

Value of Systems Engineering – SECOE Research Project Progress Report

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Abstract. This paper is a progress report on the results of a SECOE research project to collect and analyze data that describes project cost, schedule, and quality with systems engineering cost and quality. The original hypotheses to be tested are that (a) at low levels, increasing systems engineering effort results in better project quality, and (b) there is an optimum above which further increases are detrimental. The collection of data is much more difficult than anticipated. The preliminary results are presented in an attempt to encourage more individuals to submit data. Analysis of the preliminary data (25 project submissions) supports the hypotheses. The data suggests that dimensionless ratios of actual to planned cost and actual to planned schedule correlate with an independent variable defined as an index of systems engineering effort (product of systems engineering cost and systems engineering quality divided by total project cost).

difference that the relationship shown in the NASA data only loosely supports a hypothesis related to systems engineering.

BACKGROUND

For many years, project managers and systems engineers have feuded over the level of systems engineering effort that is appropriate for each project. While many individuals suggest that intuitive information exists, it has yet to be shared or made public. There is a desperate need for quantitative information that can guide managers and technical leaders. Werner Gruhl of the NASA Comptroller's office presented the only known public results that relate project quality metrics with some form of systems engineering effort (Figure 1). This data was developed in NASA in the late 1980's for 32 projects over the 1970s and 1980s. It was made public over ten years ago. While various organizations maintain similar data on their in-house efforts, these data are not shared to protect their competitive advantage.

Even the NASA data, however, does not directly apply to systems engineering. In Gruhl's research, the independent variable is the percent of funding spent on NASA Phases A and B, the project definition phases. Figure 2 shows the difference between this and true systems engineering effort. It is apparent from this

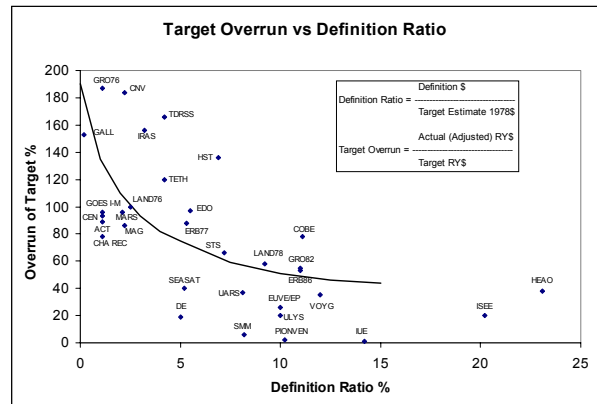


Figure 1. NASA Data on Impact of Front End Project Definition Effort

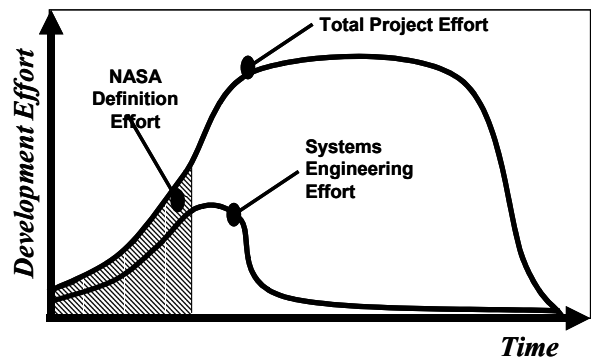


Figure 2. Definition Effort is not Equal to Systems Engineering Effort

In March of 2001, the Systems Engineering Center of Excellence (SECOE), a subsidiary research arm of INCOSE, initiated project 01-03 to collect and analyze data that would quantify the value of systems engineering. The INCOSE Board of Directors supported the project with seed grant money to leverage other sources.

