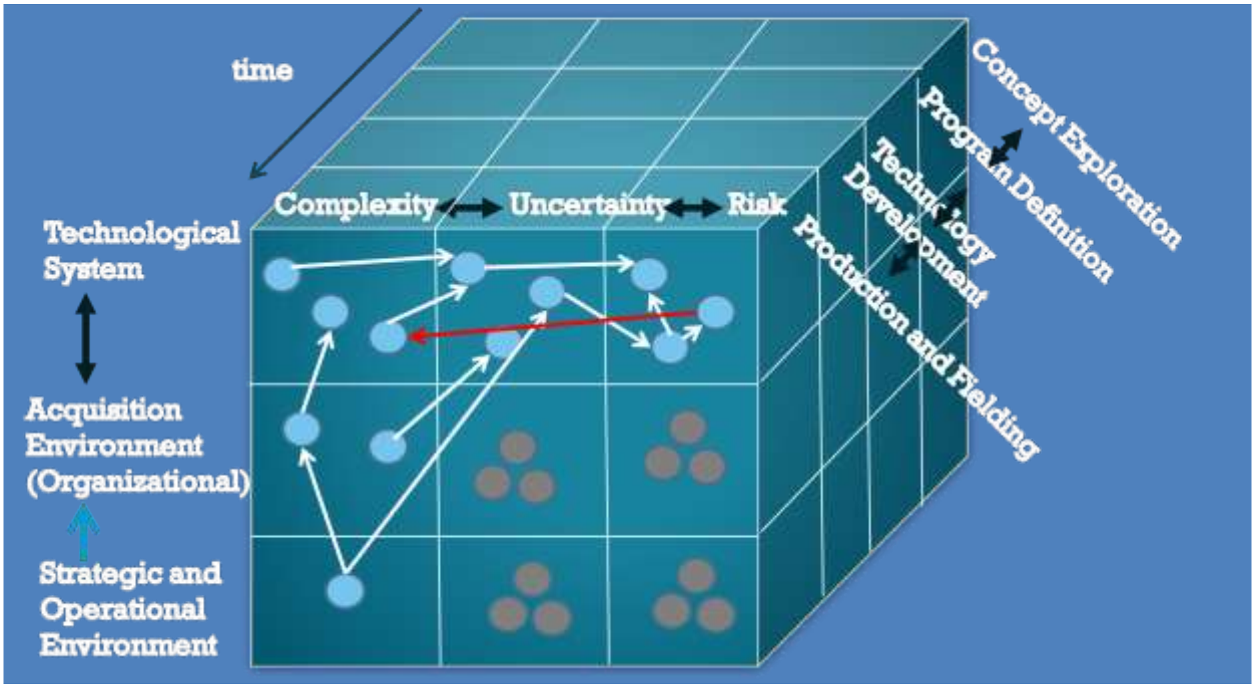


Figure 10. Complexity-Uncertainty-Risk Environment (CURE) Cube

Here we can explore the interrelationships among various aspects of technological complexity across the acquisition process phases and explore the impact of organizational complexity (capability) as well as strategic (that is, higher level, as, for example, at the mission or campaign level) complexity on uncertainties and subsequently risk. The unfolding of the technical complexity depends on the inherent requirements complexity, the system design, and the capabilities of the contractor organization(s) to match their internal organizational complexity to manage the technical complexity. In our current research we are addressing only the top row of Figure 10, the technical aspects of the system and its creation and testing.

Figure 11, below, illustrates that below the minimum required critical complexity a system cannot perform the functions that are expected and above a maximum tractable complexity level, the system development process can spiral out of control. It is the expertise, know-how and experience of the contractor organization, working with the government acquisition office (where both use standard technical management processes, such as version control, keeping dependency graphs current, keeping design changes in harmony with requirements changes, etc.), that can keep the development process within the boundaries of these two and stabilize the complexity level of a system. Thus, for the same system but different contractor + acquisition organizations, the graph in Figure 11 could have different forms.

The key to acquisition risk management will therefore be to ensure a match between the unfolding technical complexity with the internal organization, know-how and expertise of the contractor(s) + acquirer in managing complexity.

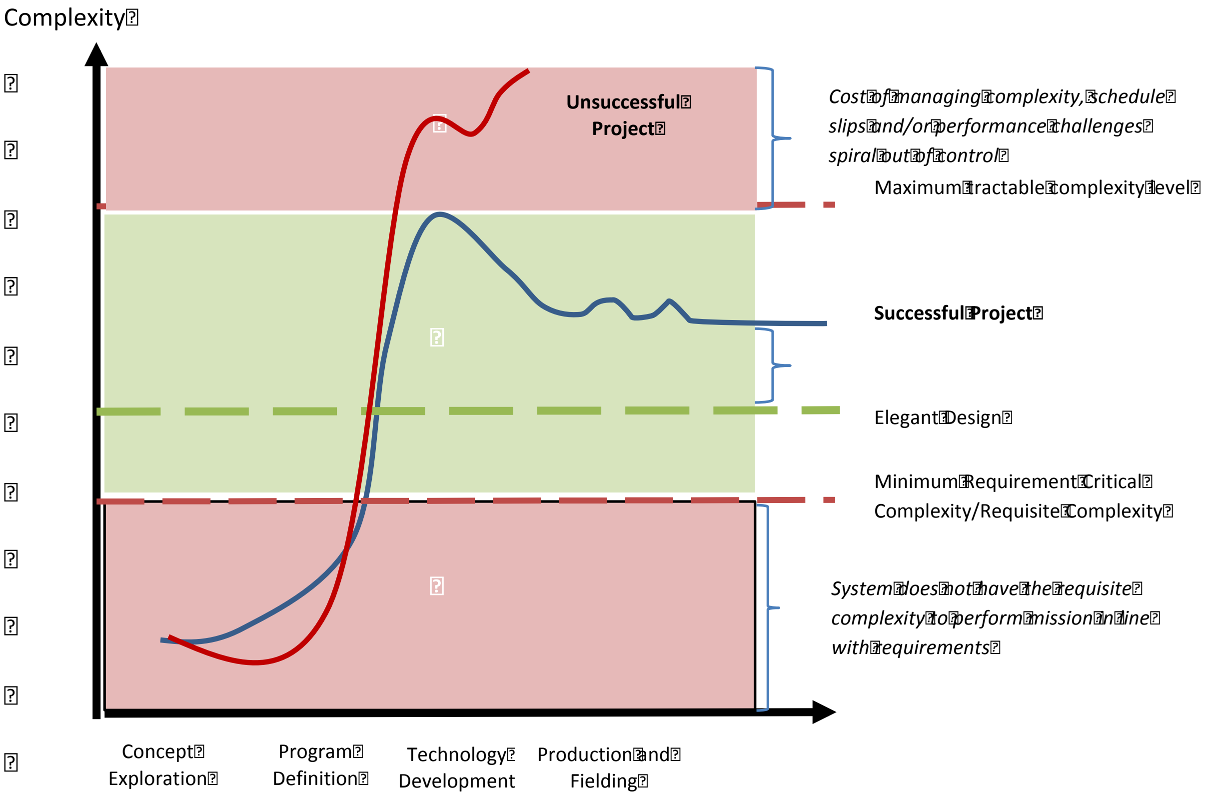


Figure 11. Complexity evolution throughout the systems acquisition lifecycle

D. ARCHITECTURAL-LEVEL COMPLEXITY MEASURES FOR ACQUISITION SYSTEMS: SUMMARY OF CASE STUDIES

The first step therefore in transitioning towards a complexity-centric risk assessment is to be able to measure systems complexity over the acquisition process. As it is possible that there is no detailed design in the early stages of the acquisition process, the measurement of complexity has to start at the architectural (high-level requirements) level. Tables 1 and 2 summarize the different types and planes of acquisition complexity at the architectural level. It should be noted that the following Tables summarize some of the major variables that contribute to the increased complexity of the system. However the list and variables may not be comprehensive and in phase 2 of the project, we are aiming at identifying the majority of variables that contribute to the complexity of the system

Table 1. Six types of complexity (Source: Sheard, 2012)

Six Types	
Structural: Size	Number of elements, number of instances, total cost, total number of requirements
Structural: Connectivity	Number of connections, density of connections, strengths of relationships, amount of conflict, distribution of connectedness
Structural: Inhomogeneity	Number of different types of entities, number of types of relationships, number of different areas within a space, diversity of sizes of elements or contractors or stakeholders
Dynamic: Short-term	Existence of loops/circuits, safety-criticality, tendency to blow up in operational time frame, seriousness of consequences of a mishap
Dynamic: Long-term	Evolution of purpose of an item, co-evolution of a variant and its environment, how much different the next iteration of a system might be
Socio-political	Fraction of stakeholder interests that are based on power, amount of disagreement among stakeholders, number of layers of management, changes of opinion of management or stakeholders, number of different cultures working together on a project, inhomogeneity of stakeholder utilities.

Table 2. Four planes of acquisition complexity (Source: Sheard, 2012)

Four Entities	
[Technical] System being built	Product, system, system-of-systems, tank, squadron, database, sensor, software algorithm.
Project or organization doing the building	Project, organization, program, tasks, team
Environment, both external systems and people	Customers, buyers, market, external technological system, future systems that need to interface with product
Cognitive: capacity of humans to understand, conceive of, build and operate the system.	Learning curve, uncertainty, confusion, operator skill set.

E. MEASURING ARCHITECTURAL LEVEL COMPLEXITY: INITIAL EXPLORATIONS

Based on a comprehensive literature and state of the art review we have converged on the following five lenses for measuring complexity. Should these prove to be inadequate for our research, we will devise new ones based on our own observations of systems. We will explore which of the following lenses of complexity measurements applied to an architecture-level systems description can dynamically predict acquisition risk and improve mid-process decision-support

1. Requirement critical (algorithmic) complexity
2. Critical control path (cyclomatic) complexity
3. Dynamic architectural complexity
4. Structural complexity
5. Modified architectural-structural complexity

We will then explore how the experience of contractors + government plays a role in managing the complexity of the system in the acquisition process.

1) Requirement Critical Complexity

Requirement critical complexity refers to the minimum amount of complexity a system needs to have in order to perform a desired set of functions in line with expressed requirements. Based on *Kolmogorov complexity* metric, it refers to the minimum set of architectural level components and linkages {*y*} that would address requirement set {x}. In other words, the requirement critical complexity of a system can be expressed as the minimal systems architecture {y} (minimum number and type of components and linkages) that would theoretically produce performance set {x}.

The determination of *{y}* given *{x}* is an important research question and this research will try to establish this threshold for various kinds of complex systems. The calculation of requirement critical complexity can be done either through modified structural complexity metrics that will be discussed further in this document.

2) Critical Control Path Complexity

Based on the concept of cycolmatic complexity in software, the critical control path complexity metric measures the number of linearly independent control paths through a systems architecture graph. This number changes as the architecture (or the resulting design) changes over time and is estimated by the following equation:

$$CCP(t) = \sum n(t,i) - l(t,i) + p(t,i)$$

$where\ CCP$(t) is the critical control path complexity at time t, n(t,i) is the number of nodes in the connected graph of the architecture expression for module (i), *l* is the number of linkages at time t in module (i) and p is the number of distinct connected components in the architectural flow graph. And the sum is over all modules.

3) UML-based Five-Views Dynamic Architectural Complexity (Lankford)

Rather than a single number, the UML-based Five Views Dynamic Architectural complexity metric allows the measurement of various system complexity metrics over time.

The five views complexity vector is calculated as follows:

$$C5V(t) = \begin{bmatrix} C_{class}(t,i) \\ C_{process}(t,i) \\ C_{component}(t,i) \\ C_{interfaces}(t,i) \\ C_{patterns}(t,i) \end{bmatrix}$$

Where:

Within

$C_{class}(t,i)$=Number of classes and objects within each module at time *t*

$C_{process}(t,i)$ =Number of processes and threads within each module at time *t*

$C_{component}(t,i)$ =Number of components = the number of nodes

$C_{interface}(t,i)$ =Number of interfaces between each of these

$C_{pattern\square}(t,i)$ =Number of identifiable design patterns within each module

4) Simple Structural Complexity (Meyer)

Simple structural complexity can provide an easy to calculate way to capture how the complexity of a system is changing, by calculating changes in the number of parts (or sub-systems or systems), types of parts and number of interfaces over time.

$$C_{structural}(t,i) = \sqrt[3]{(N_p(t,i) \times N_y(t,i)\ \times N_x(t,i)}$$

Where

$N_p(t,i)$ =Number of parts/subsystems in subsystem/system *i* at time t

$N_y(t,i)$= Types of parts/subsystems in subsystem/system *i* at time t

$N_x(t, i)$= Number of interfaces in subsystem/system *i* at time t

5) Modified Architectural-Structural Complexity (MASC)

The modified architectural-structural complexity is the most comprehensive measure of architectural complexity, taking into account size, type, interconnections and interfacial complexity of architectural modules into consideration. It is based on Kinnunen (2000). Modifying the simple architectural complexity equation for MASC we get:

$$C_{MASC}(t) = \sqrt[3]{\sqrt{[(N_p(t) \times N_y(t,i)]} \times \sqrt[3]{[(N_f(t) \times N_{obj}(t) \times N_{op}(t)]} \times {N_x}^{ICM}}$$

Where the arguments are respectively:

- Number of distinct types of objects/components
- Number of objects within each type
- Number of processes/functionalities affecting an object
- Number of objects/components affecting a process
- Number of operations per process
- Number of interfaces weighted with the interface complexity multiplier (ICM) (related to the integration readiness levels (IRLs) between different systems/subsystems).

It should be noted that these five types of architectural level complexity measures are our initial exploration of the relevant complexity measures of the technical system. Our research team may have to define novel measures based on the existing literature on complexity that may be more useful for different milestones of an acquisition program, and in particular characterizing the dynamic behavior of the architecture.

C. THE FIT BETWEEN TECHNICAL RISK OF THE PRODUCT AND AN ORGANIZATION'S CAPABILITY TO MANAGE IT

What accounts for one enterprise being able to create a complex product and another not? The primary conjecture, attributed to Ashby (Ashby, 1961), is that the successful enterprise that can construct a complex product has enough "variety" (he called it requisite variety) in the way it is organized and applies its resources. Variety is diversity, ability to react to various problems and opportunities, including unexpected ones.

