Technical Report
Value of Systems Engineering

This report contains information gathered from several sources on the quantified and qualitative value of systems engineering. It also contains recommendations for a Government-sponsored study to replace this scattered data with cohesive information usable by program managers.

This report is a follow-on from the June 2004 Air Force/Lean Aerospace Initiative Workshop on Systems Engineering for Robustness.

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1.0 EXECUTIVE SUMMARY

The challenges of developing and sustaining large complex engineering systems have grown significantly in the last decade. The practices of systems engineering promise to provide better systems in less time and cost with less risk, and this is widely accepted in the DoD and industry. However, we lack specific evidence regarding the right amount of systems engineering to bring about the best results, as well as the correct timing for the application of system engineering and the identification of those SE tools that are most effective. We propose a three-year study to address these shortfalls and provide program managers guidance they can use for the best application of system engineering practices.

Source Workshop. The Air Force/LAI Workshop on Systems Engineering for Robustness was held on June 8th and 9th in Arlington, Virginia. The workshop was sponsored by Dr. Marvin Sambur, Assistant Secretary of the Air Force for Acquisition and organized by the Lean Aerospace Initiative (LAI) Consortium. Dr. Donna Rhodes of LAI/MIT chaired the workshop. The purpose of this event was to accelerate implementation of recent Air Force and DoD policy and initiatives for systems engineering revitalization. Participants were experienced systems engineering leaders from DoD (including the services); leading aerospace prime contractors and suppliers; NASA; commercial companies; leading universities; and industry/professional societies.

One result of the workshop was a series of six initiatives to improve the knowledge and practice of better systems engineering. Initiative number one, the Value of Systems Engineering, is addressed by this report.

Studies on the Value of Systems Engineering. There is little doubt that systems engineering has value. Systems engineers tend to be the most highly-paid individuals in most system development programs, with pay scales often exceeding those of the program managers. Systems engineers are given the responsibility of technical leadership, with associate authority for technical decisions. The practices used by systems engineers seem to provide significant early risk reductions that improve quality while reducing cost and schedule. The question is not whether systems engineering has value. The question is to quantify that value in a usable way.

Only a few studies have been reported that systematically quantify the value of systems engineering to programs. Table I lists the seven known research projects that provide some indication. Summarizing the findings in these projects in the context of systems engineering value:

- ***Better technical leadership correlates to program success.*** [Ancona 1990, Miller 2000]
- ***Better/more systems engineering correlates to shorter schedules by 40% or more, even in the face of greater complexity.*** [Franz 1995, Honour 2004]
- ***Better/more systems engineering correlates to lower development costs, by 30% or more.*** [Gruhl 1992, Barker 2003, Kludze 2004, Honour 2004]
- ***Optimum level of systems engineering is about 15% of a total development program.*** [Gruhl 1992, Honour 2004]
- ***Programs typically operate at about 6% systems engineering.*** [Kludze 2004, Honour 2004]

The findings, however, are neither conclusive nor directly applicable to DoD. Each project was undertaken for limited goals, and each project reflects the limitations of its goals and its available data. In particular, none of the projects represent the typical programs of DoD or specifically the USAF. The data sets studied include NASA one-of-a-kind programs, commercial product development programs, manufacturing holding fixtures, and commercial software upgrades. While the results are useful, applying them to USAF system development programs might not be appropriate.

Table I. Summary of Research Projects on the Value of Systems Engineering

Source	Title	Summary	Findings
1992 Gruhl (NASA)	***Project Definition – NASA***	Evaluated cost growth over 20 years of major NASA programs (32 programs). Compared the cost growth to the amount spent during definition phases "A" and "B".	• Spending more during program definition phases correlates to less cost overrun during development. • Optimum definition amount appears to be 10-15% of the cost of the total program
1990 Ancona/ Caldwell	***Boundary Management Study***	Evaluated how 45 technical project teams spent their time. Identified classes of tasks that use time, one of which is "boundary management," the task of interfacing with those outside the project.	• Typical boundary management time averaged 14% of the team's total effort. • Greater boundary management correlated to greater success.
2000 Miller (MIT)	***Large Engineering Projects Study***	Studied 60 infrastructure-sized engineering projects (dams, power plants, national information networks, etc.) using objective and subjective analysis methods. Evaluated the methods and success of the projects.	• Priorities are evident in success rates: - 82% met cost targets, - 72% met schedule targets, - Only 45% met technical objectives. • Most important determinant in success was a coherent organizational structure, e.g. leadership
1995 Franz (Boeing)	***Impact of Systems Engineering on Quality and Schedule***	Three similar complex systems (Universal Holding Fixtures) were developed in parallel, using differing levels and quality of systems engineering practices.	• Teams spontaneously chose to use more rigorous systems engineering practices for the more complex systems. • With better systems engineering, the more complex systems were developed in shorter time.
2003 Barker (IBM)	***Systems Engineering Effectiveness***	Commercial software division created new systems engineering practices. Effectiveness was directly measured on 8 successive projects by using a pre-existing parametric cost estimation system.	• Implementing systems engineering practices reduced project parametric cost by 30%
2004 Kludze (NASA)	***Impact of Systems Engineering on Complex Systems***	Survey of systems engineers, project managers, and others on various aspects of systems engineering impact. Received 379 responses from NASA (36%) and INCOSE (64%) populations. Recorded and analyzed responses to 40 subjective questions.	Respondents believed: • Systems engineering has a moderate to significant impact on complex system projects. • Systems engineering has good to excellent impact on cost. • Cost of systems engineering on their projects was usually 6-10%.
2004 Honour (SECOE)	***Value of Systems Engineering***	Survey obtaining volunteer submissions of approximate cost and schedule data on major projects, as related to systems engineering costs and quality. Evaluated 43 projects in size from $1M to $6B.	• Greater systems engineering effort improves cost compliance, schedule compliance, and subjective quality. • Optimum systems engineering effort appears to be 15-20%. (Typical existing projects, however, operate at 3-8%.) • Quality of the systems engineering effort matters.

Government Sponsored Study Needed. The information so far is not directly usable by DoD managers. While it is useful to know that better or more systems engineering can reduce cost and schedule by significant amounts, the current state of knowledge does not indicate which practices are useful under what conditions. The data in the surveyed research projects has a wide degree of variance and suffers from limitations inherent in the scope of each research. When a program manager is faced with a decision to incorporate a new practice (e.g. more rigorous risk management), he/she has little information to indicate how much effort is appropriate and what return is to be expected from that effort.

This report therefore recommends a comprehensive and detailed gathering of information from DoD programs, both in-process and completed. The information to be gathered includes the time/expense used in performing specific systems engineering practices, the quality and type of those practices, and the apparent effects of those practices in terms of program quality, cost, schedule, and risk. These data will be gathered from programs in various DoD-5000 phases (CD, SDD, LRIP, FRP, Fielding) with the goal to understand the effects across phases.

Standardization of the data requires using an interview process so that interviewers can perform a consistent interpretation of the native program data into common definitions. For project success, these interviewers need to be senior with extensive program management and systems engineering experience, unbiased (have no stake in the outcome) and capable of probing, that is asking the second, third and fourth question beyond the initial question in every instance to get at the true data. Such a team is ideally composed of peers at the top working level, and is diverse so that various views emerge and can be debated to arrive at a generally accepted conclusion. In this regard, standard forms are useful, but must be understood as a point of departure; that is, they will evolve as the process proceeds and learning occurs. For in-process programs, these interviews will be repeated on a quarterly basis to evaluate the changes and effects as time progresses. For completed programs, the interviews will be conducted once and correlated with data extracted from records.

Gathering sufficient data to provide statistical significance requires access to about 30-40 programs over 3 years. Expected funding profile for the project is $500K/year for three years[1].

The expected results of this data gathering are usable information for DoD program managers that provide indications:

- ***How much budget and time to plan for systems engineering practices?***
- ***What specific benefits can be expected in terms of program quality, cost, schedule, and risk?***
- ***Which systems engineering practices produce what effects?***
- ***Under what program conditions is it appropriate to use more or less of each practice, and how much more or less?***
- ***What interdependencies exist between SE practices?***

[1] This value is a rough-order-of-magnitude estimate based on quarterly trips by the recommended high level of researchers to gather data from 30-40 programs; travel expenses; data maintenance and analysis by an academic center using research assistants; writing reports; and necessary administrative overheads. The estimate does not include labor costs for the interviewed program personnel.

2.0 TASKING: SYSTEMS ENGINEERING INITIATIVE #1

The US Air Force and the Lean Aerospace Initiative jointly sponsored a workshop in June 2004 to explore systems engineering for robustness. The 80 participants identified many known methods and six primary initiatives that were needed. This report addresses the first of those six initiatives, repeated below from the July 2004 report.