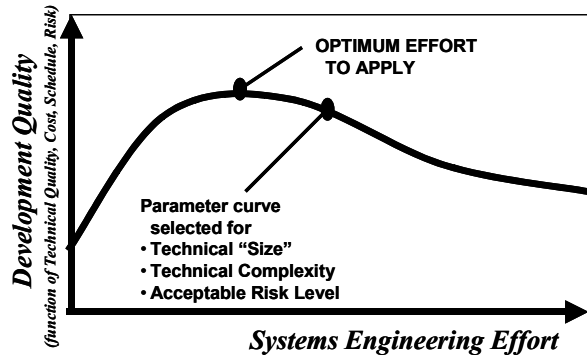


Figure 3. Initial project hypothesis

The overall goal of this project is to collect and analyze data which would relate “Development quality” with “Technical effort” for a wide range of engineering projects that employed various levels of systems engineering. The initial hypothesis as in Figure 3, based on widely accepted heuristics, was that development quality would be directly related to systems engineering effort up to an optimum level, after which additional systems engineering effort would impede quality. Development quality would include technical quality, cost, schedule and risk. The project desires to explore parameters such as technical complexity, size or scale as well as effort.

SECOE PROJECT 01-03 STATUS

In the spring of 2001, an executive summary of the project (SECOE 2001a), a grant solicitation (SECOE 2001b), and a data submission form (SECOE 2001c) were placed on the SECOE web site.

The grant solicitation defined a three-phase effort. Phase I is a volunteer effort to obtain subjective data, Phase II would be an INCOSE funded grant for up to \$15,000 to evaluate the subjective data and prepare for Phase III. Phase III would be a two-year set of grants to obtain and evaluate contractual data, to be funded from other sources at approximately \$50,000.

The schedule for submission and evaluation was defined as the month of June, 2001 with Phase II scheduled for the summer of 2001.

Unfortunately, the only proposal submitted was one by Mar to conduct the research as a volunteer effort, in case no proposals were submitted. In hindsight, it became apparent that the academic community viewed grants for less than \$100,000 per year to have a poor return on investment. The effort to prepare a proposal for the SECOE was the same as that required for a \$100,000 or greater proposal. Also the turn around time of one month in June is not feasible for academic research. Graduate students are assigned to summer research in the Fall as part of their initial research assistantships. At the latest, the good graduate students have their summer research selected by winter.

The lesson for SECOE to learn was to anticipate that grant awards must be announced and made nine to twelve months in advance of the start date. Grants smaller than \$50,000 will not be well received by graduate researchers, but possible undergrads may be sought as summer hires to perform such research if an appropriate mentor or supervisor can be found.

In addition to the lack of proposals to perform the “Value of Systems Engineering Project”, the response to the call for voluntary submission of project information for the phase I data base was poor. A survey form was prepared and placed on the SECOE web site with notice on the INCOSE home page. The same form was distributed in email and hard copy forms to many INCOSE members. The scope of the project and the implementation plan were also placed on the INCOSE home page with a special call for inputs. Only a few responses were received along with several messages indicating that the requested data was unavailable to systems engineers or that the requested data was inappropriate. Alternative actions to obtain more responses to the survey are in progress and have resulted in 25 project submissions. A search is underway for program managers or executives of engineering organization to identify people who may have such data available.

TECHNICAL PARAMETERS

Measuring development quality and technical effort is a challenge in today’s environment of heuristic knowledge. Following (Honour 2001), technical quality can be measured by the degree to which the system meets its intended objective function. Cost and schedule can be measured using both planned and actual values, thereby also allowing a measurement of how well the project met its plans for cost and schedule. As in (Honour 2001) and (Langenberg 1999), risk can be measured numerically based on the cost exposure represented by all known risks.

The original data submission form was created for total project data as well as phase-by-phase reporting for data. The form for total project data 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 can be found on the submission form. A brief definition of terms are:

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

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).

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 project failure, 5 indicates success equal to other projects, and 10 indicates unexcelled, world class success. This subjective measure is intended to be an alternate measure of the project success.

