Systems Engineering Return on Investment

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Abstract. Research work continues into Systems Engineering Return on Investment (SE-ROI) following prior work on Value of Systems Engineering and Systems Engineering Effectiveness. This paper presents major results in the form of statistically proven relationships between systems engineering (SE) activities and the technical, schedule and cost success of programs. It has been found that all defined SE activities correlate positively with program success as measured in three of four success metrics used (cost overrun, schedule overrun and perceptive success). When the effect of program characterization parameters is included, the correlation is strong with optimum levels of SE activities as much as 25% of a program cost. The paper presents quantified values for the relationships, indicating appropriate levels of each SE activity that correlate to optimum levels of success. Results show a surprising lack of correlation between SE activities and the technical quality of the product system, for which some possible explanations are provided.

Background

The challenges of developing and sustaining large complex engineering systems have grown significantly in the last decades. The practices of systems engineering promise to provide better systems in less time and cost with less risk, and this promise is widely accepted in some industries. However, we have long lacked 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.

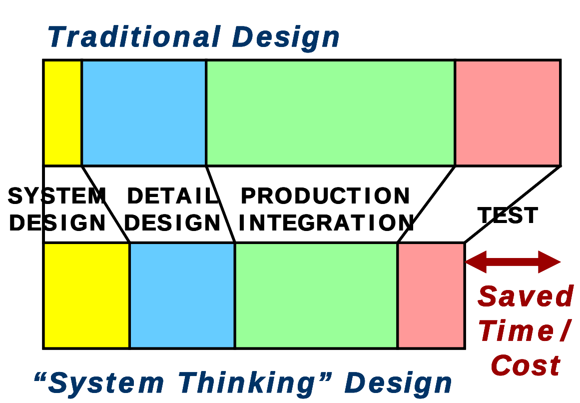

Figure 1. Intuitive Value of SE.

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

[1] This paper was published in the proceedings of the INCOSE International Symposium, Chicago 2010

engineering concepts appears to be to reduce risk early, as shown in Figure 2. By reducing risk early, the problems of integration and test are prevented from occurring, thereby reducing cost and shortening schedule. The challenge in understanding the value of SE is to quantify these intuitive understandings.

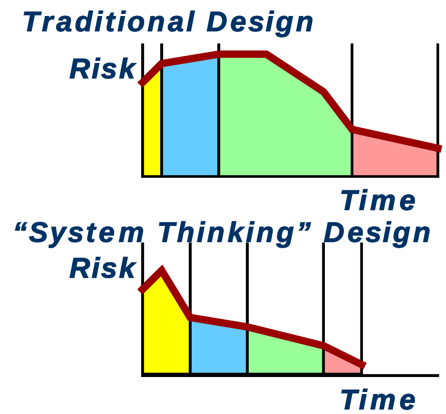

Figure 2. Risk Reduction by SE.

The Systems Engineering Return on Investment (SE-ROI) project (Honour 2006a) continues the work reported in prior publications by the author and others.

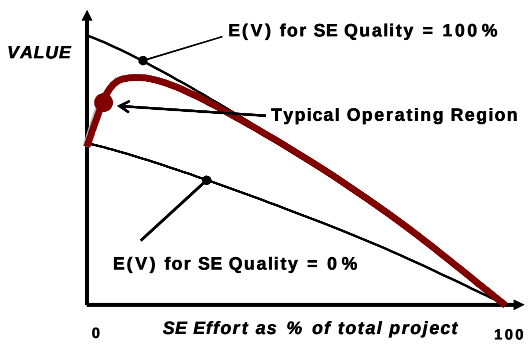

Figure 3. Seeking Optimum Level of SE Effort Within Projects.

Theoretical relationships were explored by the author concerning optimizing systems engineering value (Honour 2001) and quantitative relationships (Honour 2002). In those works, the characteristic values and mathematical relationships were explored using end-point value theory to display the forms of the relationships. One key result was the core hypothesis of the current work, which is that there exists a quantitative relationship between the systems engineering activities and the success of the program. Figure 3 shows that primary theoretical relationship. The thin lines represent the achievable value for different levels of SE Quality (SEQ). The lower thin line is the value obtainable if the SE effort that is extracted from the project performs no effective SE, i.e. reduction in effective project 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 SE effort (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 project without SE can still achieve some value), grows to a maximum, then diminishes to zero at SEE = 100% (all project effort is assigned to SE, so no system is produced).