<table>
<tr><td colspan="2">Initiative One
Value of Systems Engineering – Past Studies & Recommendations for Future Study</td></tr>
<tr><td colspan="2">Programs do not always apply the systems engineering process effectively and efficiently. Studies show that when resources are cut on complex systems programs, the systems engineering budget is one of the prime targets for such cuts. One of the underlying reasons for such decisions is that we lack the objective, quantitative data to show the value of systems engineering on a program. Further, while early studies show overall that systems engineering investment pays off, we lack knowledge about which systems engineering activities are the highest value for the investment.</td></tr>
<tr><td>2004 Action Plan
An action team has been formed to gather the work to date that has been done on “value of systems engineering” by INCOSE, NASA, RAND, and other organizations. This compilation of information can serve to guide additional efforts in this area. A sponsored study will be needed to gain the information desired on the value of systems engineering, and the action team will also formulate a recommendation concerning such a study.</td><td>Deliverable
Report on Value of SE Studies and Recommendations for Government Sponsored Study
• September 15, 2004</td></tr>
<tr><td colspan="2">Additional Recommendations: We strongly recommended that there be a government sponsored study to collect detailed quantitative data on the value of SE (at the activity level) on several programs on a real-time basis over the program development lifecycle. This study will require funding from the government (or other source) and should be performed by a knowledgeable and neutral organization such as an FFRDC or consortium. The 2004 report will include recommendations for a study of this nature. The study should be designed to provide information which will discern what systems engineering activities are highest value given program context, and should assist acquisition leadership in RFP and contract development.</td></tr>
<tr><td colspan="2">Perspectives of the Workshop Participants</td></tr>
<tr><td>What do we do well today?
Several studies have been undertaken on the value of systems engineering. These are based primarily on subjective data captured after the fact so they are inconclusive. The findings done to date do show positive trends and there is optimism that a formal study will yield results that clearly demonstrate the value of systems engineering to a program.</td><td>What are we not doing well today?
While several studies have been done, no one has stepped up to a full study and this is in part due to lack of funding as well as related to the difficulties in gaining access to the necessary data. Yet, this is very important as without objective, quantified evidence of the value-add of systems engineering on a program, we have difficulty convincing customers that money needs to be spent on front-end engineering. Softer aspects, such as the valuation of flexibility by customers, are even more difficult to discern and quantify.</td></tr>
<tr><td>What are the inhibitors or barriers?
Our inability to quantify the value of good systems engineering in the development process inhibits the sustained commitment of resources to these activities. The issue of access to data on a real time basis is a significant one. Effective levels of access would require a trusted neutral party, with authority and clearances to view program specific information. Therefore such a study may best be undertaken by an FFRDC with systems engineering expertise, perhaps in collaboration with a university and or consortium.</td><td>What are improvement opportunities?
There is high interest in research on the value of systems engineering. Research needs to be done by a neutral party with significant expertise. Such a study needs to be long term, collecting data real time during program execution. If such studies can be accomplished with positive results, then better justification can be made for funding systems engineering as an important component of the larger acquisition process. Further, we need to understand which SE activities provide the most value in context of program and organizational factors. The first step, already in progress, is raising the awareness of the importance of good systems engineering.</td></tr>
</table>

3.0 BACKGROUND

The discipline of systems engineering (SE) has been recognized for 50 years as essential to the development of complex systems. Since its recognition in the 1950s [Goode 1957], SE has been applied to products as varied as ships, computers and software, aircraft, environmental control, urban infrastructure and automobiles [SE Applications TC 2000]. Systems engineers have been the recognized technical leaders [Hall 1993, Frank 2000] of complex program after complex program.

In many ways, however, we understand less about SE than nearly any other engineering discipline. Systems engineering can rely on systems science and on many domain physics relationships to analyze product system performance. But systems engineers still struggle with the basic mathematical relationships that control the development of systems. SE today guides each system development by the use of heuristics learned by each practitioner during the personal experimentation of a career. The heuristics known by each differ; one need only view the fractured development of SE "standards" and SE certification to see how much they differ.

As a result of this heuristic understanding of the discipline, it has been nearly impossible to quantify the value of SE to programs [Sheard 2000]. Yet both practitioners and managers intuitively understand that value. They typically incorporate some SE practices in every complex program. The differences in understanding, however, just as typically result in disagreement over the level and formality of the practices to include. Presciptivists create extensive standards, handbooks, and maturity models that prescribe the practices that "should" be included. Descriptivists document the practices that were "successfully" followed on given programs. In neither case, however, are the practices based on a quantified measurement of the actual value to the program.

The intuitive understanding of the value of SE is shown in Figure 1. In traditional design, without consideration of SE concepts, the creation of a system product is focused on production, integration, and test. In a "system thinking" design, greater emphasis on the system design creates easier, more rapid integration and test. The overall result is a savings in both time and cost, with a higher quality system product. The primary impact of the systems engineering concepts is to reduce risk early, as shown in Figure 2. By reducing risk early, the problems during integration and test are prevented, thereby reducing cost and shortening schedule.

The challenge in understanding the value of SE is to quantify these intuitive understandings.

3.1 Basic SE Values

The observable values in SE management are widely known, although there is great difficulty in defining some of them.

Each system development program can be viewed as a stochastic process. At the beginning of the program, management choices are made that set the parameters for the stochastic process. Such choices include goals, process definitions, tool applications, personnel assignments and more. During the program, many factors influence the actual outcome. The resulting completed program achieves values in accordance with as-yet-unknown probability distributions. All of the observable values cited in

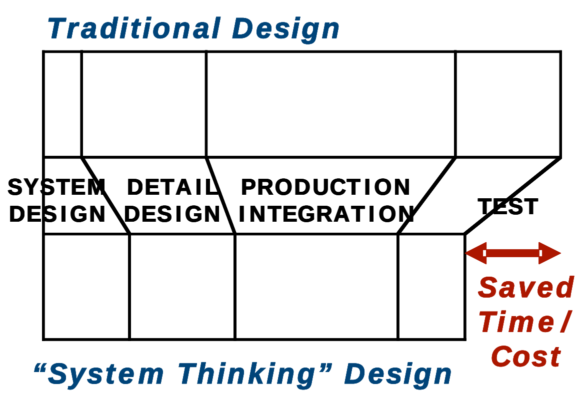

Figure 1. Intuitive Value of SE.

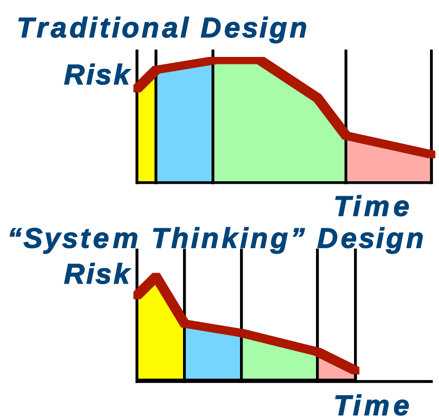

Figure 2. Risk Reduction by SE.

this section may therefore be viewed as sample values from inter-related stochastic processes. Any given program provides a single sample of the values.

Technical "size" (s) is an intuitive but highly elusive quantity that represents the overall size of the development effort. Some proposed measures of technical "size," all inadequate so far, include the number of requirements, the number of function points, the number of new-development items, and even (in a twist of cause-and-effect) the overall development cost.

Technical complexity (x) represents another intuitive attribute of the system. Size and complexity are independent characteristics. A system of any given "size" can be made more difficult by increasing its complexity, where complexity is usually related to the degree of interaction of the system components. One measure of complexity was explored well by [Thomas & Mog 1997] and then subsequently validated on a series of NASA programs [Thomas & Mog 1998].

Technical quality (q) is a third intuitive and independent attribute of the system. Quality is measured by comparing the actual resulting product system with the intended objective. Component attributes of quality vary widely and are based on the perceptions of the stakeholders, thereby resulting in what appears to be subjective measurement. One measure of technical quality was proposed by [Honour 2001] in the form of value against a pre-agreed Objective Function.

Program schedule or duration (d) is an attribute of the system development that is commonly used for management tracking and control. Duration is well understood, with extensive software tools for planning and scheduling programs. For our purposes, we are concerned with the overall development duration from concept through first 5 years of operational fielding. This duration may include activities such as operational analysis, requirements definition, system design, developmental engineering, prototyping, first article(s) production, verification, and validation and fielding.

Program cost (c) is a second attribute of the system development that is also commonly used for management tracking and control. As with duration, program cost is well understood. The scope for program cost, as with duration, is the overall development cost from concept through validation of first product(s).

Risk (r) is a third attribute of the system development. Risk is defined in the literature in many ways. In its basic form, risk represents variability in the stochastic processes for value, duration, and cost. Risk can be measured in several ways. We talk of risk applied to technical parameters, to schedule, and to cost. Most current risk definitions focus on cost, with the assumption that technical and schedule risks can be translated to cost [e.g. Langenberg 1999]. As an attribute of the overall program, a single value of program risk was proposed by [Honour 2001].

Systems engineering effort (SEE) is the effort expended during the program to perform effective systems engineering tasks. It is the primary independent variable in our heuristic relationships. In other words, SEE is the primary variable that is selectable and controllable during a system development. Other values usually occur by selecting SEE. SEE must take into account the quality of the work performed, because a group that performs systems engineering tasks poorly provides little benefit to a program.

We therefore define SEE as:

SEE = SE Quality * SE Cost / Program Cost

In this definition, SEE can be expressed as an effective percent of the total program cost. SE Quality (SEQ) is difficult to measure, but may be quantified subjectively by the program participants. It would be desirable to create a more objective measure. We emphasize that SE cost is not merely the cost of those in a SE office or charging to a SE account in a program. SE costs are generally created by others contributing to the program who may be located in other organizations or charging to different accounts or as part of other product related IPTs. One important consideration is how to account for system engineering cost, and that will be determined on a program-by-program basis, after considering each program's organizational and cost structure.

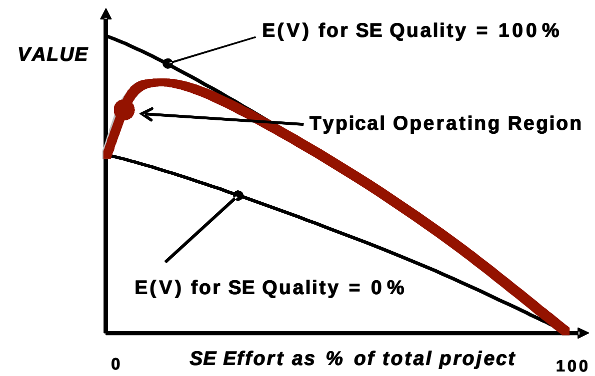

Figure 3. Seeking Optimum Level of SE Effort Within Programs.