Perhaps one of the most vivid illustrations of variety in this context was during the Apollo 13 manned space flight in 1970, when an oxygen tank aboard exploded, limiting power, causing loss of cabin heat, reducing the availability of potable water, and increasing the concentration of carbon dioxide in the cabin air. It was the mounting concentration of carbon dioxide that proved most troubling, as the astronauts would die of lack of oxygen if it were not reversed. A team on the ground was assembled and given the task of figuring out how to create a carbon dioxide removal system, given the constraints on-board. That the ground team succeeded was a tribute to its variety, its diversity of thought, as it quickly suggested and tested numerous options.

One of the biggest challenges in using variety to characterize organizations is that it is so difficult to observe, to measure. Two authors (Beer, 1979; Jaques, 2006) have suggested antidotes to this and we are exploring their methods.

D. THE PLACES OF CASE STUDIES AND QUANTITATIVE DATA

We are seeking to know what programs and organizations are "made of" that might inform the identification of risk. Our premise is that complexity is a major indicator of risk. In order to validate or invalidate the premise we need data. The most convincing data would be numeric, quantitative that showed the relationship between product complexity, say, and risk. If that data are not available, then we might use case studies.

Since we do not yet have quantitative data, we have indeed been reading case studies, supplied to us by the deep reservoir provided by our colleague, Dr. Gary Witus, at Wayne State University. At one stage he supplied 15 cases, some with multiple artifacts. Dr. Mostashari read them and in the end was not able to deduce anything general.

Dr. Witus responded to our request for additional case studies and we have not yet had a chance to absorb them, and it is a priority for our next steps.

At some point – earlier is better – we are going to need access to quantitative data that will help us confirm or deny the connection between some measure of complexity and technical program risk. This, too, is a priority for the next steps.

Both case studies and access to quantitative program information will help us steer where to look deeper, help us consider what programs are made of. In the end, it is possible that programs do not collect the measures of complexity that we think are the most indicative of risk, so we will have to work with programs on a pilot basis to install new measures and assess the ability of those measures to predict technical risk.

EXAMPLES AND SOME CASE STUDIES

CONCEPT DEMONSTRATION: COMPLEXITY AND RISK

One of the easy ways to characterize complexity for a system at an architectural level is to analyze the number of different interactions between the different subsystems.

$$Interactions_{\max} = \frac{n(n-1)}{2}$$

Interactions can be spatial, material, energy and/or information. If we look at aircraft designs over the years we can see how avionics has become more complex.

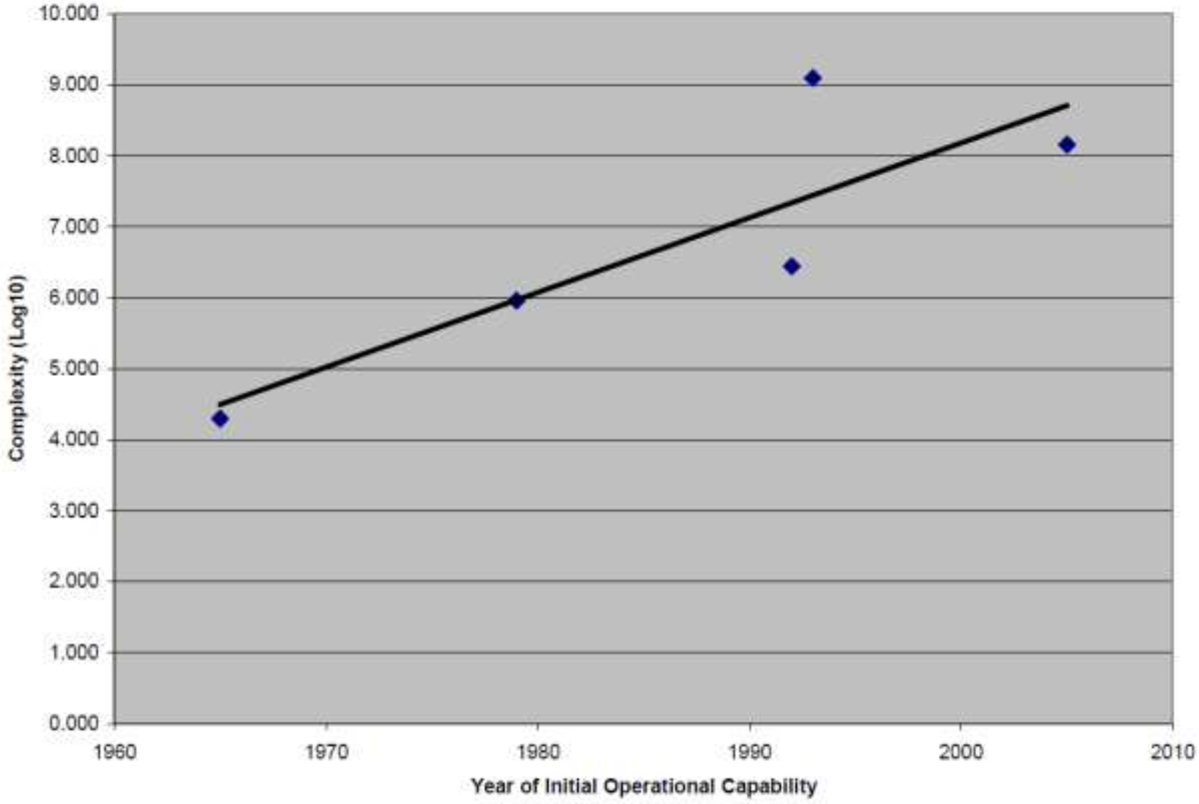


Figure 12. Increasing avionics complexity (dimensionless) over the years (Source: Diterick, 2010)

Analyzing the relationship between cost and development schedule in 154 DoD projects, McNutt (2000) estimates the relationship between cost and complexity to be estimated by the following equation:

$$DevelopmentCost = (0.03 \times DevelopmentTime_{months} + 1.36)^4$$

Where the development cost is in millions of USD.

CASE STUDIES

An analysis of the following 31 acquisition programs with a calibrated complexity metric shows the following correlation:

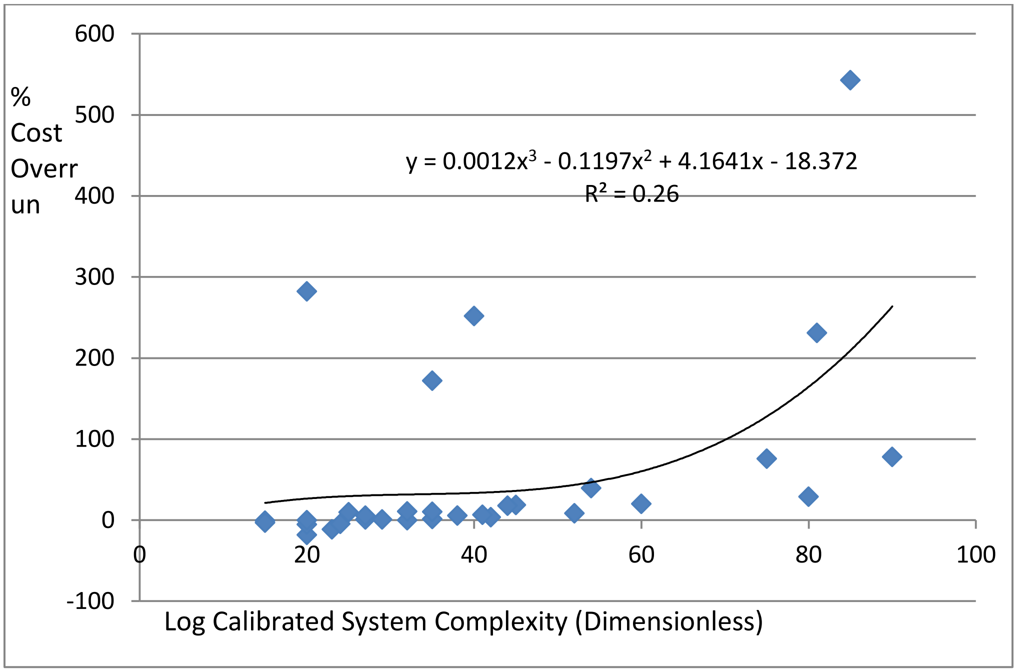


Figure 13. Cost overrun as a function of log calibrated architectural systems complexity

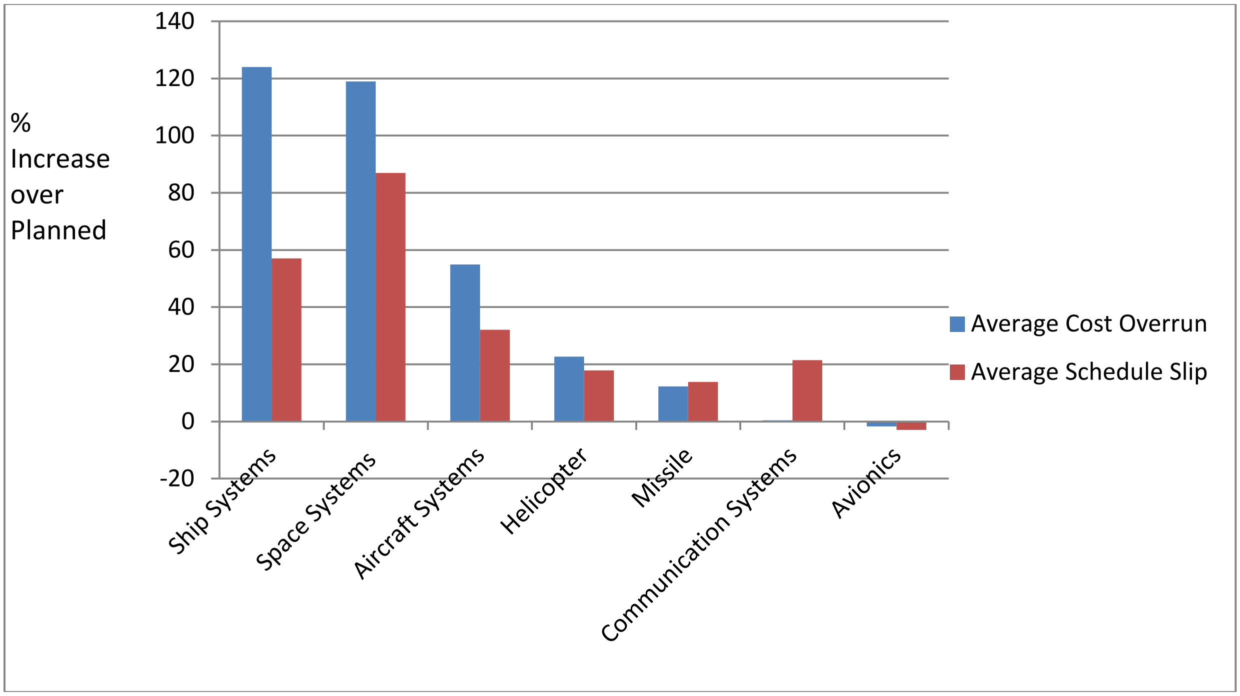
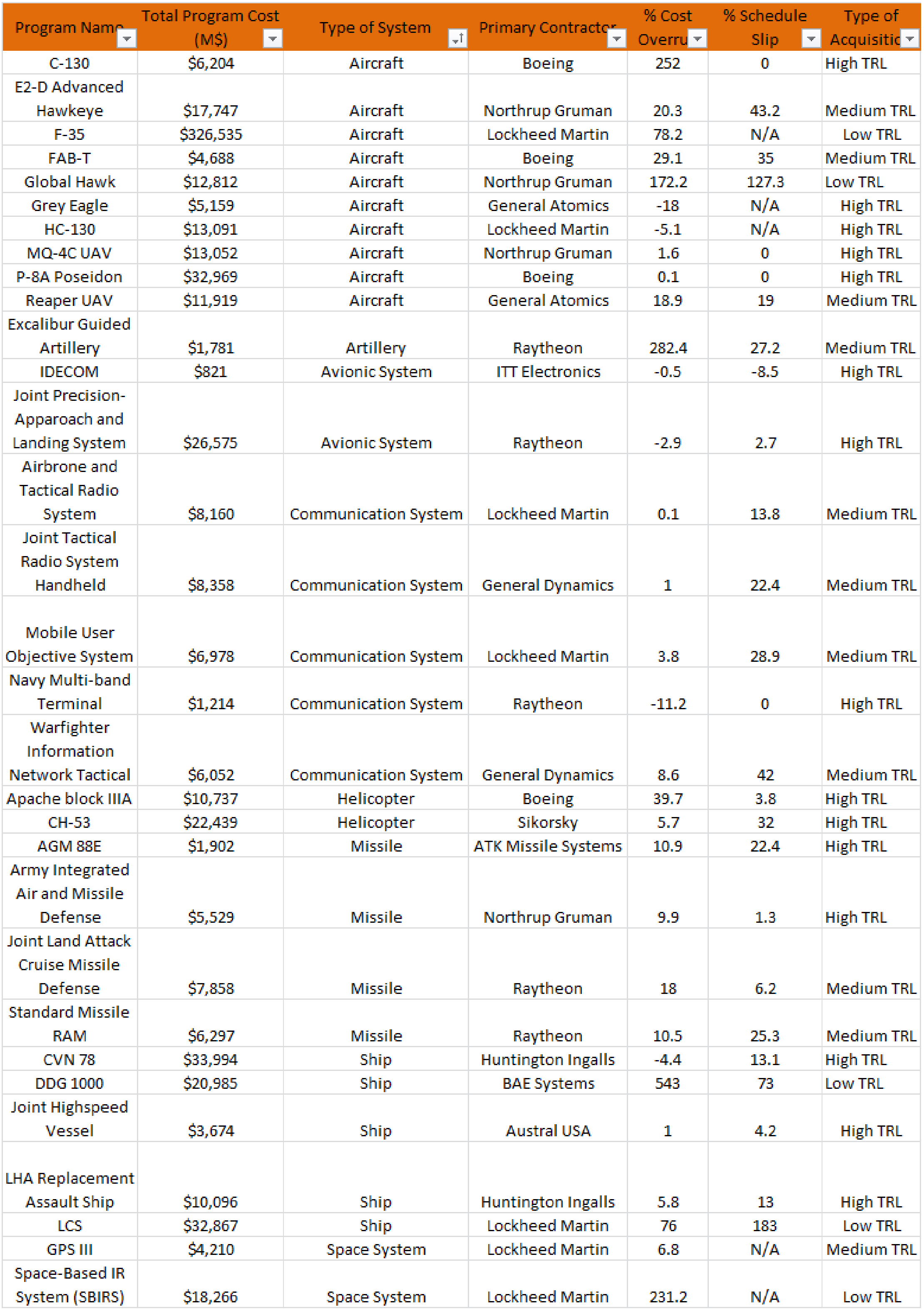


Figure 14. Cost overrun and schedule slips for different types of weapons systems. Most cost overruns occur for ship systems, while most schedule slips happen for aircraft. Avionic systems have had a good track record of beating both cost and schedule plans.