In the preliminary form, the data submission requested planned and variance values for cost and schedule rather than planned and actual values. The responses to the variance parameters indicated that the convention used to indicate over or underruns was confusing. Thus the form was modified to ask for actual and planned cost and schedule, and then the variance was computed by the analyst.

Since the request for data included a Proprietary Data policy indicating that all responses will be screened to avoid identification of data sources, the ratios of planned to actual and schedule are placed in the data base. Thus the form could be modified to request such ratios rather than the absolute values for cost and schedule. Doing so, however, would eliminate the future potential of stratifying the project information by size, complexity and risk. If more data can be solicited, this issue will need to be addressed. If requesting only ratios of planned to actual values increases the number of responses, the stratification analysis may have to be a follow up task.

DATA ANALYSIS

The analysis of data received was performed in an EXCEL worksheet. Data were entered in row format. If variance data were submitted, then the actual values were computed as planned values minus the actual values, assuming that a positive variance indicated a value below planned. For later submissions that submitted planned and actual values (no variance data) this was not necessary. To reduce the chance that a data source could be identified, ratios of planned to actual values were computed.

Cost and Schedule Performance. The initial analysis plotted the actual to planned ratios for cost and schedule (hypothesized dependent) versus the systems engineering effort (hypothesized independent), where

the effort was normalized as the ratio of systems engineering costs to total actual costs. There was no apparent trend in these relationships.

Upon further analysis, it was hypothesized that the systems engineering quality would impact the effectiveness of the systems engineering costs expended in a project in a linear relationship. Thus, if the systems engineering quality (SEQ) is zero, no amount of investment in the systems engineering effort will improve the project cost or schedule performance. A project with a SEQ of 10 should have twice as good performance as a project with a SEQ of 5.

To apply SEQ as a linear scaling factor on the ratios, the SEQ scale was compressed to a 0 to 1 scale (reported SEQ was divided by 10). This redefined the (normalized) systems engineering effort (SEE) as

$$SEE = SEQ * SE Cost / Actual Cost$$

The results of this analysis are shown in Figure 4 and Figure 5. Figure 4 shows the data for actual cost (AC) / planned cost (PC), while Figure 5 shows the data for actual schedule (AS) / planned schedule (PS).

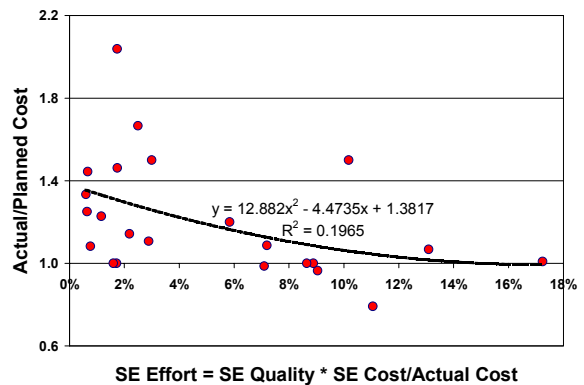


Figure 4. Cost performance as a function of systems engineering effort

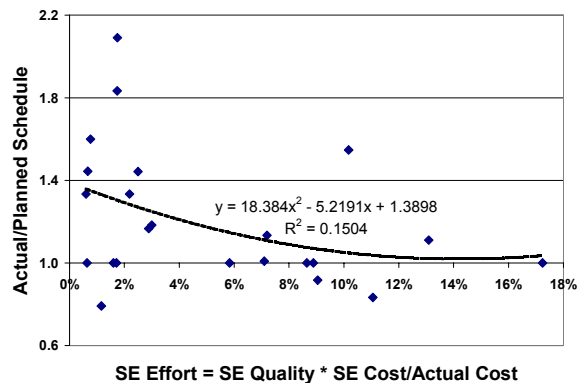


Figure 5. Schedule performance as a function of systems engineering effort.