3.2 Value of SE Hypothesis

In [Honour 2002], the author explored the heuristic relationships among the basic SE values by performing two-point end-value analysis of each pair-wise relationship. The heuristic relationships can be seen in that paper.

Among the heuristic relationships is the primary hypothesis for the value of systems engineering. That hypothesis is shown in Figure 3. The thin lines represent the achievable value for different levels of SEQ. The lower thin line is the value obtainable if the SE effort that is extracted from the program performs no effective SE, i.e. reduction in effective program budget without any systems engineering worth. The upper thin line is the value obtainable for application of "best" systems engineering. The actual relationship transitions from the lower line to the upper line as SEE is increased, because SE tasks cannot be fully effective until enough budget is allocated to them. The relationship of value to SEE therefore starts at non-zero (a program without SE can still achieve some value), grows to a maximum, then diminishes to zero at SEE = 100% (all program effort is assigned to SE, so no system is produced).

The rapid upward trend in the resulting curve for lower values of SEE corresponds to expectations of many systems engineers, that greater application of systems engineering improves the value of a program. Most programs appear to operate somewhere within this region, leading to a widespread occurrence of this common expectation.

4.0 STUDIES ON THE VALUE OF SYSTEMS ENGINEERING

This section summarizes the known prior works with conclusions that apply to the value of SE. Each subsection summarizes one research report. For full information, see the references at the end of this report. Within each summary, the differences are noted between its assumptions and the typical USAF programs. In general, it should be noted that none of these known works directly applies to the usual USAF development. While generalizations are possible from each work, such generalizations may not be applicable.

4.1 Project Definition – NASA

Werner Gruhl of the NASA Comptroller's office presented results [Gruhl 1992] that relate project quality metrics with a form of systems engineering effort (Figure 4). This data was developed within NASA in the late 1980's for 32 major projects over the 1970s and 1980s.

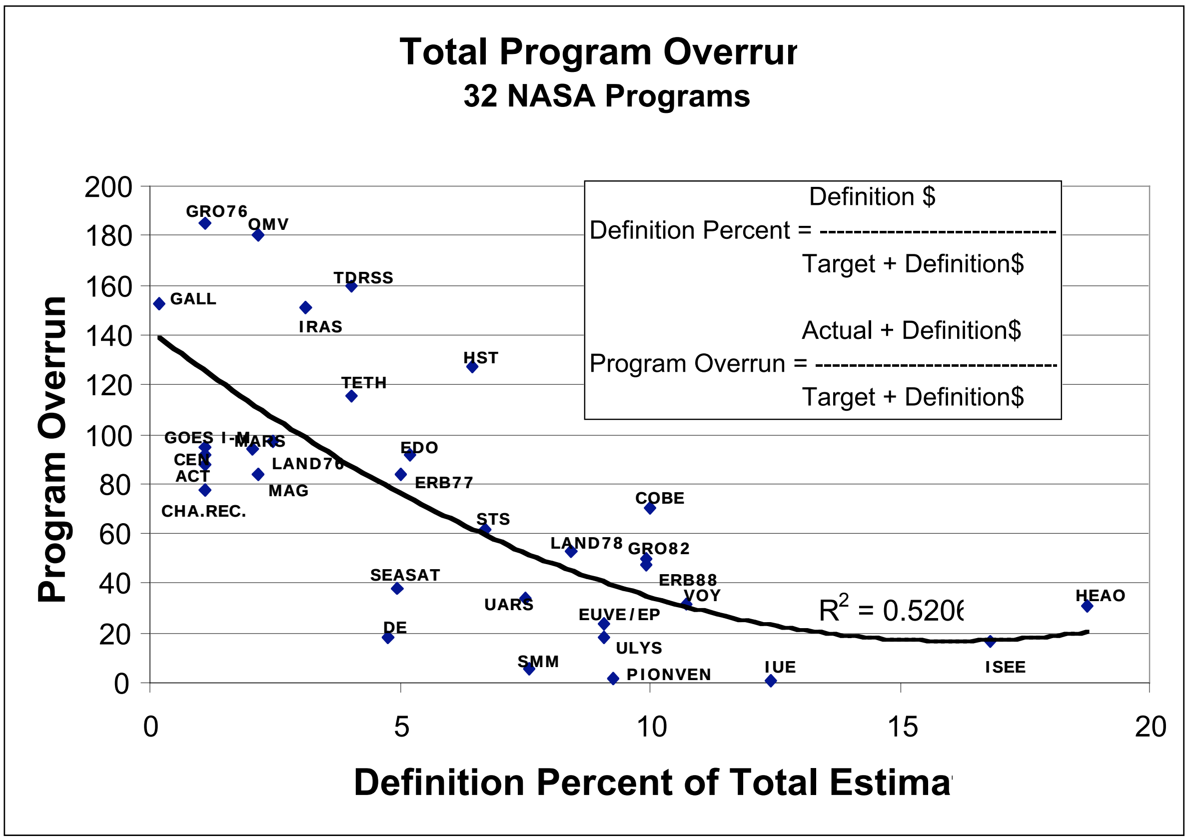

Figure 4. NASA Data on Impact of Front End Project Definition Effort.

The NASA data compares project cost overrun with the amount of the project spent during phases A and B of the NASA five-phase process (called by Gruhl the "definition percent"). The data shows that expending greater funds in the project definition results in significantly less cost overrun during project development. Most projects used less than 10% of funds for project definition; most projects had cost overruns well in excess of 40%. The trend line on Gruhl's data seems to show an optimum project definition fraction of about 15%.

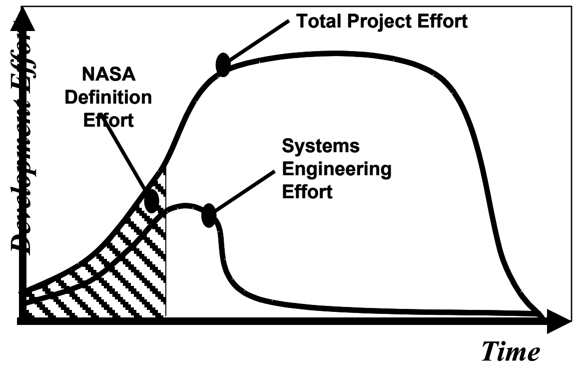

Figure 5. Definition Effort is not Equal to Systems Engineering Effort.

The NASA data, however, does not directly apply to systems engineering. In Gruhl's research, the independent variable is the percent of funding spent during NASA Phases A and B, the project definition phases. Figure 5 notionally shows the difference between this and true systems engineering effort. It is apparent from this difference that the relationship shown in the NASA data only loosely supports a hypothesis related to systems engineering.

In another difference, the NASA data applies to large one-of-a-kind spacecraft programs like Ulysses, Pioneer/Venture, and the Space Transportation System (STS), all three of which are among the data points in Figure 4. These programs are not typical of USAF programs like the F-16.

4.2 Boundary Management Study

A statistical research project in the late 1980s [Ancona 1990] studied the use of time in engineering projects. The authors gathered data from 45 technology product development teams. Data included observation and tracking of the types of tasks performed by all project members throughout the projects. Secondary data included the degree of success in terms of product quality and marketability. Of the projects studied, 41 produced products that were later successfully marketed. The remaining four projects failed to produce a viable product.

One primary conclusion of the research was that a significant portion of the project time was spent working at the team boundaries. Project time was divided as:

- Boundary management 14%
- Work within team 38%
- Individual work 48%

Boundary management included work that was typically done by a few individuals rather than by all members of the team. The research also studied how these classes changed over the life of the project from creation through development through diffusion. Discovered classes of boundary management were

- Ambassador - Buffering, building support, reporting, strategy
- Task Coordinator - Lateral group coordination, info transfer, planning, negotiating
- Scout - Obtain possibilities from outside - interface with marketing
- Guard - Withhold information, prevent disclosure

More important to the value of systems engineering, the research also concluded statistically that high-performing teams did more boundary management than low-performing teams. This relates to systems engineering because many of the boundary management tasks are those that are commonly performed as part of SE management.

A secondary discovery of the project was that internal team dynamics (goals, processes, individual satisfaction) did not correlate with performance. This conclusion seems to be contrary to the widely-held belief that defining good processes will create a good project.

For all its excellent work, however, the study was limited to relatively small product development teams apparently working in an environment very different than USAF development. It is difficult to provide much useful information for complex system development programs from the results of this study.

4.3 Large Engineering Projects Study

An international research project led by Massachusetts Institute of Technology (MIT) studied the strategic management of large engineering projects (LEP) [Miller 2000]. The project reviewed the entire strategic history of 60 worldwide LEPs that included the development of infrastructure systems such as dams, power plants, road structures, and national information networks. The focus of the project was on the strategic management rather than technical management. The project used both subjective and objective measures, including project goals, financial metrics and interviews with participants.

The statistical results of the LEPs are shown in Figure 6. Cost and schedule targets were often not met, but technical objective targets were only met in 45% of the 60 projects. Fully 37% of the projects

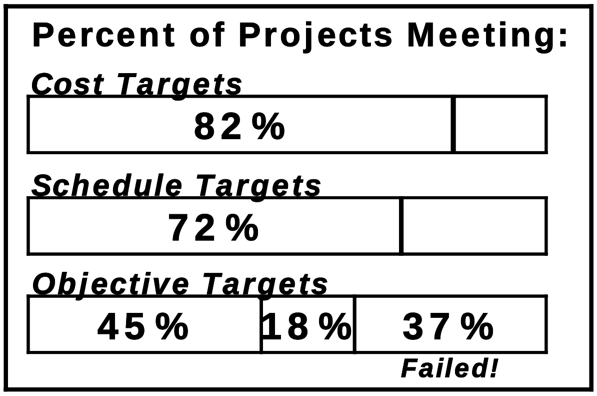

Figure 6. Many Large Engineering Projects Fail to Meet Objectives

completely failed to meet objectives, while another 18% met only some objectives.