Program Name	Total Program Cost (M$)	Type of System	Primary Contractor	% Cost Overru	% Schedule Slip	Type of Acquisitic
C-130	$6,204	Aircraft	Boeing	252	0	High TRL
E2-D Advanced Hawkeye	$17,747	Aircraft	Northrup Gruman	20.3	43.2	Medium TRL
F-35	$326,535	Aircraft	Lockheed Martin	78.2	N/A	Low TRL
FAB-T	$4,688	Aircraft	Boeing	29.1	35	Medium TRL
Global Hawk	$12,812	Aircraft	Northrup Gruman	172.2	127.3	Low TRL
Grey Eagle	$5,159	Aircraft	General Atomics	-18	N/A	High TRL
HC-130	$13,091	Aircraft	Lockheed Martin	-5.1	N/A	High TRL
MQ-4C UAV	$13,052	Aircraft	Northrup Gruman	1.6	0	High TRL
P-8A Poseidon	$32,969	Aircraft	Boeing	0.1	0	High TRL
Reaper UAV	$11,919	Aircraft	General Atomics	18.9	19	Medium TRL
Excalibur Guided Artillery	$1,781	Artillery	Raytheon	282.4	27.2	Medium TRL
IDECOM	$821	Avionic System	ITT Electronics	-0.5	-8.5	High TRL
Joint Precision-Apparoach and Landing System	$26,575	Avionic System	Raytheon	-2.9	2.7	High TRL
Airbrone and Tactical Radio System	$8,160	Communication System	Lockheed Martin	0.1	13.8	Medium TRL
Joint Tactical Radio System Handheld	$8,358	Communication System	General Dynamics	1	22.4	Medium TRL
Mobile User Objective System	$6,978	Communication System	Lockheed Martin	3.8	28.9	Medium TRL
Navy Multi-band Terminal	$1,214	Communication System	Raytheon	-11.2	0	High TRL
Warfighter Information Network Tactical	$6,052	Communication System	General Dynamics	8.6	42	Medium TRL
Apache block IIIA	$10,737	Helicopter	Boeing	39.7	3.8	High TRL
CH-53	$22,439	Helicopter	Sikorsky	5.7	32	High TRL
AGM 88E	$1,902	Missile	ATK Missile Systems	10.9	22.4	High TRL
Army Integrated Air and Missile Defense	$5,529	Missile	Northrup Gruman	9.9	1.3	High TRL
Joint Land Attack Cruise Missile Defense	$7,858	Missile	Raytheon	18	6.2	Medium TRL
Standard Missile RAM	$6,297	Missile	Raytheon	10.5	25.3	Medium TRL
CVN 78	$33,994	Ship	Huntington Ingalls	-4.4	13.1	High TRL
DDG 1000	$20,985	Ship	BAE Systems	543	73	Low TRL
Joint Highspeed Vessel	$3,674	Ship	Austral USA	1	4.2	High TRL
LHA Replacement Assault Ship	$10,096	Ship	Huntington Ingalls	5.8	13	High TRL
LCS	$32,867	Ship	Lockheed Martin	76	183	Low TRL
GPS III	$4,210	Space System	Lockheed Martin	6.8	N/A	Medium TRL
Space-Based IR System (SBIRS)	$18,266	Space System	Lockheed Martin	231.2	N/A	Low TRL

Table 3. A selection of case studies of DoD acquisition program and their percentage of cost and schedule overruns.

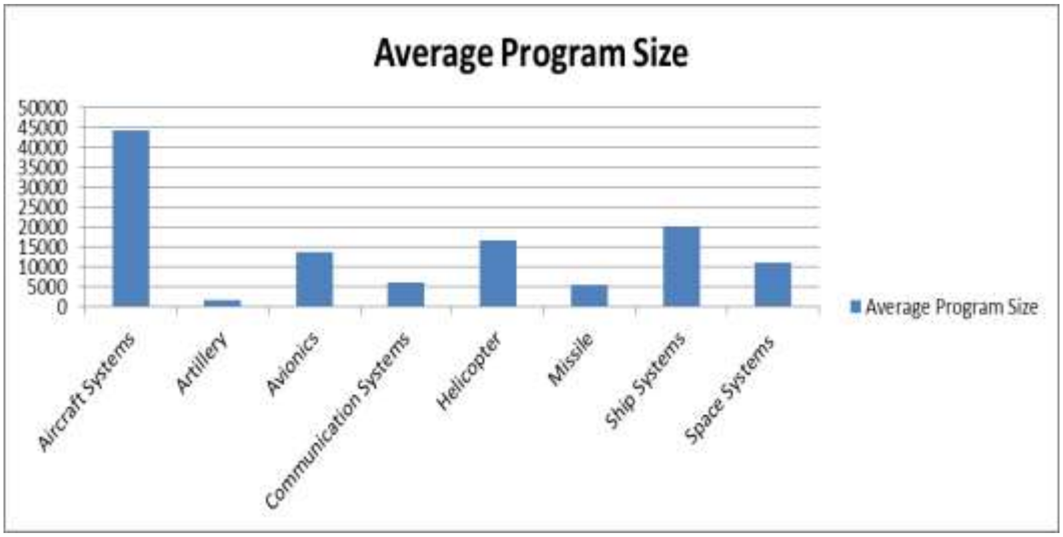


Figure 15. Average program size (total program cost) of case studies explored in this research (in million $)

ADDITIONAL CASE STUDIES (NOT INCLUDED IN COMPLEXITY ANALYSIS)

The following are additional case studies the team looked at, but most were suffering from program complexity rather than technical complexity.

A-10 THUNDERBOLT II (AIRCRAFT)

Acquisition Organization: U.S. Air Force

Risks and Weaknesses

- Technical: Concurrent development of a new technology (the GAU-8/A gun system) and the aircraft at the same time with the aircraft architecture revolving around the armament system created delays in the acquisition process. Also the original structural design proved inadequate for the design life, and even fixes during production were inadequate for all but the latest aircraft produced.

- Programmatic: Overlooked problems associated with production readiness and contractor financial stability did not go away and had to be resolved far too late in the development program. Additional problems included loss of the Original Equipment Manufacturer (OEM), on-again/off-again decisions to retire the A-10, unstable funding for inspection and repair, and major personnel disruptions resulting from a BRAC decision. Critical “health of the fleet” structural inspections were not performed during sustainment, and a subsequent repair program failed to provide the desired level of life extension.

Strengths

Close attention to key mission characteristics (lethality, survivability, responsiveness, and simplicity) allowed the concept formulation and subsequent system design to result in an effective CAS aircraft, and design-to-cost goals kept the government and contractor focused on meeting the critical requirements at an affordable cost. The A-10 did not meet all its cost goals, but it came much closer to them than most major defense development programs did in that time frame or since then.

Complexity Factors Leading to Risk

- Low TRL technology at core of systems architecture (Interface complexity)
- Requirement changes rendering architecture inadequate (Requirement Complexity)

Contractor technical and financial capability (Organizational Requisite Complexity)

Source: A-10 Thunderbolt II (Warthog) SYSTEMS ENGINEERING CASE STUDY , Air Force Center for Systems Engineering

C-5A GALAXY (AIRCRAFT)

Acquisition Organization: U.S. Air Force

Risks and Weaknesses

- Technical: A Weight Empty Guarantee was included in the specification as a performance requirement and in the contract as a cost penalty for overweight conditions of delivered aircraft. The aircraft Weight Empty Guarantee dominated the traditional aircraft performance requirements (range, payload, etc.), increased costs, and resulted in a major shortfall in the wing and pylon fatigue life. The stipulation of a Weight Empty Guarantee as a performance requirement had far-reaching and significantly deleterious unintended consequences.
- Programmatic: The Total Package Procurement Concept (TPPC) employed by the government required a fixed-price, incentive fee contract for the design, development, and production of 58 aircraft. It included a clause giving Total Systems Performance Responsibility (TSPR) to the prime contractor. TPPC was invented to control costs, but it was the underlying cause of the cost overrun and limited the number of aircraft purchased under the original contract

Strengths

The process for developing and documenting the system performance requirements involved the User (warfighter), planners, developers, and technologists from both the government and industry in a coordinated set of trade studies. It resulted in a well-balanced, well-understood set of requirements that fundamentally remained unchanged throughout the program**.**

Complexity Factors Leading to Risk

- Detrimental hard requirement with cascading effect on mission critical requirements and architectural design (Requirement complexity)
- Weight, wing and pylon design conflict (Interfacial complexity)
- Faulty procurement concept (Organizational Process Complexity)

Source: C-5A Galaxy Systems Engineering Case Study, Air Force Center for Systems Engineering

F-111 (AIRCRAFT)

Acquisition Organization: U.S. Air Force and U.S. Navy

Risks and Weaknesses

- Technical: The F-111 acquisition process suffered from a nearly impossible multi-role/multi-service requirement specification, and a protracted development cycle in which numerous serious technical problems had to be identified and corrected. Of the 1,726 total aircraft buy that had originally been planned in 1962, only 562 production models of seven different variants were completed when production ended in 1976. The F-111, like any complex weapon system development program, which provides new war-fighting capability, had areas of risk or deficiency that came to light during RDT&E even though there was perceived low risk in the design. The F-111 development program introduced concurrency (overlap) between design validation/verification and production to accelerate program

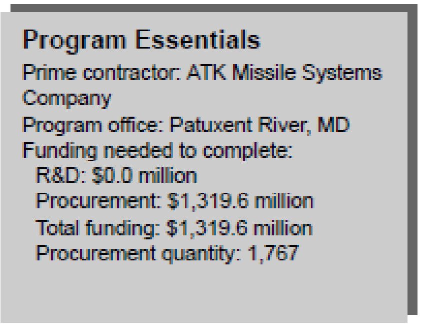
- Programmatic: Systems Architecture and Design Trade-Offs were not performed to achieve an F-111 design that was balanced for performance, cost and mission effectiveness (including survivability) and the attendant risk and schedule impacts. The F-111 suffered from poor communications between the Air Force and Navy technical staffs, and from over-management by the Secretary of Defense and the Director, Defense Research and Engineering, and it came under intense congressional scrutiny, which restricted the System Program Office (SPO) Director from applying sound systems engineering principles.

Complexity Factors Leading to Risk

- Impossible requirements with severe conflicts (Requirement complexity)
- Inadequate verification and validation (Organizational Process Complexity)
- Multi-agency acquisition process (Organizational Process Complexity)
- Sociopolitical sensitivity (Organizational Process Complexity)

Source: F111 Systems Engineering Case Study, Air Force Center for Systems Engineering

AGM-88E Advanced Anti-Radiation Guided Missile (AARGM)



Program Essentials

Prime contractor: ATK Missile Systems Company

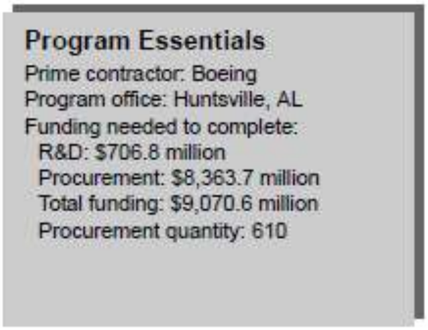
Program office: Patuxent River, MD

Funding needed to complete:
- R&D: $0.0 million
- Procurement: $1,319.6 million
- Total funding: $1,319.6 million
- Procurement quantity: 1,767

Program Performance (fiscal year 2012 dollars in millions)

	As of 07/2003	Latest 06/2011	Percent change
Research and development cost	$637.2	$722.2	13.4
Procurement cost	$963.6	$1,180.0	22.5
Total program cost	$1,600.7	$1,902.3	18.8
Program unit cost	$.894	$.991	10.9
Total quantities	1,790	1,919	7.2
Acquisition cycle time (months)	85	104	22.4

Apache Block IIIA



Program Essentials

Prime contractor: Boeing

Program office: Huntsville, AL

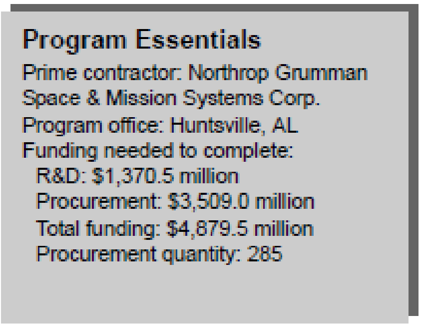
Funding needed to complete:
- R&D: $706.8 million
- Procurement: $8,363.7 million
- Total funding: $9,070.6 million
- Procurement quantity: 610

Program Performance (fiscal year 2012 dollars in millions)

	As of 08/2006	Latest 12/2010	Percent change
Research and development cost	$1,155.6	$1,640.3	41.9
Procurement cost	$6,086.9	$9,096.8	49.4
Total program cost	$7,242.5	$10,737.0	48.3
Program unit cost	$12.031	$16.803	39.7
Total quantities	602	639	6.1
Acquisition cycle time (months)	79	82	3.8

The latest cost and quantities do not include the 57 new-build helicopters that are being acquired under the AB3B major defense acquisition program.

Army Integrated Air and Missile Defense



Program Essentials

Prime contractor: Northrop Grumman Space & Mission Systems Corp.