Each figure also shows a trend line based on the statistical averaging of the data points to the hypothetical relationship. Trend lines are calculated by EXCEL using least-squares regression on the data and that curve form that results in the most favorable regression correlation. In both cost and schedule cases, the best fit is obtained with a second order polynomial. As expected, there is also a large scattering of the data indicative of the effects of many determinants other than the systems engineering effort.

Cost and Schedule Risk. The data scattering of Figure 4 can be interpreted as cost risk, i.e. the statistical variation in cost due to unplanned factors. Figure 6 shows the residual cost risk after removal of the correlated trend line values. Figure 6 suggests that the larger the SEE, the smaller is the residual from the fit. Thus at lower SEE the actual to planned costs are not only higher, but there is a greater risk that the residual deviation from the predicted value is higher.

This cost risk can be evaluated statistically as the second moment of the distribution. By applying least-squares regression analysis to the residual values, Figure 7 shows the cost risk as 90% probability bounding curves around the trend line. Values for the cost risk bounding curves are based on a statistical variance of $\sigma^2 = 0.036 * e^{-16 * SEE}$. It is a significant addition to the project findings to note that the risk reduces significantly with increased SEE. Specifically, the risk at 15% SEE is approximately 1/3 of the risk at 1% SEE.

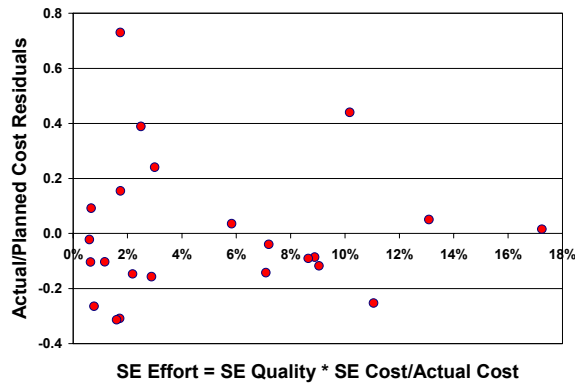


Figure 6. Residual of actual/planned cost

A similar analysis of schedule risk results in the 90% probability bounding curves shown in Figure 8. As with cost risk, schedule risk is also shown to reduce significantly with increased SEE. Values for the schedule risk bounding curves are based on a statistical variance of $\sigma^2 = 0.039 * e^{-13 * SEE}$. The schedule risk at 15% SEE is once again approximately 1/3 of the risk at 1% SEE.

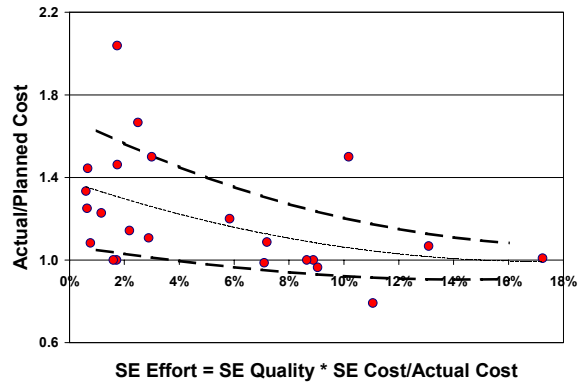


Figure 7. Cost risk shown as 90% assurance curves around trend

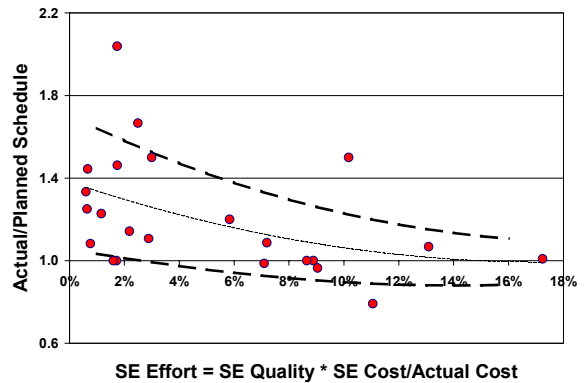


Figure 8. Schedule risk shown as 90% assurance curves around trend

Cost and Schedule Correlation. The similarities in cost and schedule performance and in cost and schedule risk imply that cost and schedule themselves are highly correlated. This hypothesis matches heuristic management wisdom. As a check, Figure 9 plots AC/PC against AS/PS to show that performance in each dimension is highly correlated.