Three of the many findings appear to have significance to the value of SE:

- The most important determinant in success was a coherent, well-developed organizational structure; in other words, a structure of leadership creates greater success.
- Technical difficulties, social disturbance, size were not statistically linked to performance; all projects had turbulent events.
- Technical excellence could not save a socially unacceptable project, therefore technical process definition is important but not sufficient.

As with the boundary management study, this last finding appears contrary to the widely-held belief in the efficacy of process definitions. Both of these studies (Boundary Management, LEPs) seem to indicate that technical leadership is more important than the processes used.

As with the other studies, however, the data obtained is on projects that are very different than the typical USAF project. The 60 LEPs were selected for their one-of-a-kind size and their impact on the surrounding society.

4.4 Impact of Systems Engineering on Quality and Schedule

A unique opportunity occurred at Boeing as reported by [Frantz 1995], in which three roughly similar systems were built at the same time using different levels of systems engineering. The three systems were Universal Holding Fixtures (UHF), used for manipulating large assemblies during the manufacture of airplanes. Each UHF was of a size on the order of 10' x 40', with accuracy on the order of thousands of an inch. The three varied in their complexity, with differences in the numbers and types of sensors and interfaces.

The three projects also varied in their use of explicit SE practices. In general, the more complex UHF also used more rigorous SE practices. Some differences in process, for example, included the approach to stating and managing requirements, the approach to subcontract technical control, the types of design reviews, the integration methods, and the form of acceptance testing.

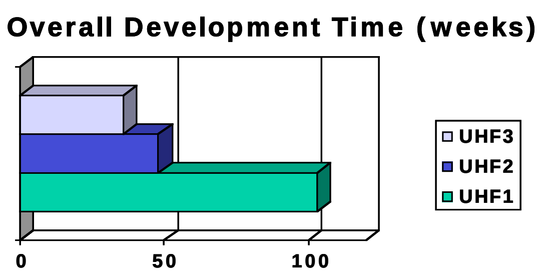

Figure 7. Better SE Shortens Schedule

The primary differences noted in the results were in the subjective quality of work and the development time. Even in the face of greater complexity, the study showed that the use of more rigorous SE practices reduced the durations (a) from requirements to subcontract Request For Proposal (RFP), (b) from design to production, and (c) overall development time. Figure 7 shows the significant reduction in overall development time. It should be noted that UHF3 was the most complex system and UHF1 the least complex system. Even though it was the most complex system, UHF3 (with better SE) completed in less than _ the time of UHF1.

These Universal Holding Fixtures, while still one-of-a-kind projects, are of a size more compatible with typical USAF programs than in the prior three reports. In addition, the contractor developing the UHFs is a known large USAF contractor (Boeing), so that the systems engineering practices used on these UHFs can be assumed to be similar to those used on USAF programs.

4.5 Systems Engineering Effectiveness

IBM Commercial Products division recently implemented new SE processes in their development of commercial software. While performing this implementation, they tracked the effectiveness of the change through metrics of productivity.

As reported by [Barker 2003], productivity metrics for cost estimation existed prior to the implementation. These metrics were based on the cost per arbitrary "point" assigned as a part of system architecting. (The definition of "point" is deemed to be proprietary.) The number of "points," once assigned, became the basis for costing of project management, business management, systems engineering, system integration, and delivery into production. (Note that this costing metric did not include the software development cost, which was not covered by the report.)

During the SE implementation, the actual costs of eight projects were tracked against the original estimates of "points." Three projects used prior "non-SE" methods, while the remaining five used the new SE methods.

In the reported analysis, the preliminary data indicates that the use of SE processes improves project productivity when effectively combined with the project management and test processes. Cost per point for the prior projects averaged $1350, while cost per point for the projects using SE processes averaged $944. The reported costs, as noted, are only the costs for project management, business management, systems engineering, system integration, and delivery into production. When questioned, the author reported verbally that an even larger reduction occurred in software development cost, but he was unable to track that reduction.

Year	Project	"Points"	Cost ($K)	SE Costs (%)	$ / Point
2000	Project 1	12,934	18,191	0	1,406
2000	Project 2	1,223	2,400	0	1,962
2001	Project 3	10,209	11,596	9.2	1,136
2001	Project 4	8,707	10,266	0	1,179
2001	Project 5	4,678	5,099	10.7	1,090
2002	Project 6	5,743	5,626	14.4	980
2002	Project 7	14,417	10,026	10.2	695
2002	Project 8	929	1,600	16.0	1,739

Figure 8. Implementation of SE Processes Resulted in Statistically Significant Cost Decrease

This report specifically aimed at the commercial software business base of this IBM division. Such commercial software products are not typical of USAF programs. Yet it should be noted that this linkage between systems engineering practices and software development is also apparent on USAF programs; many DoD software development contractors stumble in their capability maturity evaluations on exactly the higher-order issues typically associated with systems engineering. This IBM division found that implementing new SE practices actually reduced the cost of the management functions alone.

4.6 Impact of Systems Engineering on Complex Systems

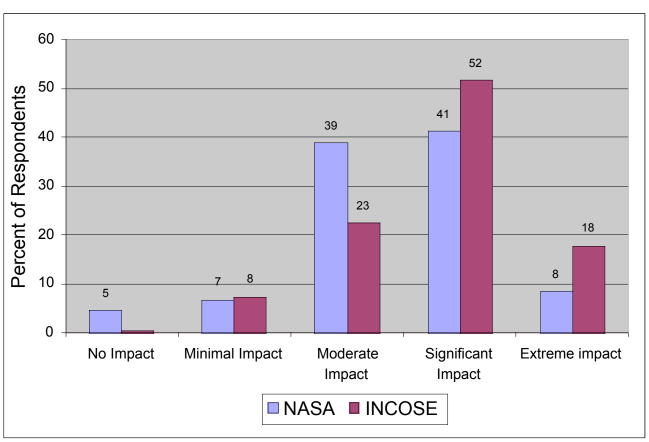

Figure 9. Overall Impact of SE

Another recent study was reported by [Kludze 2004], showing results of a survey on the impact of SE as perceived by NASA employees and by INCOSE members. The survey contained 40 questions related to demographics, cost, value, schedule, risk, and other general effects. Aggressive pursuit of responses generated 379 valid responses from a sample of 900 surveys sent out. Respondents were 36% from within NASA and 64% from INCOSE membership. NASA respondents were approximately equally distributed among systems engineers, program managers, and others, while INCOSE respondents were predominately systems engineers.

While most of the survey relates in

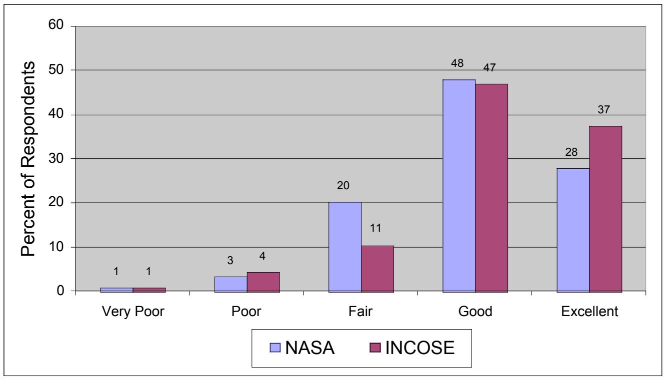

Figure 10. Cost Benefits of Systems Engineering

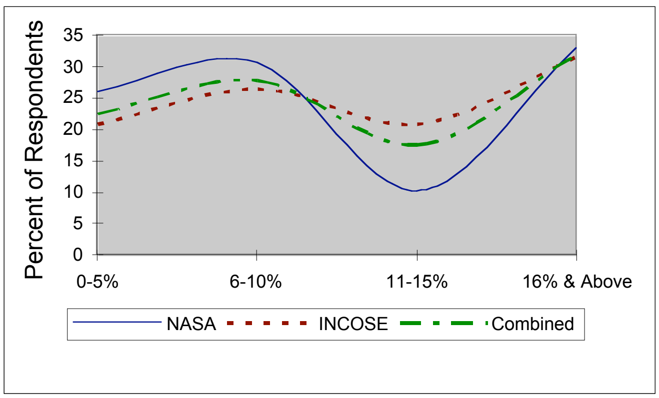

Figure 11. Percent of Total Project Cost Spent on Systems Engineering

some ways to the value of systems engineering, three primary results stand out. First, respondents were asked to evaluate the overall impact of systems engineering. The results, shown in Figure 9, indicate that the respondents believed that systems engineering has a moderate to significant impact on complex systems projects. It is noted that the response from the INCOSE group is considerably more positive than from the NASA group.

Second, respondents were asked to evaluate the impact of SE on cost of the complex systems projects. The results are shown in Figure 10, in which it is clear that respondents believed SE to have good to excellent impact on cost. Again, it is noted that the INCOSE group is more positive than the NASA group.

Third, respondents were asked to indicate the percent of their most recent project cost that was expended on SE, using aggregated brackets of 0-5%, 6-10%, 11-15%, and 16% or more. Figure 11 shows the result. As expected, the respondents believed that their projects most often spent between 6-10% on SE, with few projects spending more than 10%. It appears that INCOSE respondents worked on projects that spent proportionately more on SE than in NASA. There is, however, an anomaly in this data that is represented by the bimodal characteristic of the responses. Many respondents indicated that their projects spent 16% or above. It is believed that this anomaly occurs because the respondents interpreted “project” to include such projects as a system design effort, in which most of the project is spent on SE.

As noted by the issue of the word “project,” there was little control in this project over the individual definitions of terms used by the respondents. Survey results were likely influenced by different perceptions of systems engineering in the NASA and INCOSE groups; in addition, the INCOSE group was likely comprised of individuals from many business domains. These results, while indicative, are not definitive for USAF programs.