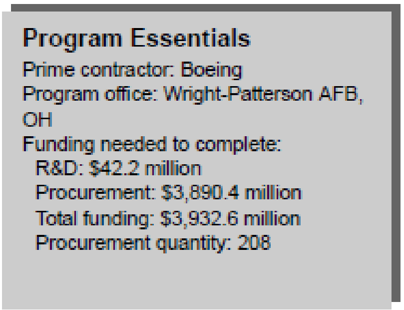
Program office: Huntsville, AL

Funding needed to complete:
- R&D: $1,370.5 million
- Procurement: $3,509.0 million
- Total funding: $4,879.5 million
- Procurement quantity: 285

Program Performance (fiscal year 2012 dollars in millions)

	As of 12/2009	Latest 08/2011	Percent change
Research and development cost	$1,595.2	$2,019.8	26.6
Procurement cost	$3,433.4	$3,509.0	2.2
Total program cost	$5,028.6	$5,528.8	9.9
Program unit cost	$16.988	$18.678	9.9
Total quantities	296	296	0.0
Acquisition cycle time (months)	80	81	1.3

C-130 Avionics Modernization Program



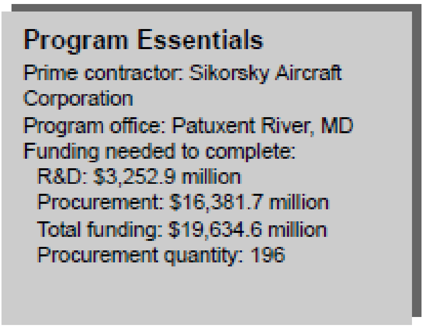
Program Essentials

Prime contractor: Boeing
Program office: Wright-Patterson AFB, OH
Funding needed to complete:
R&D: $42.2 million
Procurement: $3,890.4 million
Total funding: $3,932.6 million
Procurement quantity: 208

Program Performance (fiscal year 2012 dollars in millions)

	As of 07/2001	Latest 12/2010	Percent change
Research and development cost	$775.4	$1,948.3	151.3
Procurement cost	$3,356.8	$4,256.0	26.8
Total program cost	$4,132.3	$6,204.3	50.1
Program unit cost	$7.962	$28.074	252.6
Total quantities	519	221	-57.4
Acquisition cycle time (months)	NA	NA	NA

CH 53-K Heavy Lift Replacement



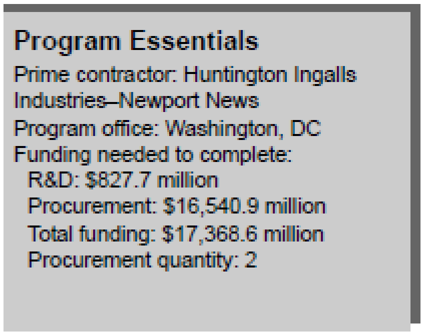
Program Essentials

Prime contractor: Sikorsky Aircraft Corporation
Program office: Patuxent River, MD
Funding needed to complete:
R&D: $3,252.9 million
Procurement: $16,381.7 million
Total funding: $19,634.6 million
Procurement quantity: 196

Program Performance (fiscal year 2012 dollars in millions)

	As of 12/2005	Latest 08/2011	Percent change
Research and development cost	$4,378.9	$6,058.1	38.3
Procurement cost	$12,178.3	$16,381.7	34.5
Total program cost	$16,557.1	$22,439.9	35.5
Program unit cost	$106.136	$112.199	5.7
Total quantities	156	200	28.2
Acquisition cycle time (months)	119	157	31.9

CVN 78 Class



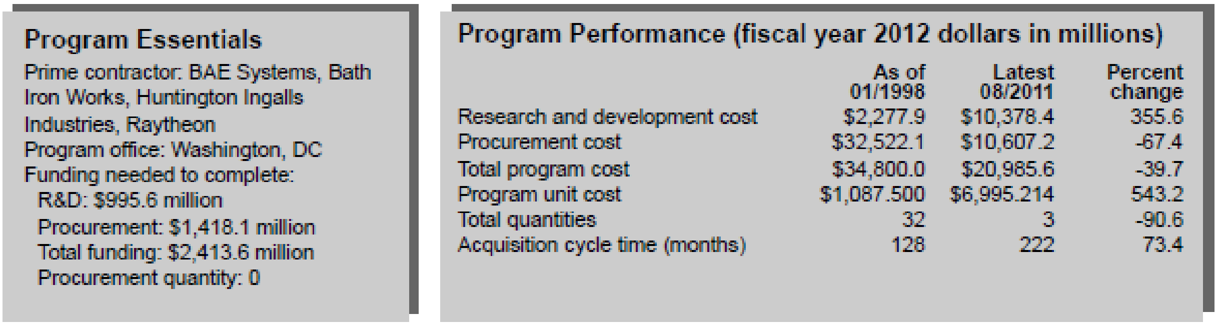
Program Essentials

Prime contractor: Huntington Ingalls Industries–Newport News
Program office: Washington, DC
Funding needed to complete:
R&D: $827.7 million
Procurement: $16,540.9 million
Total funding: $17,368.6 million
Procurement quantity: 2

Program Performance (fiscal year 2012 dollars in millions)

	As of 04/2004	Latest 08/2011	Percent change
Research and development cost	$4,803.3	$4,646.8	-3.3
Procurement cost	$30,770.8	$29,346.8	-4.6
Total program cost	$35,574.1	$33,993.6	-4.4
Program unit cost	$11,858.040	$11,331.185	-4.4
Total quantities	3	3	0.0
Acquisition cycle time (months)	137	155	13.1

DDG 1000 Destroyer



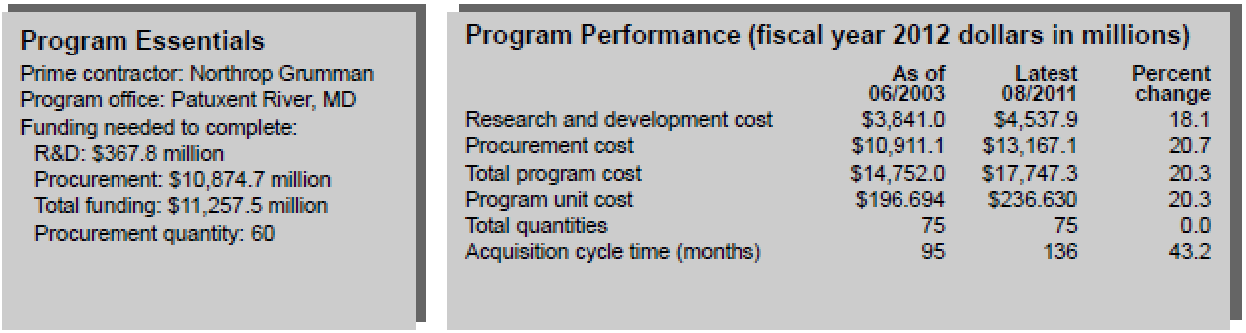
Program Essentials

Prime contractor: BAE Systems, Bath Iron Works, Huntington Ingalls Industries, Raytheon
Program office: Washington, DC
Funding needed to complete:
- R&D: $995.6 million
- Procurement: $1,418.1 million
- Total funding: $2,413.6 million
- Procurement quantity: 0

Program Performance (fiscal year 2012 dollars in millions)

	As of 01/1998	Latest 08/2011	Percent change
Research and development cost	$2,277.9	$10,378.4	355.6
Procurement cost	$32,522.1	$10,607.2	-67.4
Total program cost	$34,800.0	$20,985.6	-39.7
Program unit cost	$1,087.500	$6,995.214	543.2
Total quantities	32	3	-90.6
Acquisition cycle time (months)	128	222	73.4

E2-D Advanced Hawkeye



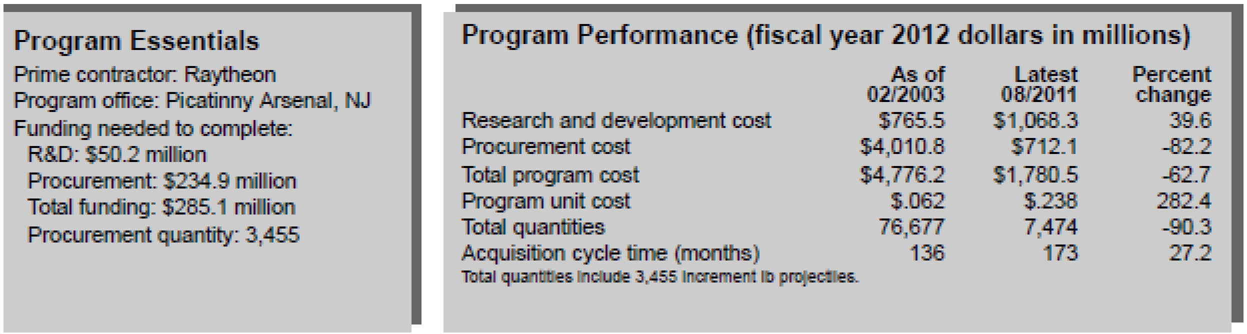
Program Essentials

Prime contractor: Northrop Grumman
Program office: Patuxent River, MD
Funding needed to complete:
- R&D: $367.8 million
- Procurement: $10,874.7 million
- Total funding: $11,257.5 million
- Procurement quantity: 60

Program Performance (fiscal year 2012 dollars in millions)

	As of 06/2003	Latest 08/2011	Percent change
Research and development cost	$3,841.0	$4,537.9	18.1
Procurement cost	$10,911.1	$13,167.1	20.7
Total program cost	$14,752.0	$17,747.3	20.3
Program unit cost	$196.694	$236.630	20.3
Total quantities	75	75	0.0
Acquisition cycle time (months)	95	136	43.2

Excalibur Precision Guided Artillery



Program Essentials

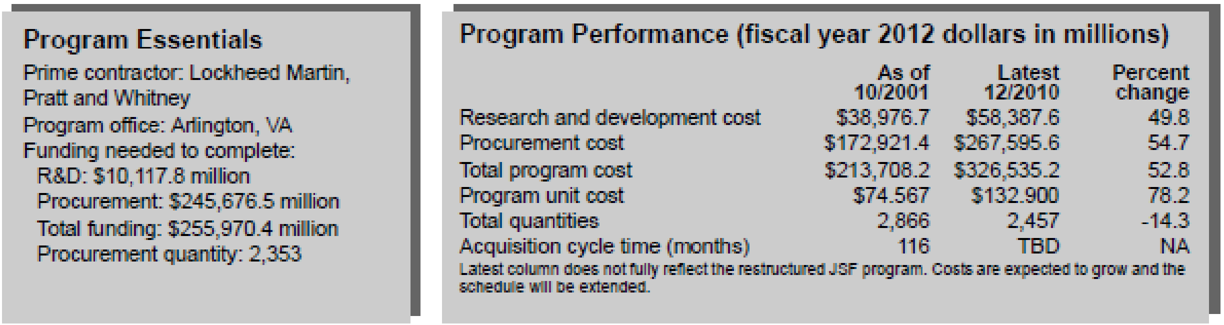
Prime contractor: Raytheon
Program office: Picatinny Arsenal, NJ
Funding needed to complete:
- R&D: $50.2 million
- Procurement: $234.9 million
- Total funding: $285.1 million
- Procurement quantity: 3,455

Program Performance (fiscal year 2012 dollars in millions)

	As of 02/2003	Latest 08/2011	Percent change
Research and development cost	$765.5	$1,068.3	39.6
Procurement cost	$4,010.8	$712.1	-82.2
Total program cost	$4,776.2	$1,780.5	-62.7
Program unit cost	$.062	$.238	282.4
Total quantities	76,677	7,474	-90.3
Acquisition cycle time (months)	136	173	27.2

Total quantities include 3,455 Increment Ib projectiles.

F-35 Lightning II



Program Essentials

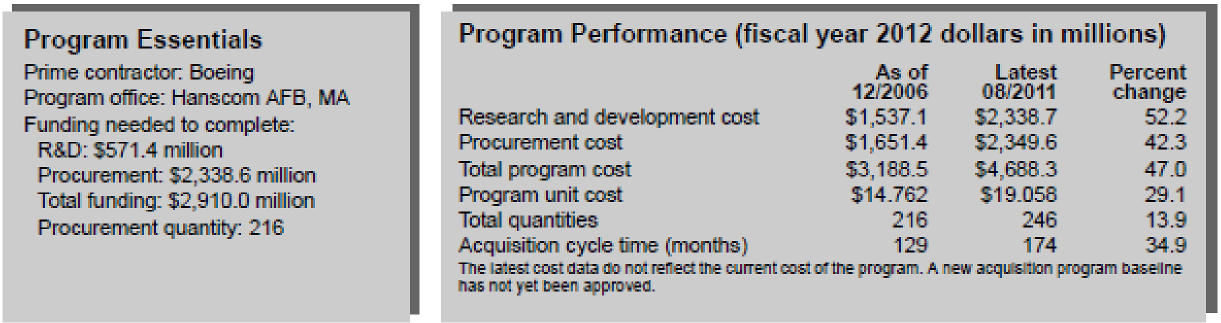
Prime contractor: Lockheed Martin, Pratt and Whitney
Program office: Arlington, VA
Funding needed to complete:
  R&D: $10,117.8 million
  Procurement: $245,676.5 million
  Total funding: $255,970.4 million
  Procurement quantity: 2,353

Program Performance (fiscal year 2012 dollars in millions)

	As of 10/2001	Latest 12/2010	Percent change
Research and development cost	$38,976.7	$58,387.6	49.8
Procurement cost	$172,921.4	$267,595.6	54.7
Total program cost	$213,708.2	$326,535.2	52.8
Program unit cost	$74.567	$132.900	78.2
Total quantities	2,866	2,457	-14.3
Acquisition cycle time (months)	116	TBD	NA

Latest column does not fully reflect the restructured JSF program. Costs are expected to grow and the schedule will be extended.