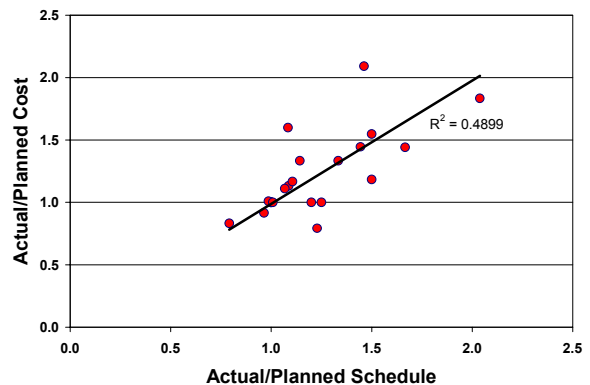


Figure 9. Correlation of cost and schedule.

Parametric Evaluation of Risk. The large scatter in the data at low levels of the independent variable SEE was explored. In the original hypothesis, “development quality” is heuristically expected to be a function of technical size, complexity, and risk. The variance seen in the earlier figures may be explained by these as-yet-unmeasured factors. It was hypothesized that actual cost might be a valid measure of technical size. Thus, large projects would do less well than smaller projects at any given expenditure of SE Effort. To explore this secondary relationship, the impact of total costs on the actual to planned costs was examined for SEE values of 2%-3%. The results are shown in

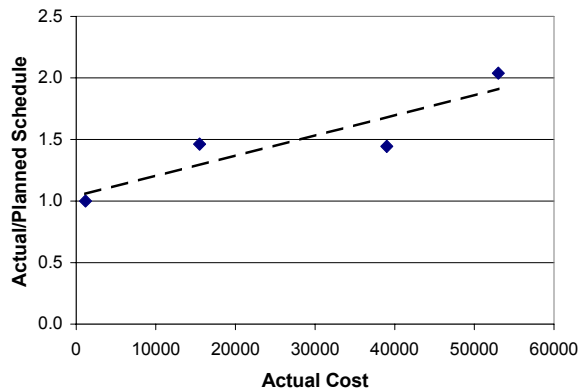


Figure 10. While there are few data points, the relationship appears to exist and more data needs to be collected.

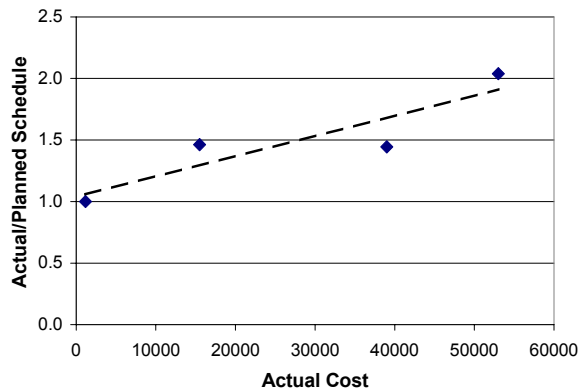


Figure 10. Impact of project size on schedule performance (SEE = 2%-3%)

Development Quality. In the original hypothesis of Figure 3, Development Quality (DQ) is expected to be a function of technical product quality, project cost, project 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:

$$DQ = 1 / (\frac{1}{2} * (AC/PC + AS/PS))$$

Figure 11 shows this rudimentary DQ plotted against SEE. There is already 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. It is noted that none of the projects submitted so far appear to be beyond the assumed optimum.