4.7 SECOE Value of Systems Engineering Study

In March 2001, the Systems Engineering Center of Excellence (SECOE), a subsidiary research arm of the International Council on Systems Engineering (INCOSE), initiated project 01-03 to collect and analyze data that would quantify the value of systems engineering. The original hypothesis for the project is similar to that presented above in Figure 3. The INCOSE Board of Directors supported the project with seed grant money to leverage other sources. Interim results of the continuing project were reported in [Mar 2002]. A final report for the survey phase was in [Honour 2004]. This section summarizes the final data on the survey phase of the project. Because this project is closest in profile to the recommended USAF study of section 5, this summarized report is more complete than the prior sections.

4.7.1 Data Submission

The data submission form used to survey data from volunteer participants included

- Planned & actual cost
- Planned & actual duration
- Systems engineering (SE) cost
- Systems engineering quality
- Objective success
- Comparative success

Each of the parameters was defined, and these definitions were on the submission form to guide respondents. A brief definition of terms are:

Costs (planned/actual) – program costs up to delivery of first article, not including production costs

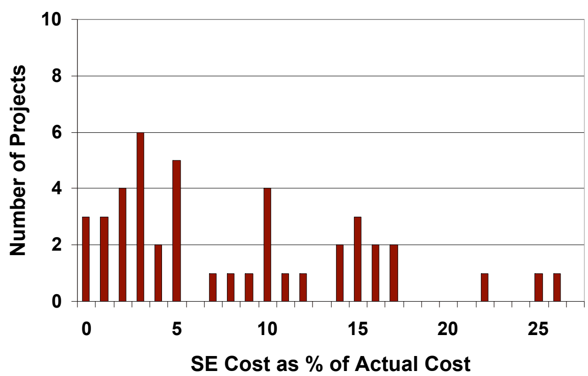

Figure 12. Histogram of Raw Submissions by SE Cost % of Total Program

Duration (planned/actual) – schedule up to delivery of first article

SE Costs – actual costs of performing traditional SE tasks, no matter who performed them. For this project, "traditional SE tasks" are viewed with the broad definitions of [Frank 2000]. The form included a list of example SE tasks including "…technical management and coordination, mission and/or need analysis, system architecting, system-level technical analysis, requirements management, risk management, and other tasks associated with these."

SE Quality – subjective evaluation using a 0-10 scale where 0 represents SE of no value, 5 indicates a normal SE effort, and 10 is unexcelled, world class SE

Objective success – subjective evaluation using a scale where 0 indicates no objectives met, 1.0 indicates all objectives met, and >1.0 indicates exceeding the objectives. This subjective measure is intended to be an approximation of the "Objective Function" based technical quality of [Honour 2001].

Comparative success – subjective evaluation using a 0 to 10 scale where 0 indicates program failure, 5 indicates success equal to other programs, and 10 indicates unexcelled, world class success. This subjective measure is intended to be an alternate measure of the program success.

Respondent Data. Data points submitted can be seen in Figures 12 and 13 for the 44 respondent programs. Figure 12 shows the percentage of SE cost as reported by the respondents, ranging from less than 1% to 26% with a mode at about 4%. Figure 9 shows the effective percentage of SE cost in terms of our defined SEE, ranging from less than 1% to 26% with one primary mode at 1% and a secondary, much smaller, mode at 8%. We note that the demographic in Figure 12 seems to corroborate the survey data obtained by Kludze. Most programs appear to spend on the order of 5% of the program cost on SE tasks, with considerably fewer programs spending over 10%.

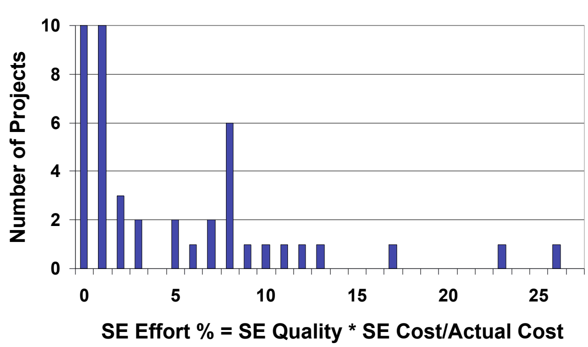

Figure 13. Histogram of Submissions by SE Effort (as % of Total Program)

4.7.2 Analysis – Cost and Schedule

The results of the primary analysis concerning cost and schedule compliance are shown in Figures 14 and 15. Figure 14 shows the data for actual cost (AC) / planned cost (PC), while Figure 15 shows the data for actual schedule (AS) / planned schedule (PS). Both charts show (a) the best-fit statistical mean for the values using a least-sum-of-squares fit (solid line), and (b) 90% assurance values (1.6σ) assuming a Normal distribution at each vertical value of SEE (dashed lines). In both cases, the best-fit curve for the statistical mean appeared to be a second-order polynomial with minimum between 15-20% SEE. The actual location of the minimum has little confidence because so few programs reported values of SEE above 10%. Covariance correlations for the curve-fitting were considerably better when using SEE than when using the raw SE Cost %, indicating that the quality of the SE is an important factor in the mathematical quantification of SE value.

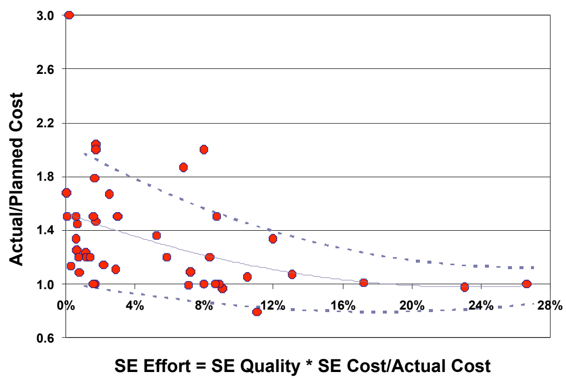

Figure 14. Cost performance as a function of SE effort

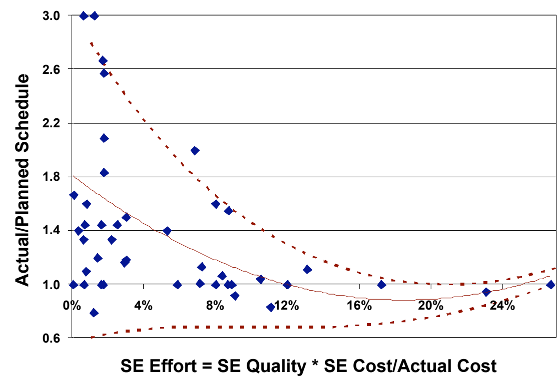

Figure 15. Schedule performance as a function of SE effort.

These results correlate well with the past research reported above. The NASA research data shows an optimum of about 15% based on definition percent, corresponding to the 15% SEE shown in Figures 14 and 15. The Frantz data shows a significant reduction in schedule based on better application of SE, similar to Figure 15. The LEP data shows better cost control than schedule control, which trend is also evident by comparing the forms of Figures 14 and 15. Finally, the Barker data shows significant reduction in cost based on better application of SE, similar to Figure 14.

4.7.3 Analysis – Program Size

A secondary analysis correlated cost and schedule compliance with program size, where program size was approximated by using the total actual cost. Figure 16 shows the overall trend in a logarithmic plot of program size from $1 million to $10 billion. It is an interesting phenomenon that programs at both ends of this range appear to be better cost-controlled than programs in the $10 million to $100 million range.

Figures 17 and 18 show the slight trend in cost and schedule for programs <$100M. Figure 12 shows the relationship of actual cost (AC) / planned cost (PC) to program size, while Figure 13 shows the relationship of actual schedule (AS) / planned schedule (PS) to program size. In both cases, the smallest programs appear to have better cost/schedule control than do the mid-size (~$100M) programs.