Family of Advanced Beyond Line of Sight Terminals (FAB-T)



Program Essentials

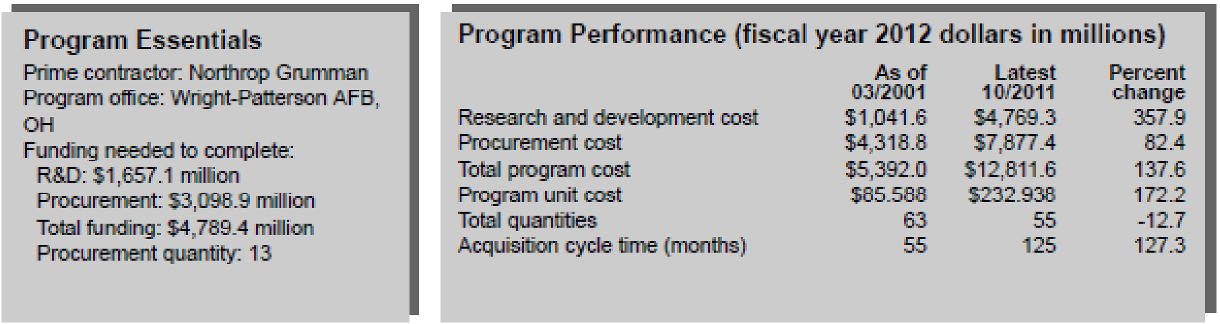
Prime contractor: Boeing
Program office: Hanscom AFB, MA
Funding needed to complete:
  R&D: $571.4 million
  Procurement: $2,338.6 million
  Total funding: $2,910.0 million
  Procurement quantity: 216

Program Performance (fiscal year 2012 dollars in millions)

	As of 12/2006	Latest 08/2011	Percent change
Research and development cost	$1,537.1	$2,338.7	52.2
Procurement cost	$1,651.4	$2,349.6	42.3
Total program cost	$3,188.5	$4,688.3	47.0
Program unit cost	$14.762	$19.058	29.1
Total quantities	216	246	13.9
Acquisition cycle time (months)	129	174	34.9

The latest cost data do not reflect the current cost of the program. A new acquisition program baseline has not yet been approved.

Global Hawk



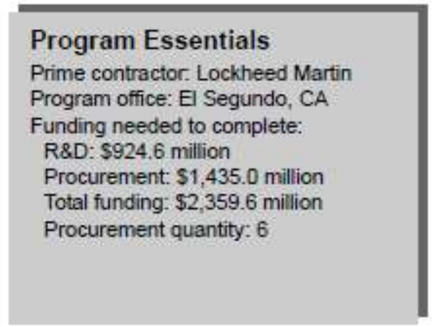
Program Essentials

Prime contractor: Northrop Grumman
Program office: Wright-Patterson AFB, OH
Funding needed to complete:
  R&D: $1,657.1 million
  Procurement: $3,098.9 million
  Total funding: $4,789.4 million
  Procurement quantity: 13

Program Performance (fiscal year 2012 dollars in millions)

	As of 03/2001	Latest 10/2011	Percent change
Research and development cost	$1,041.6	$4,769.3	357.9
Procurement cost	$4,318.8	$7,877.4	82.4
Total program cost	$5,392.0	$12,811.6	137.6
Program unit cost	$85.588	$232.938	172.2
Total quantities	63	55	-12.7
Acquisition cycle time (months)	55	125	127.3

Global Positioning System III



Program Essentials

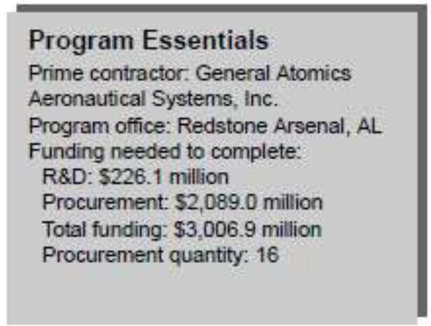
Prime contractor: Lockheed Martin
Program office: El Segundo, CA
Funding needed to complete:
R&D: $924.6 million
Procurement: $1,435.0 million
Total funding: $2,359.6 million
Procurement quantity: 6

Program Performance (fiscal year 2012 dollars in millions)

	As of 05/2008	Latest 08/2011	Percent change
Research and development cost	$2,524.2	$2,694.8	6.8
Procurement cost	$1,417.2	$1,515.8	7.0
Total program cost	$3,941.4	$4,210.6	6.8
Program unit cost	$492.672	$526.323	6.8
Total quantities	8	8	0.0
Acquisition cycle time (months)	NA	NA	NA

We could not calculate acquisition cycle times for the first increment of the GPS III program because initial operational capability will not occur until satellites from a future increment are fielded.

Gray Eagle UAV



Program Essentials

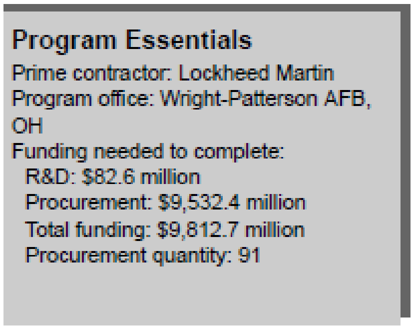
Prime contractor: General Atomics Aeronautical Systems, Inc.
Program office: Redstone Arsenal, AL
Funding needed to complete:
R&D: $226.1 million
Procurement: $2,089.0 million
Total funding: $3,006.9 million
Procurement quantity: 16

Program Performance (fiscal year 2012 dollars in millions)

	As of 04/2005	Latest 08/2011	Percent change
Research and development cost	$344.9	$946.2	174.4
Procurement cost	$670.4	$3,400.2	407.2
Total program cost	$1,015.2	$5,158.9	408.2
Program unit cost	$203.046	$166.416	-18.0
Total quantities	5	31	520.0
Acquisition cycle time (months)	50	TBD	NA

Total quantities include 31 platoon sets with 4 aircraft each. The program will also buy 21 aircraft to replace those lost through attrition and 7 training aircraft, for a total of 152.

HC-130/MC -130 Recapitalization Program



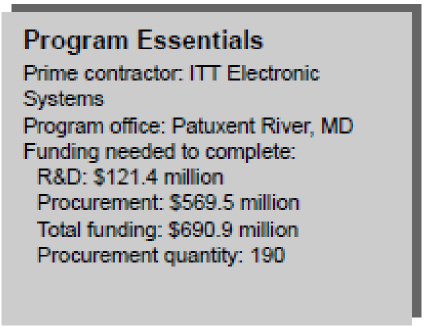
Program Essentials

Prime contractor: Lockheed Martin
Program office: Wright-Patterson AFB, OH
Funding needed to complete:
R&D: $82.6 million
Procurement: $9,532.4 million
Total funding: $9,812.7 million
Procurement quantity: 91

Program Performance (fiscal year 2012 dollars in millions)

	As of 03/2010	Latest 12/2010	Percent change
Research and development cost	$153.2	$152.8	-0.3
Procurement cost	$7,699.3	$12,621.9	63.9
Total program cost	$8,364.2	$13,090.8	56.5
Program unit cost	$113.029	$107.302	-5.1
Total quantities	74	122	64.9
Acquisition cycle time (months)	NA	NA	NA

IDECOM Block 4



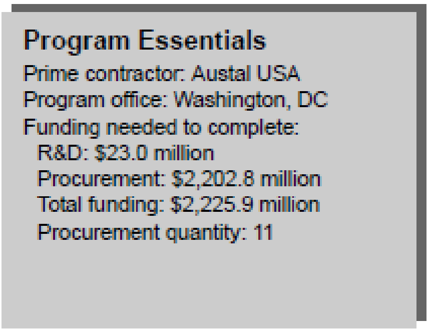
Program Essentials

Prime contractor: ITT Electronic Systems
Program office: Patuxent River, MD
Funding needed to complete:
R&D: $121.4 million
Procurement: $569.5 million
Total funding: $690.9 million
Procurement quantity: 190

Program Performance (fiscal year 2012 dollars in millions)

	As of 06/2008	Latest 10/2011	Percent change
Research and development cost	$220.2	$252.0	14.5
Procurement cost	$474.2	$569.5	20.1
Total program cost	$694.4	$821.5	18.3
Program unit cost	$4.340	$4.324	-0.4
Total quantities	160	190	18.8
Acquisition cycle time (months)	59	54	-8.5

Joint High-Speed Vessel



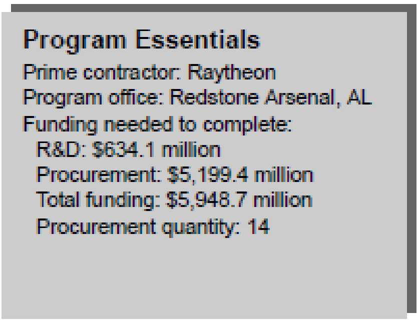
Program Essentials

Prime contractor: Austal USA
Program office: Washington, DC
Funding needed to complete:
R&D: $23.0 million
Procurement: $2,202.8 million
Total funding: $2,225.9 million
Procurement quantity: 11

Program Performance (fiscal year 2012 dollars in millions)

	As of 02/2009	Latest 12/2010	Percent change
Research and development cost	$128.4	$138.0	7.4
Procurement cost	$3,507.9	$3,536.1	0.8
Total program cost	$3,636.4	$3,674.1	1.0
Program unit cost	$202.020	$204.116	1.0
Total quantities	18	18	0.0
Acquisition cycle time (months)	48	50	4.2

Joint Land Attack Cruise Missile Defense



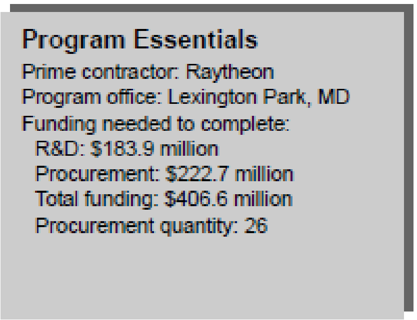
Program Essentials

Prime contractor: Raytheon
Program office: Redstone Arsenal, AL
Funding needed to complete:
R&D: $634.1 million
Procurement: $5,199.4 million
Total funding: $5,948.7 million
Procurement quantity: 14

Program Performance (fiscal year 2012 dollars in millions)

	As of 08/2005	Latest 12/2010	Percent change
Research and development cost	$2,005.5	$2,523.2	25.8
Procurement cost	$4,588.7	$5,199.4	13.3
Total program cost	$6,665.9	$7,857.8	17.9
Program unit cost	$416.619	$491.112	17.9
Total quantities	16	16	0.0
Acquisition cycle time (months)	97	103	6.2

Joint Precision Approach and Landing System



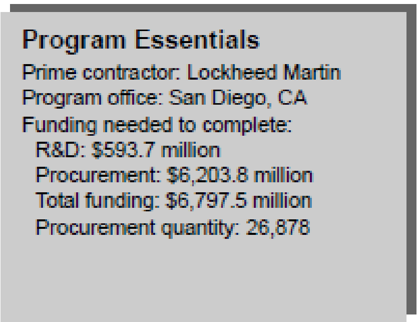
Program Essentials

Prime contractor: Raytheon
Program office: Lexington Park, MD
Funding needed to complete:
  R&D: $183.9 million
  Procurement: $222.7 million
  Total funding: $406.6 million
  Procurement quantity: 26

Program Performance (fiscal year 2012 dollars in millions)

	As of 07/2008	Latest 08/2011	Percent change
Research and development cost	$792.1	$753.5	-4.9
Procurement cost	$213.2	$222.7	4.4
Total program cost	$1,012.3	$983.3	-2.9
Program unit cost	$27.359	$26.575	-2.9
Total quantities	37	37	0.0
Acquisition cycle time (months)	75	77	2.7

Airborne and Maritime Joint Tactical Radio System



Program Essentials

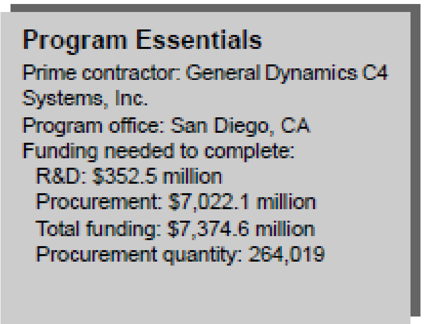
Prime contractor: Lockheed Martin
Program office: San Diego, CA
Funding needed to complete:
  R&D: $593.7 million
  Procurement: $6,203.8 million
  Total funding: $6,797.5 million
  Procurement quantity: 26,878

Program Performance (fiscal year 2012 dollars in millions)

	As of 10/2008	Latest 08/2011	Percent change
Research and development cost	$1,945.0	$1,957.0	0.6
Procurement cost	$6,209.0	$6,203.8	-0.1
Total program cost	$8,154.1	$8,160.8	0.1
Program unit cost	$.301	$.301	0.1
Total quantities	27,102	27,102	0.0
Acquisition cycle time (months)	80	91	13.8

The program office reported quantities in terms of channels rather than radios.