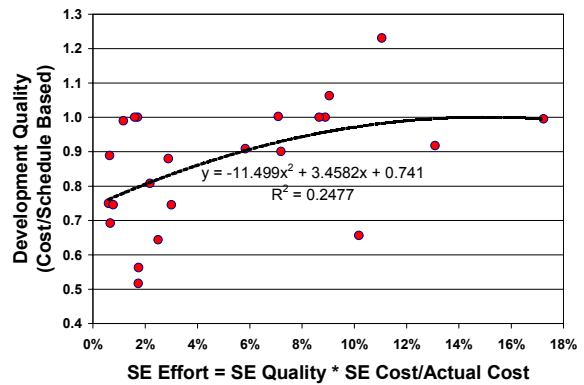


Figure 11. Test of original hypothesis

As a second test of the original hypothesis, Figure 12 plots the comparative success values as reported by respondents. This shows that respondents perceived significantly lower success with projects that had low SEE (in comparison to other projects) than with projects with high SEE. The shape of the comparative success also approximates the original hypothesis, indicating that this subjective value might also be a rough measure of the hypothesized DQ.

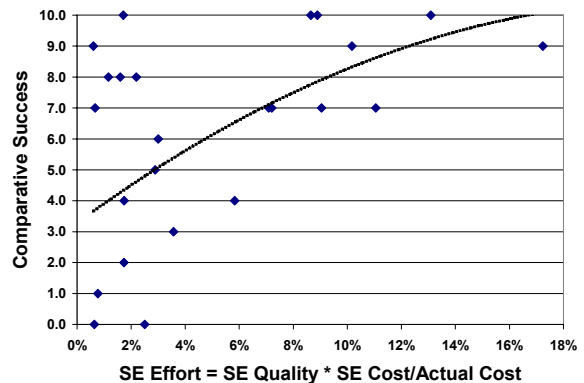


Figure 12. Subjective quality as reported

LIMITATIONS

The data available for analysis in this project presents 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.

The number of data points is small, only barely sufficient to support the statistical conclusions made.

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

FUTURE WORK

The initial data analysis suggests that there is a strong case to be made for a quantitative relationship between systems engineering investment and the quality of project performance. Far more data is needed, however, to quantify and parameterize the relationships. It is hoped that this project report will stimulate organizations to share their data on systems engineering effectiveness to support work such as this research project.

A significant future benefit of this continuing work is in the estimation of systems engineering effort. If the original hypothesis can be proven, quantified, and parameterized, then future systems project will be able to select a level of systems engineering investment that is appropriately optimum for the desired product quality and risk.

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BIOGRAPHIES

Dr. Brian Mar is an Emeritus Professor of the University of Washington. Prior to his retirement, he was at the University of Washington for over 30 years and was a Professor of Civil and Systems Engineering. The Boeing Company employed him for 10 years prior to his joining the University of Washington. He holds a Ph.D. in Chemical/Nuclear Engineering as well as several degrees in Civil and Chemical Engineering and has served on International and National councils and advisory boards. He is a member of Phi Beta Kappa and Tau Beta Pi Honor Societies. Currently he is mentoring the development of a web based MS Systems engineering program at Portland State University. He is one of the founders, a Past President and a Fellow of INCOSE. He has published several books and over 100 papers.

Eric Honour was the 1997 INCOSE President. He has a BSSE from the US Naval Academy and MSEE from the US Naval Postgraduate School, with 34 years of systems experience. He was a naval officer for nine years, using electronic systems in P-3 anti-submarine warfare aircraft. He has been a systems engineer, engineering manager, and program manager with Harris, E-Systems, and Link. He has taught engineering at USNA, at community colleges, and in continuing education courses. He was the founding President of the Space Coast Chapter of INCOSE. He was the founding chair of the INCOSE Technical Board. Mr. Honour provides technical management support and systems engineering training as President of Honourcode, Inc., and is the director of the INCOSE Systems Engineering Center of Excellence.