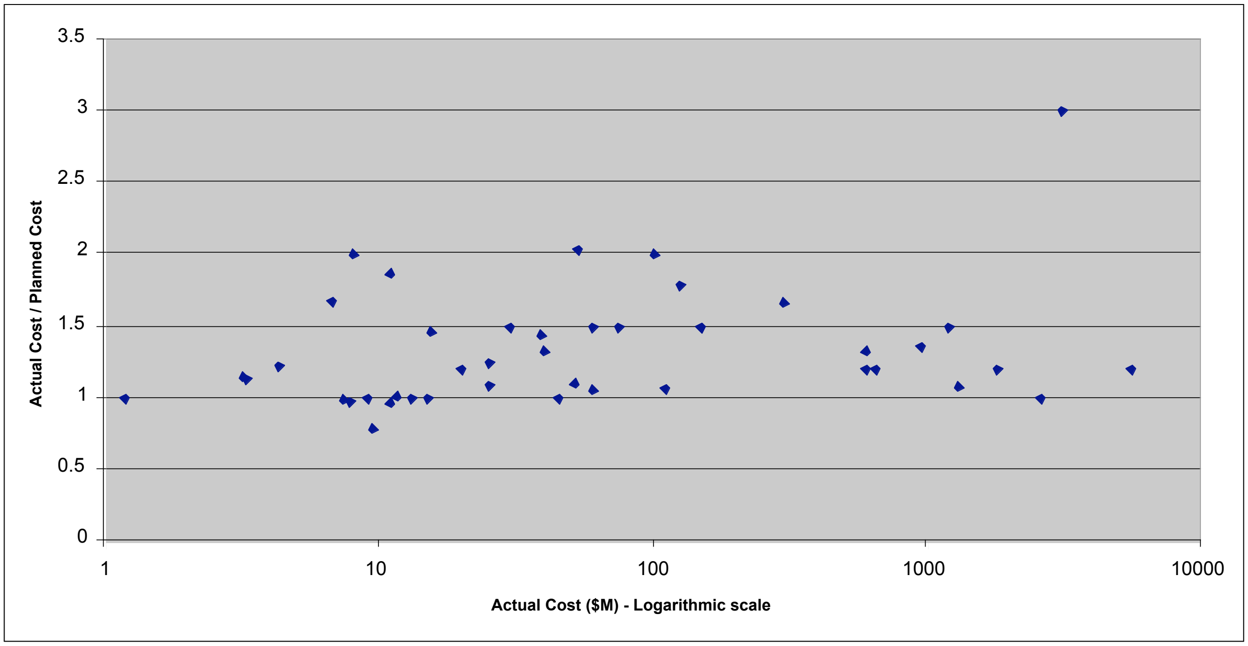

Figure 16. Cost performance as a function of program size

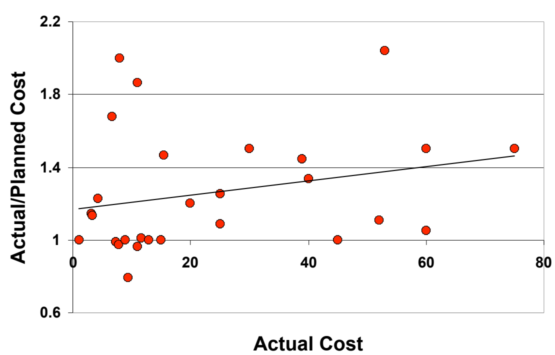

Figure 17. Cost performance as a function of program size (<$100M)

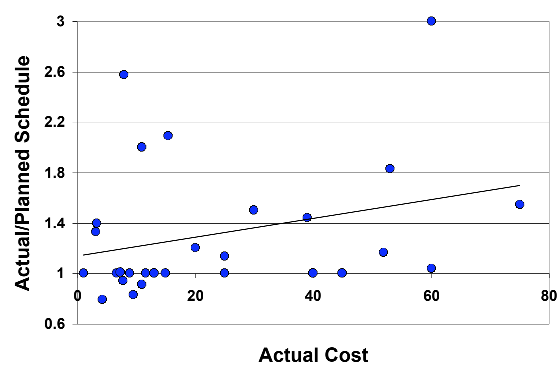

Figure 18. Schedule performance as a function of program size (<$100M).

4.7.4 Test of Hypothesis

In the original hypothesis of Figure 3, the value of SE is expected to rise for low values of SEE, reach a maximum, and then fall away. Development Quality (DQ) can be defined as a function of technical product quality, program cost, program schedule, technical "size," technical complexity, and risk. The few data points gathered do not support exploration of all these factors, but a tentative approach to DQ can be calculated as the inverse average of the cost and schedule ratios:

DQ = 1 / (_ * (AC/PC + AS/PS)) (4)

Where AC is actual cost, PC is planned cost, AS is actual schedule, and PS is planned schedule. If a program completes on-cost and on-schedule, the value of DQ is 1. Programs that overrun cost and

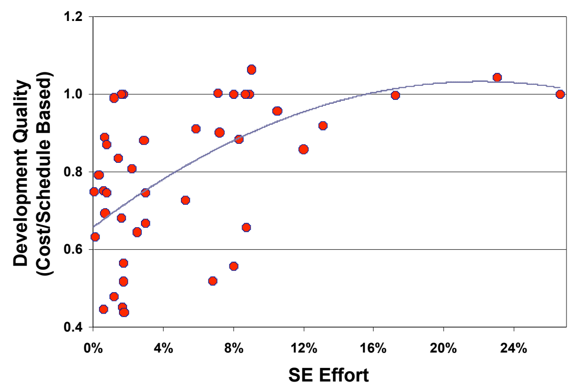

Figure 19. Test of original hypothesis

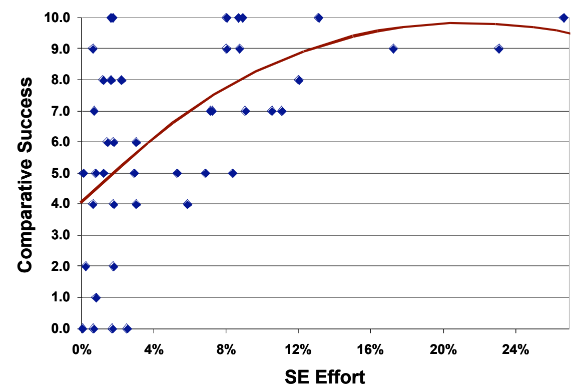

Figure 20. Subjective quality as reported

schedule have values of DQ < 1.

Figure 19 shows this rudimentary DQ plotted against SEE. There is a trend that appears to follow the pattern of the original hypothesis. However, because this approach does not yet include the factors of product quality, technical size, complexity, or risk, there is significant variability around the expected trend. Variability (scatter) also occurs due to other program factors beyond SE, such as political pressures and program management quality. As before, we note that most of the programs submitted appear to operate well below the apparent optimum.

The data submitted for objective success provided no apparent correlation with SEE.

As a second independent test of the original hypothesis, Figure 20 plots the comparative success values as reported subjectively by respondents. This shows that respondents perceived significantly lower success with programs that had low SEE than with programs with high SEE. The shape of the comparative success approximates the original hypothesis, indicating that this subjective value might also be a rough measure of the hypothesized DQ.

4.7.5 Known Limitations

The data available for analysis in this project present several important limitations to the results. Any use of the values herein should be tempered by these limitations.

The data are self-reported and largely subjective, without checking. Those responding to the data requests may be assumed to be senior engineering personnel by nature of their association with INCOSE; such personnel can be expected to have the kind of data requested. Nonetheless, there have been no quality controls on the submission of data.

Perceptive influences likely color the data. The underlying hypotheses for this project are well-known and widely accepted. Because of the wide acceptance, respondents can be expected to include a subconscious bias toward supporting the hypotheses. This single fact might have caused much of the correlation observed.

Systems engineering effort is also self-reported based on the respondents' individual perceptions of systems engineering. There is no certainty that different respondents had the same perceptions about the scope of work to be included within SEE.

Respondents come from the population of INCOSE members and others with whom the author had contact. This limits the scope of programs included within the data.

4.7.6 Conclusions

Under the limitations presented, however, some interim conclusions can be made from this data.

- **SE effort improves development quality.** The data presented shows that increasing the level and quality of systems engineering has positive effect on cost compliance, schedule compliance, and subjective quality of the programs. In this, the original project hypothesis is supported by the data received.

- **Optimum SE effort is 15-20%.** While there are few data points in the region of optimum SE effort, the trend lines appear to reach maximum in the range of 15-20%. This same optimum value appears in the analyses of cost compliance, schedule compliance, and subjective quality. This data is contrary to the usual program SE budgets of 3% - 8%. This optimum value is further supported by the prior works by NASA and by Kludze.
- **Quality of the SE effort matters.** There is significant scattering of the data due to many factors, some of which are beyond the scope of SE. Nonetheless, correlation of the data is better when the subjective factor of SE Quality is included. This corroborates the widely-held assumption that lower quality SE reduces its effectiveness.

For the purposes of this report, it should be noted again that there are some significant differences between these results and the typical USAF program. First, because the data was obtained anonymously, there was no control on the source business domains. With some knowledge of the methods used to obtain data points, the data likely came from US Navy, USAF, NASA, and aerospace programs – but there was purposefully no retention of the sources that would allow any segmentation of the data. Second, the data specifically aimed at the effects of systems engineering on the development program alone, not including the effects on later production or fielding. It is highly desirable to understand the effects of systems engineering on the entire system.

5.0 GOVERNMENT SPONSORED STUDY

The data analysis of the SECOE project suggests that there is a strong case to be made for a quantitative relationship between systems engineering investment and the quality of program performance. These conclusions are further supported by the six other projects reported herein. Far more data is needed, however, to quantify and parameterize the relationships. It is ***highly recommended*** that the Government sponsor a funded study to gather and correlated the necessary information.

There is high interest in research on the value of systems engineering, but the needed study cannot be performed at the level of an individual company. Such a study needs to be long term, collecting data both *ex post facto* and real time during program execution. It also needs to gather data from many programs under different conditions. Without such objective, quantified evidence of the value-add of systems engineering on a program, we frequently have difficulty convincing programs that money needs to be spent on front-end engineering. Softer aspects, such as the valuation of flexibility and robustness by customers, are even more difficult to discern and quantify. These difficulties constantly affect DoD programs. This is why it is appropriate for DoD to sponsor the study.

5.1 Objective of the Study

The objective of the study is to provide quantified answers to basic questions about systems engineering and its effects on programs:

- ***How much budget and time should be planned for systems engineering practices?*** Using the results, a program manager will be able to select an effective level of systems engineering tailored for the parameters of the program. The selection will take into account the size and complexity of the program and the desired level of quality and risk.

- ***What specific benefits can be expected in terms of program quality, cost, schedule, and risk?*** The program manager will be able to plan the program with greater assurance of achieving the desired quality, cost, and schedule. The program manager will understand the true level of variance that may occur and will be better able to assess the quantified risk.

- ***Which systems engineering practices produce what effects?*** The program manager will be able to select specific systems engineering practices – requirements management, risk management, architecting, technical analysis, prototyping – and understand which practices will affect what aspects of quality, cost, schedule and risk. (For example, investing in modeling, trades, etc likely has positive impact on decision making that can increase system robustness.)

- ***Under what program conditions is it appropriate to use more or less of each practice, and how much more or less?*** Based on the statistical data, the program manager can select how much effort to plan for each systems engineering practice based on the parameters of the program, with knowledge of the impact his decisions will make on the program.

- ***What interdependencies exist between SE practices?*** The PM will be able to understand when investment and realization of the derived benefits of a given practice are dependent upon the adequate investment in a related practice.