Joint Tactical Radio System Handheld



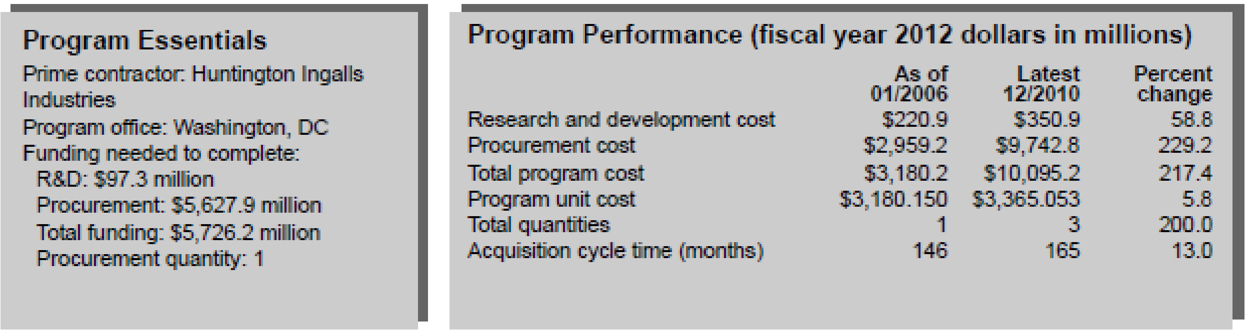
Program Essentials

Prime contractor: General Dynamics C4 Systems, Inc.
Program office: San Diego, CA
Funding needed to complete:
  R&D: $352.5 million
  Procurement: $7,022.1 million
  Total funding: $7,374.6 million
  Procurement quantity: 264,019

Program Performance (fiscal year 2012 dollars in millions)

	As of 05/2004	Latest 11/2011	Percent change
Research and development cost	$544.7	$1,272.3	133.6
Procurement cost	$9,492.8	$7,085.7	-25.4
Total program cost	$10,037.5	$8,357.9	-16.7
Program unit cost	$.031	$.031	1.0
Total quantities	328,674	270,951	-17.6
Acquisition cycle time (months)	85	104	22.4

LHA Replacement Amphibious Assault Ship



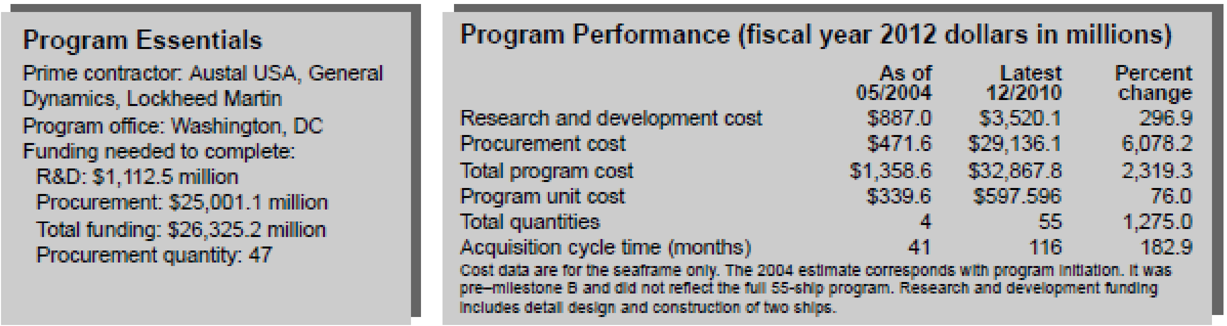
Program Essentials

Prime contractor: Huntington Ingalls Industries
Program office: Washington, DC
Funding needed to complete:
R&D: $97.3 million
Procurement: $5,627.9 million
Total funding: $5,726.2 million
Procurement quantity: 1

Program Performance (fiscal year 2012 dollars in millions)

	As of 01/2006	Latest 12/2010	Percent change
Research and development cost	$220.9	$350.9	58.8
Procurement cost	$2,959.2	$9,742.8	229.2
Total program cost	$3,180.2	$10,095.2	217.4
Program unit cost	$3,180.150	$3,365.053	5.8
Total quantities	1	3	200.0
Acquisition cycle time (months)	146	165	13.0

Littoral Combat Ship



Program Essentials

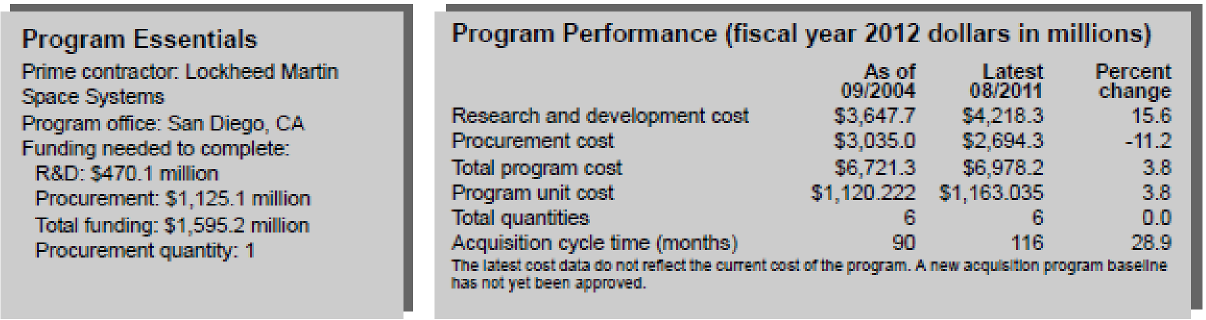
Prime contractor: Austal USA, General Dynamics, Lockheed Martin
Program office: Washington, DC
Funding needed to complete:
R&D: $1,112.5 million
Procurement: $25,001.1 million
Total funding: $26,325.2 million
Procurement quantity: 47

Program Performance (fiscal year 2012 dollars in millions)

	As of 05/2004	Latest 12/2010	Percent change
Research and development cost	$887.0	$3,520.1	296.9
Procurement cost	$471.6	$29,136.1	6,078.2
Total program cost	$1,358.6	$32,867.8	2,319.3
Program unit cost	$339.6	$597.596	76.0
Total quantities	4	55	1,275.0
Acquisition cycle time (months)	41	116	182.9

Cost data are for the seaframe only. The 2004 estimate corresponds with program initiation. It was pre–milestone B and did not reflect the full 55-ship program. Research and development funding includes detail design and construction of two ships.

Mobile User Objective System



Program Essentials

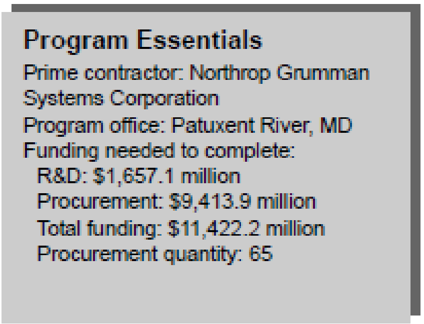
Prime contractor: Lockheed Martin Space Systems
Program office: San Diego, CA
Funding needed to complete:
R&D: $470.1 million
Procurement: $1,125.1 million
Total funding: $1,595.2 million
Procurement quantity: 1

Program Performance (fiscal year 2012 dollars in millions)

	As of 09/2004	Latest 08/2011	Percent change
Research and development cost	$3,647.7	$4,218.3	15.6
Procurement cost	$3,035.0	$2,694.3	-11.2
Total program cost	$6,721.3	$6,978.2	3.8
Program unit cost	$1,120.222	$1,163.035	3.8
Total quantities	6	6	0.0
Acquisition cycle time (months)	90	116	28.9

The latest cost data do not reflect the current cost of the program. A new acquisition program baseline has not yet been approved.

MQ-4C BAMS UAV



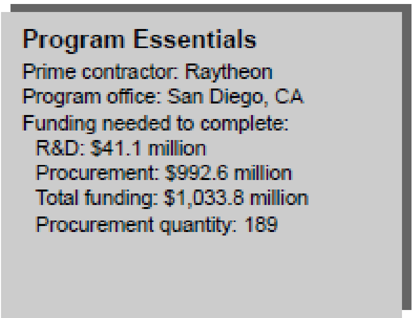
Program Essentials

Prime contractor: Northrop Grumman Systems Corporation
Program office: Patuxent River, MD
Funding needed to complete:
  R&D: $1,657.1 million
  Procurement: $9,413.9 million
  Total funding: $11,422.2 million
  Procurement quantity: 65

Program Performance (fiscal year 2012 dollars in millions)

	As of 02/2009	Latest 12/2010	Percent change
Research and development cost	$3,141.7	$3,245.6	3.3
Procurement cost	$9,323.4	$9,413.9	1.0
Total program cost	$12,847.6	$13,052.4	1.6
Program unit cost	$183.537	$186.463	1.6
Total quantities	70	70	0.0
Acquisition cycle time (months)	92	92	0.0

Navy Multi-band Terminal



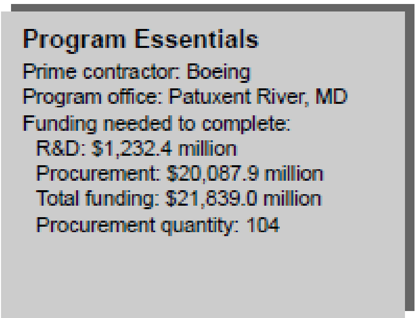
Program Essentials

Prime contractor: Raytheon
Program office: San Diego, CA
Funding needed to complete:
  R&D: $41.1 million
  Procurement: $992.6 million
  Total funding: $1,033.8 million
  Procurement quantity: 189

Program Performance (fiscal year 2012 dollars in millions)

	As of 12/2006	Latest 08/2011	Percent change
Research and development cost	$697.2	$666.2	-4.4
Procurement cost	$1,623.7	$1,214.4	-25.2
Total program cost	$2,321.0	$1,880.7	-19.0
Program unit cost	$6.970	$6.186	-11.2
Total quantities	333	304	-8.7
Acquisition cycle time (months)	107	107	0.0

P-8A Poseidon



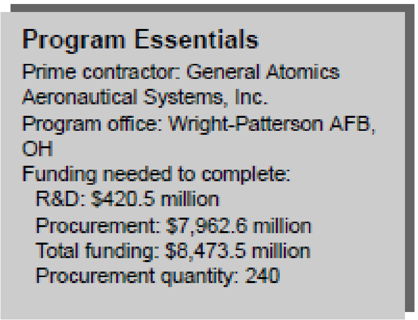
Program Essentials

Prime contractor: Boeing
Program office: Patuxent River, MD
Funding needed to complete:
  R&D: $1,232.4 million
  Procurement: $20,087.9 million
  Total funding: $21,839.0 million
  Procurement quantity: 104

Program Performance (fiscal year 2012 dollars in millions)

	As of 05/2004	Latest 08/2011	Percent change
Research and development cost	$7,531.5	$8,215.3	9.1
Procurement cost	$23,365.2	$24,157.2	3.4
Total program cost	$31,034.3	$32,969.3	6.2
Program unit cost	$269.864	$270.240	0.1
Total quantities	115	122	6.1
Acquisition cycle time (months)	160	160	0.0

Reaper UAV



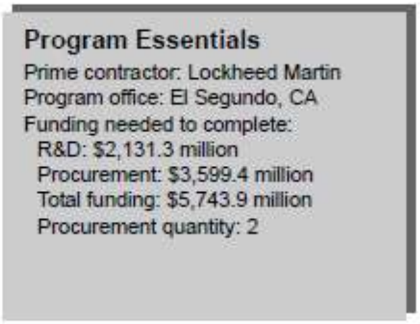
Program Essentials

Prime contractor: General Atomics Aeronautical Systems, Inc.
Program office: Wright-Patterson AFB, OH
Funding needed to complete:
R&D: $420.5 million
Procurement: $7,962.6 million
Total funding: $8,473.5 million
Procurement quantity: 240

Program Performance (fiscal year 2012 dollars in millions)

	As of 02/2008	Latest 08/2011	Percent change
Research and development cost	$420.1	$920.3	119.1
Procurement cost	$2,111.5	$10,848.3	413.8
Total program cost	$2,637.1	$11,918.7	352.0
Program unit cost	$25.115	$29.871	18.9
Total quantities	105	399	280.0
Acquisition cycle time (months)	79	94	19.0

Space-based Infrared System Program



Program Essentials

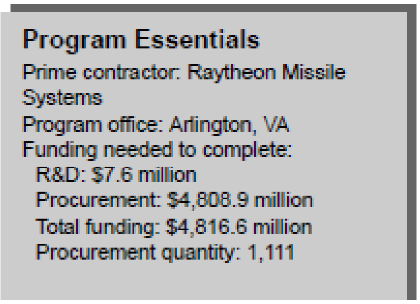
Prime contractor: Lockheed Martin
Program office: El Segundo, CA
Funding needed to complete:
R&D: $2,131.3 million
Procurement: $3,599.4 million
Total funding: $5,743.9 million
Procurement quantity: 2

Program Performance (fiscal year 2012 dollars in millions)

	As of 10/1996	Latest 07/2011	Percent change
Research and development cost	$4,376.3	$11,586.3	164.7
Procurement cost	$0.0	$6,429.3	NA
Total program cost	$4,596.5	$18,266.7	297.4
Program unit cost	$919.301	$3,044.443	231.2
Total quantities	5	6	20.0
Acquisition cycle time (months)	86	TBD	NA

The 1996 data show no procurement cost as the Air Force planned to use research and development funds to buy all five satellites. The cost of the two HEO replenishment sensors is not included in either column.

Standard Missile 6 ERAM



Program Essentials

Prime contractor: Raytheon Missile Systems
Program office: Arlington, VA
Funding needed to complete:
R&D: $7.6 million
Procurement: $4,808.9 million
Total funding: $4,816.6 million
Procurement quantity: 1,111

Program Performance (fiscal year 2012 dollars in millions)

	As of 07/2004	Latest 12/2010	Percent change
Research and development cost	$1,073.8	$973.5	-9.3
Procurement cost	$4,626.4	$5,323.2	15.1
Total program cost	$5,700.2	$6,296.7	10.5
Program unit cost	$4.750	$5.247	10.5
Total quantities	1,200	1,200	0.0
Acquisition cycle time (months)	75	94	25.3

IV. NEXT STEPS

The most pressing need in this research is access to information on completed programs that will help characterize the connection between some definitions of complexity and the post hoc prediction/realization of technical risk.

In addition, we shall pursue more case studies, more literature, and more methods of characterizing complexity of products and organizations, including interviewing acknowledged experts.

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APPENDIX A: LITERATURE REVIEW ON SYSTEM COMPLEXITY AND RISK

This section provides a summary and synthesis of findings from a survey of the literature on system complexity and cost, schedule and performance risk in engineering development programs. Several relevant and exemplar papers discussed in detail.

The survey was restricted to publically-accessible, freely-available documents via the Internet found by searching on combinations of the keywords “complexity”, “complex”, “complicated”, “risk”, “uncertainty”, “overrun”, “slip”, “shortfall”, “cost”, “schedule”, “performance”, “acquisition”, “development”, “engineering”, “engineered”, “technical”, “quantitative”, “indicators”, “factors”, “modular”, “adaptive”, “adaptable”, “system”, “model”, “architecture”, “analysis”, and “assessment”. From over 2,000 web sites visited, approximately 600 articles were reviewed. Roughly three-quarters focused on risk in system acquisition, with some reference to system complexity. The remaining quarter focused on complexity of engineered systems, with some reference to development.

A.1 SUMMARY OF FINDINGS

This section summarizes both what was found in the literature, and what was notable by its absence.

Many papers asserted that increased complexity was correlated with increased development time and cost. Data and evidence supporting this intuitive claim was sparse. Most of the papers were theoretical, often using a “toy” system model to illustrate the methods, but did not provide evidence that their complexity metrics

(1) could be evaluated from data on DoD systems available during their development,

(2) were good predictors of development time and cost, or

(3) were predictors of cost increase, schedule slip or performance shortfall.