These questions will be answered by gathering data from real DoD programs. The project will perform validated statistical analysis on the correlations between systems engineering practices and program success. The results will provide a quantified understanding that will enhance the effective commitment of resources to these activities.

5.2 Selection of Programs

The project will select DoD programs for data selection in concert with the sponsoring USAF agency. Programs will be selected from ongoing and completed system programs that evidence a requisite Design of Experiments variety in characteristics such as single items versus high-rate production; product families versus unique systems; single systems versus systems-of-systems; contract types; parent agency and organization; program stability versus disruptions, etc. Selection of programs will be the subject of an early project meeting with the USAF sponsor to scope the effort.

Completed programs will be selected for access to the applicable data and personnel, thereby requiring recently completely programs. For completed programs, the intent is to gather sufficient data on the actual production and fielding costs to allow correlation with the development systems engineering. Ideal programs will have been fielded for a minimum of five years, with the necessary interview personnel still identifiable and available, and with full cost and contract records.

Ongoing programs will be selected for accessibility to the applicable data and personnel in-process. For ongoing programs, the intent is to gather sufficient data to correlate the systems engineering practices with the short-term effect during development. Ideal programs will be in various stages of development, will progress through a variety of changes during the course of the research, and will complete development during the research.

For both completed and ongoing programs, it is essential that the responsible contractor and contracting agency both be willing to take part in this research. It is highly preferable that they support the research by providing interviewees at no cost. It is believed that this can be accomplished by offering the contractors and agencies early reports on the research products. Particularly for contractors, these reports can be presented to the contractors as a competitive advantage to be gained. This incentive can be strengthened with an appropriate Government influential request that they participate.

5.3 Data Gathering

The data needed to answer the questions of section 5.1 includes both quantified and subjective elements. Quantified elements provide the statistical basis for study. Subjective elements provide information to fully understand the statistical results. Actual data items to be gathered will be defined at the beginning of the project in conjunction with USAF guidance.

Quantified data includes items such as the following:

- Program characterization values such as overall program size, duration, number of components, etc.
- Program success values such as cost, return on investment, schedule, cost/schedule variances, technical performance measures, etc.
- Time and cost expended in defined systems engineering activities.
- Metrics used by the program
- Life-cycle and phase definitions

Subjective data includes items such as:

- Evaluations of the technical program complexity, stability, constraints severity, system robustness, etc.
- Evaluation of the technical team, including quality, knowledge level, experience level of the key individuals.
- Customer and stakeholder satisfaction measures.
- Evaluation of the quality of the systems engineering activities.
- Methods used and their apparent effects.
- User evaluations (for fielded programs).

Depending on the specific data collected (to be defined in the project), these types of data will support quantifying hypotheses such as: “System engineering activity A (e.g. requirements management) correlates to X level with lowered overall program cost.” Such quantified hypotheses can lead to directly quantified guidelines for program managers such as: “On this type of program, budget Y% of the program for requirements management.”

This data must be collected repeatedly from a consistent set of programs over time. It is a long-recognized aspect of systems engineering that its effects occur months or years after the activities. (e.g. Reducing a risk during system architecture causes less expense during operational testing.) Only by such repetition can the effects of earlier activities be understood. Given a typical DoD system development cycle of one to five years, repetition of data collection every 3-4 months is appropriate because it allows sufficient time for change to occur while not allowing so much time as to mask the cause-and-effect.

There are several ways to obtain this kind of data. It is highly recommended that the data be obtained through interviews of key program personnel conducted by highly knowledgeable, recognized senior systems engineers. This method is considered preferable due to the variability of definitions within the systems engineering community. Each company and each program creates its own definitions during work breakdown and cost estimation. One Work Breakdown Structure includes all systems engineering tasks within a "Program Engineering" category, while another scatters them through "Subsystem Development" numbers. Only through interviews and expert interpretation can the true information be gathered. This is similar to the effective data gathering that is performed during a Capability Maturity Model – Integration (CMMI) Assessment.

The program interviewees likewise need to have the necessary qualifications to provide valid information. The best interviewees for each program include the contractor's Program Manager, Chief Systems Engineer, and Cost Accountant, with separate interviews with the Program Manager's superior (Senior Program Manager, Program Director, etc.) and with the similar personnel in the Government program office. These separate interviews are necessary to obtain several valid viewpoints on the success level of the program. It is also necessary that the different viewpoints be handled in separate interviews so that lower-grade personnel will be free to speak without attribution.

One data collection alternative that is specifically not recommended is an approach that was attempted during the 1990s for software engineering improvement. In that alternative, contracts carried specific clauses requiring repetitive reporting of selected metrics related to software engineering such as Lines of Code, Productivity, Error Rates, Rework Rates, etc. While this approach might seem attractive in its efficiency, it suffers from two significant problems that would invalidate the data for the use of this study: (a) interpretation of the metrics is left to the individual programs, and (b) the metrics are always subject to "gaming" to improve the appearance of the program. Both of these effects were frequently evidenced during the software data collection period.

Data collection must be performed in such a way as to protect the program, the contractor, and the contracting office. This protection is necessary to assure the validity of the data; if personnel perceive that their programs (or they themselves) are being evaluated, then data hiding and data manipulation will skew the study. Data needs to be separated from the program identity at the earliest possible stage, with ironclad protection of the sources. This data protection is another reason for relying on expert interviews, for trusted experts can be contracted with terms to protect the data. Even more, selection of trustworthy experts provides assurance that no contract can give. The selected experts will execute Non-Disclosure Agreements (NDA) with companies and organizations as required.

Efficient data collection through interviews can be managed by identifying programs in groups of four at individual contractor sites. In one day, a pair of interviewers can interview key personnel from four programs.

Appendix A contains a series of interview data sheets created as part of the SECOE project for such an interview process. These data sheets can be a starting place for the data collection for this Government sponsored study, although early work in the project will define the actual data and forms to be used.

5.4 Analysis

Analysis of the gathered data takes two forms: statistical analysis and subjective analysis. Statistical analysis provides the numerical correlations that prove the relationships to be discovered. Subjective analysis explores the cause-and-effect that helps to understand the relationships.

Statistical analysis primarily explores the correlations among the various numeric values obtained. Results will be similar to those obtained in the SECOE project, that show the relationships among the values, except with more detailed structure. It is expected (working hypothesis) that the statistical results will show positive correlation between each widely-accepted systems engineering activity and the quality/cost/schedule success of the programs. Where such correlation cannot be found, it will call into question the worth of the specific activity. In this analysis, the independent variables are considered to be the time and expense incurred for each activity. The dependent variables are the quantified or subjective success measures. Further correlation is needed to incorporate some subjective quantities such as the perceived quality of the activities.

Subjective analysis primarily explores the perceived cause-and-effect relationships over time. Through the subjective analysis, further hypotheses may be identified and included in the statistical analysis.

Throughout the analysis and reporting, the identity of source programs and organizations will be kept strictly in confidence through a double-blind method of maintenance. The linkage between programs/organizations and the collected data will be accessible only to those study participants who have signed NDAs. All other analysts will work only with sanitized data.

5.5 Reporting

With interviews on each ongoing program every 3-4 months, technical reports can be assembled on six-month intervals. Each report would provide results of the statistical and subjective analyses to date, with conclusions and bounds of confidence. Early reports will have insufficient data for partitioning into specific activities, but should provide overall information on the value of systems engineering. As the study project progresses, the reported data should improve in two ways: (a) the bounds of confidence of prior conclusions will be tighter, and (b) conclusions will become available at more resolution into individual activities.

Reports will not identify the programs, contractors, or developing offices. The double-blind protection of the sources will ensure that the identification is restricted to those with signed NDAs. In addition, report results will be carefully evaluated to prevent possible recognition of the source programs through the inherent data itself.

If incentive is needed for DoD contractors to cooperate with the study, then it is also possible to provide those participating contractors with the reports. Contractors will typically view this data as a competitive edge, thereby enhancing their cooperation.

5.6 Project Cost and Structure

Research needs to be managed by a neutral party with significant expertise. There are several reasons for this. First, a neutral party provides the necessary ethical distance to prevent skewing the results due to personal bias. Second, publication of results by a neutral party provides better acceptance of the unskewed answers by the public recipients. Third, effective levels of access require a trusted neutral party, with authority and clearances to view program specific information. It is recommended that the study be undertaken by a center with systems engineering expertise, perhaps in collaboration with a university and/or consortium.

Data gathering must be performed by highly experienced, knowledgeable, and respected ('greyhair") systems engineers with program management experience who can both elicit and interpret the necessary data during the interview process. The interviewers must also be neutral parties who can move among contractor offices and Government offices without conflicts of interest. Dr. Axelband and Mr. Honour are recommended for this role based on (1) organizational neutrality; (2) senior systems engineering expertise; (3) program management experience, (4) experience with value-of-SE projects; and (5) knowledge of DoD policies, practices, and programs.

The project cost is anticipated to be on the order of $500K per year over a three year period. This rough-order-of-magnitude estimate is based on quarterly trips by the recommended high level of researchers to gather data from 30-40 programs; travel expenses; data maintenance and analysis by an academic center using research assistants; writing reports; and necessary administrative overheads. The estimate does not include labor costs for the interviewed program personnel.

After suitable discussions to define scope, relationships and expectations, the authors can be available to provide a more detailed proposal.

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APPENDIX A – INTERVIEW DATA SHEET

Value of Systems Engineering
Project 01-03
Interview Data Sheet

DEFINITIONS

Systems Engineering includes all efforts expended to perform traditional systems engineering tasks, no matter who performs them or where they are performed organizationally. Typical such tasks include technical management, requirements management, system architecting, system technical analysis, system integration, verification/validation, risk management, and other tasks associated with these.

- **Technical Management** includes all effort to guide and coordinate the technical personnel toward the appropriate completion of technical goals. These tasks encompass elements of project planning, technical progress assessment, technical control, team leadership, inter-discipline coordination, and providing common language and goals.
- **Requirements Management** includes all technical effort explicitly oriented toward the requirements or specification of the system. Typical such efforts include mission and/or need analysis, customer or market analysis, domain analysis, requirements elicitation, requirements negotiation, requirements analysis, requirements tracking, and specification development.
- **System Architecting** includes all technical effort whose objective is to synthesis a system solution to the requirements. Typical such efforts include generation of alternatives, architectural diagrams, system synthesis, system design, requirements allocation, interface development or specification, trade-offs, flow analysis or description, or thread analysis.
- **System Technical Analysis** includes all technical effort toward determining the technical performance of the designed system. Typical such efforts include performance analysis, timing analysis, capacity analysis, quality analysis, trending, sensitivity, failure modes and effects analysis, technical performance measurement, and other similar technical evaluations of the system configuration and components.
- **System Integration** includes all technical effort toward the integration of system elements into a working system. Typical such efforts include integration planning, facilities control, integration testing, and regression testing.
- **Verification/Validation** includes all technical effort toward proving the quality of the system. Verification refers to checking the proper execution of the system development processes; validation refers to checking the completed system against operational goals. Typical such efforts include requirements validation, system design verification, element design verification, system verification against requirements, and system validation in its intended environment.
- **Risk Management** includes explicit evaluation of the technical risks in the designed system, system project, or project approach. Typical such efforts include risk identification, risk analysis, mitigation planning, and risk tracking.

Project Cost (Planned or Actual) includes the life cycle costs for the system, broken into phases and categories as available, which may include engineering, management, support, prototyping, first article(s) production, full production, verification/validation, and operation/maintenance.

Project Duration (Planned or Actual) is the schedule duration for the entire system, broken into DoD-5000 phases as available

Systems Engineering Quality is a subjective evaluation of the overall quality of the systems engineering effort. The evaluation is on a scale of 0-10, where 0 represents SE having no useful value, 5 represents a normally effective systems engineering effort, and 10 represents unexcelled, world-class quality. The project may also explore other representations of SE quality, such as those derived from Cost and Schedule Variance or from the source interviewees.

Objectives Success is a normalized number indicating how well the project met its ***original*** system objectives as adjusted for program changes brought about by specification changes, reprogrammings, budget adjustments, etc. **0.0** Project met ***no*** objectives. **1.0** Project met ***all*** objectives. **>1.0** Project ***exceeded*** objectives.

Comparative Success is a subjective evaluation of the overall project success against other comparable projects. The evaluation is on a scale of 0-10, where 0 represents a failed project, 5 represents a project comparable in success to most other projects, and 10 represents unexcelled, world class success.

User Satisfaction is a subjective evaluation of the overall satisfaction perceived by the user in regard to expectations.

Production Quantity is the number of systems produced over the life of the system.

Unit Life Cycle Cost is the estimated total cost, per system, over the entire life cycle of that system. This cost does not include the design and development costs, but does include production, installation, training, operation, maintenance, and disposal.

System Project Characterization

DATE	PERIOD COVERED	PROJECT ID*

*Make **no** entries in any area that identify the project, the company, or the personnel involved

LIFE-CYCLE IDENTIFICATION – Check one appropriate box in each group.

ENTERPRISE LIFE-CYCLE PHASE	ENGINEERING LIFE-CYCLE PHASE
❑ System conceptualization ❑ Simulation prototyping ❑ Advanced technology prototype ❑ Pre-production prototype ❑ Production	❑ Operational definition ❑ Requirements definition ❑ System architecting ❑ Preliminary design ❑ Detailed design ❑ End product physical integration, test, evaluation

QUANTITIES – Enter specific numeric value for each.

SYSTEM QUANTITIES	PROJECT QUANTITIES	PRODUCT QUANTITIES
Number of system requirements	Number of developing organizations	Number of operational scenarios
Number of subsystems	Total number of system trade studies	System production quantity
Number of system elements designed	Number of engineering technologies	Number of customers or customer agencies
Number of off-the-shelf system elements	Number of key performance parameters	Number of installation locations
Number of system elements integrated per system	Number of formal tests	Number of critical algorithms
Number of external system interfaces (system to system)	Number of test locations	
Number of internal system interfaces (element to element)		

SUBJECTIVE PARAMETERS - Evaluate each parameter on a scale of 0 (low) to 10 (high).

SYSTEM PARAMETERS	TEAM PARAMETERS
System element complexity	Quality of tools and methods employed
Requirements stability	Knowledge of the team about the system mission or purpose
Environmental requirements	Experience level of system analysts and systems engineers
Reliability, maintainability, availability severity	Experience level of the lead system engineer
Verification severity	

Project Success

DATE	PERIOD COVERED	PROJECT ID*

*Make **no** entries in any area that identify the project, the company, or the personnel involved

FINANCIAL SUCCESS MEASURES

RETURN ON INVESTMENT (Percent to nearest tenth)	**PROJECTED PERIOD OF RETURN (Months ahead)**
QUARTERLY PROFIT (Percent of cost to nearest tenth)	**QUARTERLY PROJECT COST (Dollars)**
PROJECT COST TO DATE ($)	

CUSTOMER SUCCESS MEASURES

MARKET SHARE (Percent to nearest tenth)	**PROJECTED PERIOD OF MARKET SHARE (Months ahead)**
CUSTOMER SATISFACTION	**SATISFACTION MEASURE (Describe units used)**

PROJECT SUCCESS MEASURES

ORIGINAL PLANNED SCHEDULE (Months, total)	**CURRENT PLANNED SCHEDULE (Months, total)**
ORIGINAL PLANNED COST ($ total)	**CURRENT PROJECTED COST ($ total)**

TECHNICAL SUCCESS MEASURES

NUMBER OF KEY PERFORMANCE PARAMETERS	
TARGET VALUE TPMs (Weighted sum)	**PROJECTED VALUE TPMs (Weighted sum)**

OTHER SUCCESS MEASURES

Describe other success measures used on the project, with value of each. If possible, maintain consistency with prior quarterly data.

Systems Engineering Effort

DATE	PERIOD COVERED	PROJECT ID*

*Make **no** entries in any area that identify the project, the company, or the personnel involved

TECHNICAL MANAGEMENT

EFFORT EXPENDED DURING THE PERIOD (HR)	COSTS EXPENDED DURING THE PERIOD ($)

METHODS – TECHNICAL MANAGEMENT
Describe the methods used to manage the technical effort during this period and subjective evaluations of the quality and effectiveness of the methods.

METRICS – TECHNICAL MANAGEMENT
List any metrics used by the project to evaluate the technical management. Include the current value of each metric

REQUIREMENTS MANAGEMENT

EFFORT EXPENDED DURING THE PERIOD (HR)	COSTS EXPENDED DURING THE PERIOD ($)

METHODS – REQUIREMENTS MANAGEMENT
Describe the methods used to perform requirements management during this period and subjective evaluations of the quality and effectiveness of the methods.

METRICS – REQUIREMENTS MANAGEMENT
List any metrics used by the project to evaluate the system requirements. Include the current value of each metric

Systems Engineering Effort

DATE	PERIOD COVERED	PROJECT ID*

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SYSTEM ARCHITECTING

EFFORT EXPENDED DURING THE PERIOD (HR)	COSTS EXPENDED DURING THE PERIOD ($)

METHODS – SYSTEM ARCHITECTING
Describe the methods used to perform system architecting during this period and subjective evaluations of the quality and effectiveness of the methods.

METRICS – SYSTEM ARCHITECTING
List any metrics used by the project to evaluate the system architecture. Include the current value of each metric

SYSTEM TECHNICAL ANALYSIS

EFFORT EXPENDED DURING THE PERIOD (HR)	COSTS EXPENDED DURING THE PERIOD ($)

METHODS – SYSTEM TECHNICAL ANALYSIS
Describe the methods used to perform system technical analysis during this period and subjective evaluations of the quality and effectiveness of the methods.

METRICS – SYSTEM TECHNICAL ANALYSIS
List any metrics used by the project to evaluate system technical performance. Include the current value of each metric

Systems Engineering Effort

DATE	PERIOD COVERED	PROJECT ID*

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SYSTEM INTEGRATION

EFFORT EXPENDED DURING THE PERIOD (HR)	COSTS EXPENDED DURING THE PERIOD ($)

METHODS – SYSTEM INTEGRATION
Describe the methods used to perform system integration during this period and subjective evaluations of the quality and effectiveness of the methods.

METRICS – SYSTEM INTEGRATION
List any metrics used by the project to evaluate system integration. Include the current value of each metric

VERIFICATION/VALIDATION

EFFORT EXPENDED DURING THE PERIOD (HR)	COSTS EXPENDED DURING THE PERIOD ($)

METHODS – VERIFICATION/VALIDATION
Describe the methods used to perform verification or validation during this period and subjective evaluations of the quality and effectiveness of the methods.

METRICS – VERIFICATION/VALIDATION
List any metrics used by the project to evaluate verification/validation. Include the current value of each metric

Systems Engineering Effort

DATE	PERIOD COVERED	PROJECT ID*

*Make **no** entries in any area that identify the project, the company, or the personnel involved

RISK MANAGEMENT

EFFORT EXPENDED DURING THE PERIOD (HR)	OTHER COSTS EXPENDED DURING THE PERIOD ($)

METHODS – RISK MANAGEMENT Describe the methods used to perform risk management during this period and subjective evaluations of the quality and effectiveness of the methods.
METRICS – RISK MANAGEMENT List any metrics used by the project to evaluate technical risks. Include the current value of each metric