Of the half-dozen articles that applied complexity metrics to acquisition program data and analyzed the relationship to cost and schedule, there were only three distinct analyses. A series of papers by the same authors analyzed from different perspectives one set of Major Defense Acquisition Program (MDAP) data provided by OSD. The final report by the Boeing team on the DARPA META II program analyzed data from two different divisions of the Boeing Corporation. A PhD thesis out of the Air Force Institute of Technology analyzed an aircraft avionics data set. These papers are reviewed in detail.

The papers on complexity addressed the complexity of the system design, but did not specify the appropriate level of architecture and design data for analysis. This begs the question of whether the design information is available early enough in the acquisition process to guide architecture and design decision. The papers using the MDAP data provided by OSD, used Systems Engineering artifacts produced at Milestone B.

Many of the articles on acquisition risk identified the turbulence in the system requirements and interdependencies among the requirements (either antagonistic or synergistic) as sources of delay, cost increase, time and cost uncertainty. It is possible that complexity analysis could be applied to the network of requirements (or, more generally the system baseline, which consists of the capability needs, the system requirements, system functional decomposition and requirements), and to the change in the baseline over time. This might provide useful and timely insights into acquisition risk and complexity of the system baseline. These data are available to the acquisition Program Manager’s Office, are developed over time, and could potentially benefit from feedback. No analyses of requirements or system baseline complexity and/or change in complexity were found in the literature.

The term "complexity" was not used consistently throughout the literature. Many of the papers, especially those focused primarily on development risk, used the terms "complex" and "complicated" interchangeably, generally meaning "systems with lots distinct parts and lots of connections among the parts." The papers focusing primarily on the complexity of engineered systems used a variety of descriptions and definitions of complexity. A number of the papers distinguished between "structural complexity" and "dynamic complexity".

"Structural complexity" was used to refer to complexity in the architecture of the system. Structural complexity was commonly based on a graph of nodes (processors) and links (interfaces) representing the system architecture. Metrics ranged from simple counts of the number of links and nodes (similar to the measures of "complicated" systems), to refinements using algebraic network analysis of interconnectedness. Some of the approaches distinguished between the number of instances of a type of node and the number of distinct types of nodes. Some distinguished between uni-directional and bi-directional interfaces.

"Dynamic complexity" refers to the behavior or response of the system (e.g., states and transitions). The term was used variously to refer to systems exhibiting adaptive response to external states, non-linear change in response depending on internal state, adaptive response to internal states, self-organization, cascading effects, unexpected responses, or "emergent behavior". The dynamic complexity metrics require a model of the system behavior and response. Many of the papers discussing dynamic complexity did not present computational metrics. Some papers used a system state transition diagram model of the system dynamics, then applied analysis methods similar to those used for architecture structure graph complexity.

Some of the papers distinguished between observable complexity in the system model, and hidden complexity within nodes and links. Some of the papers distinguished between complexity inherent in the system design, and apparent complexity due to incomplete models, incomplete analysis, and incomplete characterization of the boundary conditions. These distinctions are related to the unresolved issue of selecting the granularity or level of resolution of the system description, i.e., the level or scope of components or subsystem to represent as distinct nodes. There is a tradeoff between the size of the model, and risk of errors in the model, versus errors due to ignorance of the behavior, response, and internal states of nodes and links. None provided guidelines for determining the appropriate level of granularity for analysis.

State transition diagrams to analyze dynamic complexity suffer from combinatorial explosion. A network with 5 nodes and 5 links, where each node and link has two possible states (e.g., busy and not busy, or operative and not operative, at capacity or below capacity), has 1024 possible states (2 to the 10th power), and over 1,000,000 possible state transitions (1024 squared minus 1024). Complexity analysis requires determining which states the system can actually occupy, and which transitions it can experience. Reducing the level of granularity to limit the size of the model increases the "hidden" complexity.

Most of the complexity metrics relied on a node-and-link graph representations of the system in which nodes perform processes, and interfaces exchange data, energy, material, physical position, etc. between nodes. Processors and interfaces have performance properties beyond being logical nodes and links in a graph: capacity, latency, noise, losses, etc. When there is sufficient design margin (reserve capacity) so that there is negligible risk that the component or interface is overloaded or non-operative, then it may be possible to omit the node or link and its internal states from the analysis. When there is non-negligible risk, then the node or link and its internal states should be included in the analysis.

An important class of interfaces not addressed in the papers is insulators and isolators whose purpose is to *prevent* exchange of force, energy, signals, etc. between nodes and between links (e.g., prevent cross-talk, short-circuits, vibration transfer, thermal degradation, etc.). Failure of insulators and isolators, or temporary failure when they reach their excursion limit, create short circuits that can radically change the response of the system.

A widely used approach to compute graph complexity involved the "graph energy", computed from the eigenvalues of the adjacency matrix representing the graph of either the architecture structure or the state transition diagram. Closed-form calculation of the graph energy is only possible for simple graphs, e.g., trees structures without loops or lattice structures. Research on robust methods to estimate the approximate graph energy for arbitrary graphs is an area of on-going research.

A less widely adopted approach to complexity was to use a measure of the information content in a minimal, irreducible, specification of the system model.

Axiomatic Design provides an alternative view of complexity in terms of the probability that the system can perform the functions required of it at any given time. Axiomatic Design focusses on the relationship between system structure and functions. In principle, it addresses the frequency and duration of functions, and multiple simultaneous functions.

Axiomatic Design suggests approaches to understand the modularity inherent in a design, either by modules associated with overlapping functions, or block-diagonal modularization to minimize interfaces between blocks. Several papers contained analytic approaches or metrics incorporating modularity into the complexity metrics. There is a small body of literature on multi-scale complexity, but it is oriented towards biological organisms, not engineered systems.

A.2 REVIEWS OF SELECTED PAPERS AND PRESENTATIONS

This section contains reviews of all of the papers and presentations analyzing the relationship of complexity to cost and schedule performance (beginning with the three analyzing the OSD MDAP data set), followed by reviews of selected papers exemplify major issues and approaches in complexity metrics for engineered systems. The reviews are organized under the following topics:

- Systems complexity and development risk
- Structural and dynamic complexity metrics from graph complexity
- Modularity considerations and metrics in system complexity
- Axiomatic Design approach to complexity
- Functional and contextual complexity
- Apparent complexity in flight software
- Adaptability metrics to measure complexity
- Aspects of complexity in design

A.2.1 SYSTEM COMPLEXITY AND DEVELOPMENT RISK

Programmatic and Constructive Interdependence: Emerging Insights and Predictive Indicators of Development Resource Demand, M. Kasunic, M.M. Brown, P.L. Hardin, J.M. McCurley, 2010

http://repository.cmu.edu/cgi/viewcontent.cgi?article=1008&context=sei

Kasunic et al [1] describe a series of research efforts investigating the role of interdependence in the acquisition of Major Defense Acquisition Programs (MDAPs). The research initiative was sponsored by the Office of the Secretary of Defense (OSD). The overall goal of the research was to identify, quantify, and assess the degree of programmatic and constructive interdependence and to assess the effects of interdependence on program risk. The report summarizes the results of five research studies that were conducted from 2004 to 2009.

Study 1 explored the qualitative factors that confound program cost and schedule estimation. The study identified specific risk indicators related to requirements, institutional factors, sustainment, and team performance.

Study 2 employed data-mining and statistical analyses to determine whether Defense Acquisition Executive Summary (DAES) reports and Select Acquisition Reports (SARs) can be used to forecast program performance. An interesting result from this study is that there was no evidence that such indicators are effective in predicting program breaches.

Studies 3-5 employed network analysis techniques to quantitatively characterize programmatic and constructive interdependencies in the acquisition enterprise. These last three studies culminated in graphical models that relate interdependence and program cost. The research study found no evidence that indicators reported within DAES reports or SARs predict program breach events.

Simple Parametric Model For Estimating Development (RDT&E) Costs for Large-Scale Systems, R.R. Jones, P. Hardin, A. Irvine, 2005

http://www.technomics.net/files/downloads/papers/ISPASCEA0609-Parametric.pdf

Jones, Hardin and Irvine [2] analyzed data provided by OSD(AT&L). The sponsor provided data on 21 Major Defense Acquisition Programs (MDAPs). The data included the initial RDT&E cost estimates from Selected Acquisition Reports (SARs), and architecture structure metrics calculated from DoDAF SV-6 architecture views: numbers of send-only nodes, receive-only nodes, send-and-receive nodes, all nodes, one-way links, two-way links, and all links. The analysis of the relationship between the total number of nodes and the total number of links showed a strong linear correlation, with one noticeable outlier. The analysis initial RDT&E cost showed a strong correlation with the square of the number of links. The data clustered into three groups (a large number of data points with low cost and low number of links, three points with mid-range cost and number of links, and one point with high cost and number of links), so from a statistical analysis view, there were only three distinct data points. The authors found a complicated non-linear formula relating cost to the architecture structure metrics with almost perfect correlation. However the number of implicit and explicit parameter exceeded the statistically significant degrees of freedom in the data set as analyzed. Regardless of the statistical details, the report presents system architecture metrics derived from required artifacts (DoDAF SV-6 architecture is required prior to Milestone B), with strong correlation to RDT&E cost.

The sponsoring agency was kind enough to provide the SERC with the original data, updated to include the RDT&E cost estimates as of 2008. We re-analyzed the data, with care not to “over-fit.” We conducted a bootstrap analysis (replicated random partitions of the data into “training/calibration” and “test/evaluation” data sets). Analysis in log-log space showed a strong linear correlation between the initial RDT&E cost estimates and the number of links in the DoDAF SV-6 diagrams. In log-log space, the RDT&E cost estimates and the number of links were nicely distributed over their range. The dispersion about the linear fit provided an estimate in the uncertainty (error) between initial RDT&E estimates and predictions from the number of links. These results showed that 70-percent of the variance in the logarithm of the initial estimates of RDT&E cost in one data set was predicted by (a) the logarithm of the number of links, and (b) the linear relationship between the logarithm of initial RDT&E cost estimates and logarithm of the number of links derived from a sequestered data set.

No relationship in the change in RDT&E costs from the initial estimates and the 2008 RDT&E cost estimate bore any relationship to the architecture parameters. Since the programs were started at different times and on different schedules, the programs developments from inception to 2008 were not samples from the same population. The DoDAF SV-6 diagrams and architecture data were not updated.

Programmatic Complexity & Interdependence: Emerging Insights and Predictive Indicators of Development Resource Demand, R. Flowe, M. Brown, P.L. Hardin, 2000

http://acquisitionresearch.net/_files/FY2009/NPS-AM-09-058.pdf

Flowe, Brown and Hardin [3] prepared report for the Defense Science Board addressing the effects of technical interdependence among programmatically-independent acquisitions, whether explicit as in Systems-of-Systems, or implicit. The report finds that interdependencies have non-linear scaling effects that are not captured in technical development and integration cost estimates. The research used data extracted from formal program documentation including Defense Acquisition Executive Summary (DAES) Charts, Selected Acquisition Reports (SARs), Budget Item Justification Exhibits, Information Support Plans (ISPs), etc. The research analyzed dependencies of MDAP programs on other MDAP programs and on non-MDAP programs that were not required to report program status. The report presented a network diagram program interdependence and cost growth of the MDAPs, but did not quantitatively analyze the data.

The network consisted of 21 MDAPs, 162 non-MDAP programs, 10 direct dependencies between MDAPS, and 257 dependencies of MDAPs on non-MDAP programs. On average, an MDAP program had 13 external dependencies (one to another MDAP program, and 12 to non-MDAP programs). 78-percent of the non-MDAP programs had exactly one dependent MDAP; the remaining 22-percent had, on average, 2.6 dependent MDAPs.

The fourteen MDAPs with less than 50% cost growth had an average of 11 external dependencies (sample standard deviation of 4), while the seven MDAPs with more than 50% cost growth had an average of 17 external dependencies (sample standard deviation of 7). The difference suggests that more external dependencies was correlated with greater cost overrun, but the statistical confidence is low due to the large variance.

Impact of weapon system complexity on systems acquisition, R.A. Dietrick, 2006

http://dtlweb.au.af.mil///exlibris/dtl/d3_1/apache_media/L2V4bGlicmlzL2R0bC9kM18xL2FwYWNoZV9tZWRpYS81MDk3Nw==.pdf

In his PhD thesis, Dietrick [4] used the number interactions among components as the theoretical complexity metric. Interactions include space, energy, information, and material exchange. Due to the difficulty in counting the actual interactions among system components, as a practical metric the paper uses the theoretical upper bound on the number of interactions among components as the practical measure. The upper bound is N(N-1)/2 where N is the number of components. The paper acknowledges that the level of resolution to identify components will affect the results, and comparison across systems required analysis at the same level of resolution. It does not consider modularity and hierarchical organization.

The thesis presents empirical data for USAF aircraft showing: (1) increase of complexity with increase of year of operating capability, (2) increase of development time with year of operating capability, and (3) increase of development cost with increase of development time. The thesis does not directly analyze system development time or cost as function of complexity on an individual system basis. The thesis provides an analysis of trends, not an analysis of systems. The paper does not address cost increase, schedule slip, or performance shortfall.

META II Complexity and Adaptability Final Report, D. Stuart, R. Mattikalli, D. DeLaurentis, J. Shah, 2011

http://www.darpa.mil/uploadedFiles/Content/Our_Work/TTO/Programs/AVM/Boeing%20META%20Final%20Report.pdf

The Boeing team's final report on complexity and adaptability metrics for the DARPA META program (Stuart et al [5]) took an investigative, opportunistic and integrated approach. They did not pursue a sequence of first developing a theory or computational model of complexity, then seeking data to evaluate metrics, then seeking data on cost and schedule, then testing the ability of the model/metric to explain the variance in cost and schedule. Instead, the team identified 28 already-defined factors with potential value in a complexity metric, that could be evaluated from available system architecture data. Calculation methods for each of the inputs are included in the report. The identified two sources of aircraft program data (Boeing Commercial Aircraft, BCA, and Boeing Defense Systems, BDS) for which system architecture data, cost data and schedule data were available (peak labor was used as a proxy for cost). Armed with this data, the team conducted a "combinatorial search" for combinations of input terms models to explain the variances in peak labor and in schedule, using regression to estimate the coefficients, including linear and logarithm operations on the inputs, additive and multiplicative relationships. The models that were finally selected contained up to six terms.

The report noted that significant manual effort was required to extract the architecture data for the BDS programs, including interviews with the chief engineers. The BCS data were extracted from an automated project management system. The sample size was approximately 15 BCA projects and 15 BCD projects. The modeling was conducted separately for the BCA and BCD projects, presumably because the team suspected differences due to the type of project and data sources. Not only did the coefficients for the models differ between the two data sets, but different inputs and functional forms ended up being selected.

"Combinatorial search" modeling is at risk of using up the degrees of freedom in the data, unless the sample size is large. There were 28 inputs, with the option of taking logarithm or squaring for each, and the options of mixed addition and multiplication, there were many more possible models than the sample size supported. The report acknowledges the sample size issue.

The team could have used bootstrap or similar techniques to examine the stability and validity of the models. They did not randomly divide the data into a pair of disjoint groups, apply the process to the different groups to test if the same input parameters were selected for both groups. Ideally, in this model development approach, iterative replication of the following steps are used to develop and justify the model: (1) divide the population into three groups, (2) use the first group to select the input terms and non-linear functions of the model, (3) use the second group to estimate the values of the coefficients, and (4) use the third group to evaluate the explanatory power of the model. This process is repeated with different random partitions to analyze the stability and validity of the modeling results.

A.2.2 STRUCTURAL AND DYNAMIC COMPLEXITY METRICS FROM GRAPH COMPLEXITY

Meta II Complex Systems Design and Analysis (CODA) Final Report, B. T. Murray, A. Pinto, R. Skelding, O. de Weck, H. Zhu, S. Nair, N. Shougarian, K. Sinha, S. Bopardikar, and L. Zeidner, 2011

http://www.dtic.mil/dtic/tr/fulltext/u2/a552676.pdf

Murray et al [6] reported on the United Technologies team results on the DARPA META II program. The report covers all aspects of the United Technologies effort on the program. Section 3.16, "Complexity and Adaptability Metrics in Design" is particularly relevant. The project did not apply the methods to real systems or attempt to investigate their ability to explain cost, schedule, overruns and slippage. This paper was selected to review as an exemplar of the architecture graph analysis methods.

The technical approach used a "graph" model of the system, i.e., a model consisting of nodes and interfaces (information, energy, force, momentum, data, signals, fluids, positional relationship, etc. exchanged between nodes). For computational purposes, the graph is represented by the Design Structure Matrix (DSM): one row and column for each node, a one in the matrix if there is an interface from the row node to the column node, zero otherwise, and zero on the diagonal. A simplified, non-directional versions of the DSM is the association matrix: one row and column for each node, a one in the matrix if there is an interface in either direction between the row node to the column node, zero otherwise, and zero on the diagonal.

Structural complexity refers to the complexity of connections between subsystems. The proposed metric was the number of components plus the product of the number of interfaces times the "Graph Energy". Graph Energy is computed from the adjacency matrix, a non-directional simplification of the DSM, has a one in each cell if the row node and column node have an interface in either direction, and zero otherwise. For simple graphs, i.e., tree structures without loops, the Graph Energy is computed as the sum of the absolute values of the eigenvalues of the adjacency matrix. In very simple geometries, loops can be isolated are treated as a single node. In complex geometries, e.g., multiple input and output nodes within loops, nested loops, intersecting loops, etc. other computational means are needed, such as Gibbs sampling, the elimination algorithm, and belief propagation. These methods are approximate and not guaranteed to converge.

Dynamic complexity refers to the complexity of connections between transient states of the system. Instead of analyzing the links between nodes of the system architecture, dynamic entropy examines links between states of the system. The state of the system is a vector with an element for each node and link. Two states are connected if there is a single event that will cause the system to transition from one state to the other. Dynamic complexity is computed in the same manner as structural complexity, except applied to the state association matrix: the number of states plus the number of state transitions times the graph energy of the state association matrix.

The SVD calculation of graph energy works only for simple graphs, i.e., systems without feedback loops. Other methods computational methods are needed to estimate the graph energy for arbitrary graphs, and specifically for systems with nested and intersecting feedback loops.

A.2.3 MODULARITY CONSIDERATIONS AND METRICS IN SYSTEM COMPLEXITY

Degree of Modularity in Engineering Systems and Products with Technical and Business Constraints, K. Holtta-Otto and O. de Weck, 2007

http://strategic.mit.edu/docs/2_19_CERA_15_2_113.pdf

Holtta-Otto and de Weck [7] present a structural modularity metric and "packing factor" metric to complement structural complexity metrics (such as the number of nodes plus the number of links times the graph energy). The graph energy measures the total system connectivity. The goal of the modularity index is to measure the concentration of connectivity. The idea behind the modularity index is that important information describing system connectivity is concentrated in the subset of components that are highly connected across the network. The modularity index is an attempt to measure connectivity concentration.

The structural modularity metric is derived from the SVD of the adjacency metric, as is the graph energy. The graph energy is the sum of the absolution values in the SVD. Since the SVD is a diagonal matrix, it can be collapsed to a vector, and sorted in decreasing order of absolute value. The authors use exponential decay as a model of the decrease in sorted absolute value SVD elements. The structural modularity metric is derived from the estimated rate of decay. Other measures of concentration that do not assume an exponential decay could be formulated to measure the concentration of magnitudes in the SVD. The authors show how the modularity in structural modularity metric dex discriminates among several architectures with equal numbers of nodes, links and graph energy.

Using the SVD to compute the structural modularity metric has the same drawback as using the SVD to compute graph energy: it only works for "simple" graphs – tree structures without loops. The authors do not propose an approach to compute the metric for arbitrary graphs.

The authors also propose "packing density" as a modularity metric to complement the structural modularity metric. The packing density metric is the ratio of the sum of the volume of space needed for each component to operate (including space to move, as appropriate) divided by the total volume of the system. A similar metric could be generated for weight and other cumulative constraints. The packing density metric does not account for systems that share space (one moves out as the other moves in; since the motion is coordinated, presumably these are considered to be one component).

A.2.4 AXIOMATIC DESIGN APPROACH TO COMPLEXITY

Complexity Theory in Axiomatic Design, T. Lee, 2003

http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.135.4528&rep=rep1&type=pdf

Lee's PhD thesis [8] was selected for review because it presents a principled approach that expands the notion of complexity as a function of the structure and dynamics of a system to include the functions of the system.

The complexity concept in axiomatic design theory is defined as a measure of the likelihood of not achieving a desired set of functional requirements. In this thesis, four different types of complexity are identified in axiomatic design complexity theory: time-independent real complexity, time-independent imaginary complexity, time-dependent combinatorial complexity and time-dependent periodic complexity. Time-independent real complexity is equivalent to the information content, which is a measure of a probability of achieving functional requirements. Time-independent imaginary complexity is defined as the uncertainty due to ignorance of the interactions between functional requirements and design parameters. Time-dependent complexity consists of combinatorial complexity and periodic complexity, depending on whether the uncertainty increases indefinitely or occasionally stops increasing at certain point and returns to the initial level of uncertainty. In this thesis, existing definitions for each of the types of complexity are further elaborated with a focus on time-dependent complexity. In particular, time-dependent complexity is clearly defined using the concepts of time-varying system ranges and time-dependent sets of functional requirements.

The Axiomatic Design model is that a Design Matrix (DM) specifies how the Design Parameters (DP) are related to the Functional Requirements (FR). The FR are input to the design process, the DP are output. The axioms (or principles) of Axiomatic Design are:

- Independence Axiom: Maintain the independence of functional requirements
- Information Axiom: Minimize the information content.

Information content is defined as the negative probability of achieving the functional requirements over the range of conditions. The paper defines real complexity as sensitivity of the information content to changes in Functional Requirements, and imaginary complexity as uncertainty in DP values, due to uncertainty in FR and DM.

A.2.5 FUNCTIONAL AND CONTEXTUAL COMPLEXITY

The mathematics of IT simplification, R. Sessions, 2011

https://dl.dropboxusercontent.com/u/97323460/WebDocuments/WhitePapers/MathOfITSimplification-103.pdf

Sessions [9] addresses functional complexity (as opposed to structural or dynamic complexity). The paper suggests that functional complexity has two complementary components: internal functional complexity and external coordination complexity. The goal of the paper is to develop principles to partition a system to simplify development. The approach is inherently hierarchical and can be applied to hierarchical partitioning or embedding systems. The paper does not explicitly relate the metrics to development risk.

In principle the paper takes two views of the system: as a stand-alone system, and as an integral component of a system-of-systems. Internal functional complexity is a measure of complexity as a stand-alone system. External coordination complexity is a measure of complexity of the role in a system of systems. The fundamental difference is the perspective, not the computational method. Analogous methods are applied in both perspectives.

The approach computes complexity as the number of interactions of states of a system over the system functions. The number of states of a system computed from the number of variables (elements; nodes), the number of possible states for each node, and the interdependencies among the nodes to accomplish system functions. For a single function, it disregards all nodes whose state does not affect the function. It determines independent groupings according to the rule that two nodes are in the same group if the performance of the function is a non-linear function of the two nodes. Within a grouping, the number of states is the product of the number of states pertaining to that function over all nodes in the group. Different functions may produce some of the same groups. The measure of complexity is the sum over all groups.

Further rationalization in defining groupings may be possible (using the framework of normal forms in rational database). The approach does not analyze overlap between functions. Consider two groupings A and B based on two different functions. If A and B are disjoint, the complexity of the union is equal to the complexity of the sum (the formulation in the paper). If the nodes A and B are identical, the combined complexity should be equal distinct states over both function, i.e., the sum of the individual complexity minus the number of overlapping states. If A and B partially intersect, the complexity is the sum of the individual complexity minus the number of overlapping states.

A.2.6 APPARENT COMPLEXITY IN FLIGHT SOFTWARE

NASA Study on Flight Software Complexity, D.L. Dvorak, 2009

http://www.nasa.gov/pdf/418878main_FSWC_Final_Report.pdf

The NASA study on flight software complexity [10] was driven by a perception that flight software was a major source of cost and time growth. The goal of the study was to identify the problems and find ways to mitigate those problems. In this sense, the study was an empirical, investigative study, not a theoretical study. It did not develop a formal complexity metric, but instead develop a list of potential causes and indicators to track. The study identified a handful of software complexity metrics in the literature (e.g., cyclomatic complexity, Halstead complexity, Henry and Kafura metrics, Bowles metrics, Trot and Zweben metrics, Ligier metrics), but did not devote resources to the study of complexity metrics because the issues they identified were not well addressed by the metrics.

The study adopted the IEEE Standard Computer Dictionary definition of 'complexity' as "the degree to which a system or component has a design or implementation that is difficult to understand and verify". The phrase "difficult to understand" indicates that complexity is inherently about the knowledge and understanding of the personnel involved in the project. Complexity in this sense is not a computable property of the engineered system. But this sense of complexity is directly related to the likelihood of inaccurate estimates and mistaken decisions.

Flight software complexity is related to:

- How difficult it is for a programmer to implement the requirements the code must satisfy?
- How difficult it is for a tester to verify that the code satisfies the requirements and operates in an error-free fashion?
- How difficult it is for a lead developer to manage the development of the flight software within cost and schedule?
- How difficult it is for a flight software maintenance programmer to understand the original programmer's work if the software must be modified after launch?
- How difficult it is for a new programmer on a later mission to adapt the original flight software as heritage for the new mission?
- How difficult it is to predict the flight software's behavior, which in turn can drive much more extensive testing and more operational "hand-holding" along with their associated higher labor costs?

Factors used to measure a flight software system's essential complexity include:

- How many functions the flight software must execute and monitor?
- How many hardware components the flight software must monitor, command, control, and query for information?

- How many connections (both hardware and software) between components the flight software must monitor and manage?
- How many control modes must be managed and executed?
- How many software modules must be implemented in order to satisfy the flight software's requirements?
- How much coupling there is between software modules?
- How intricate/convoluted the code is within a module (assuming best programming practices, this is a measure of the complexity of an associated requirement or algorithm itself)?
- How many tests must be created and executed in order to verify that the flight software has satisfied its requirements and, in fact, whether it is even possible given limited time and cost to verify satisfaction of those requirements under all likely scenarios?
- How "state-of-the-art" the requirement is (reflected in how demanding performance and accuracy requirements are relative to contemporary, heritage systems)?

A.2.7 ADAPTABILITY METRICS TO MEASURE COMPLEXITY

Designing Systems for Adaptability by Means of Architecture Options, A. Engel and T. R. Browning, 2006

http://www.incose.org/symp2008/dmdocuments/paper_example01.pdf

In [11], Engel and Browning assert that the objectives of design for adaptability are to make complexity manageable, to enable parallel work, to enable efficient recovery from mistakes, and to accommodate future uncertainty. Adaptability mitigates against the risk of changing needs and technologies. In the sense of the IEEE Standard Computer Dictionary definition of 'complexity' as "the degree to which a system or component has a design or implementation that is difficult to understand and verify", adaptability is the antithesis of complexity.

The paper by Engel and Browning [] develops static and dynamic approaches to evaluate adaptability. It develops metrics for six dimensions of adaptability (functionality, reliability, usability, efficiency, maintainability, and portability). Each of these dimensions is further subdivided. The paper applies real options theory to assess value of a design including the present value of the future options the design provides.

A.2.8 ASPECTS OF COMPLEXITY IN DESIGN

Complexity models in design, C. Earl, C. Eckert, and J. Johnson, 2004

http://oro.open.ac.uk/7420/1/Complexity_Models_2004.pdf

Earl, Eckert and Johnson [12] distinguish product organization complexity, product function complexity, product operational complexity, development process complexity, and development organization complexity. The paper describes a variety of aspects of complexity including structure, uncertainty (knowledge in hand versus sufficient knowledge for design, evaluation and operation), dynamic cascading effects, and dynamic adaptation. The goal of the paper is to advance understanding of design processes and design outcomes. No metrics are given. No direct relationship to acquisition risk is presented.

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APPENDIX B: LITERATURE REVIEW ON SYSTEM COMPLEXITY AND RISK CONDUCTED BY WAYNE STATE UNIVERSITY

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