In the Value of Systems Engineering work (Honour 2004), the author quantitatively demonstrated this relationship between systems engineering and program success using anonymous surveys. The graphic results reported in that work, shown here as Figures 4 and 5, indicated that systems engineering effort is optimized at a level of 15% or greater of the total program cost. At this level, both cost and schedule overrun appear to be minimized. Other prior works also provide anecdotal quantifications based on limited source data or limited conditions. There is a summary of prior works in (Honour 2004).

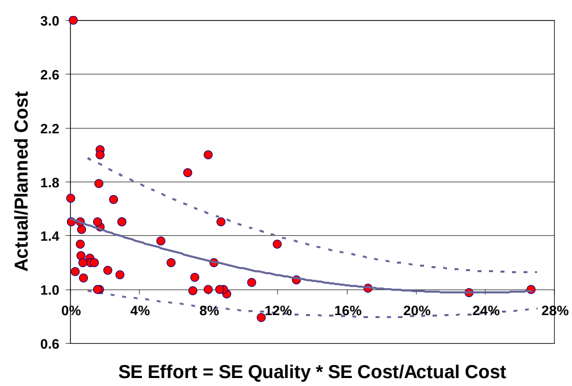

Figure 4. Cost performance as a function of SE effort

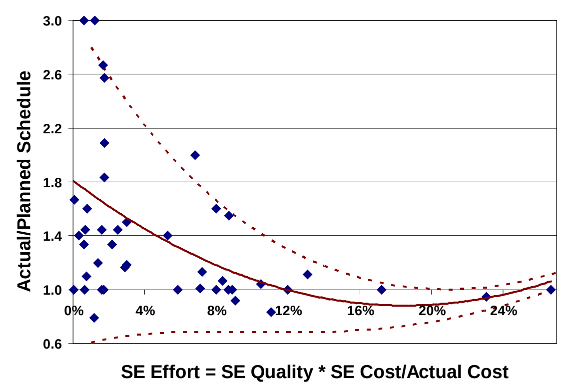

Figure 5. Schedule performance as a function of SE effort.

Yet as powerful as they are, the 2004 results were admitted by the author as not academically rigorous. The work discussed its own limitations. Included among those limitations were

- The anonymous survey method, leading to lack of quality control on the source data.
- The possibility of perceptive influences by the largely SE body of respondents who had access to the surveys.
- Potential definition differences by the respondents, who may have reported differing scope of work as being "SE activities."
- Self-selection of programs from among those that typically use formal SE.
- Lack of detailed structure data from which to obtain more definitive conclusions.

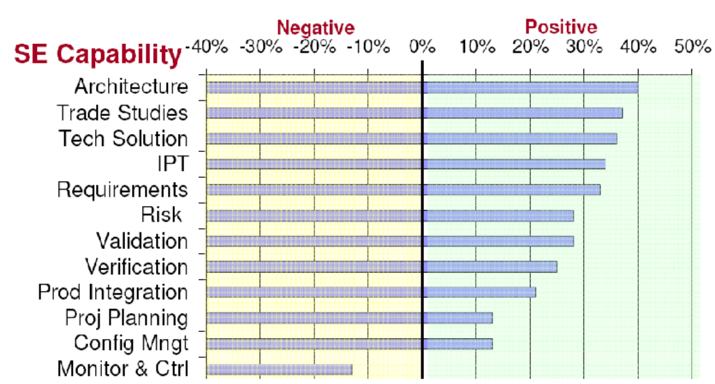

Figure 6. SE Capabilities Correlate to Project Success

Some of these weaknesses have been addressed by later work. In the Systems Engineering Effectiveness report (Elm et al. 2007), more extensive surveys provided further detail into the relationships between specific systems engineering activities and program success. As shown in Figure 6, the results indicated moderately strong correlation with success for the following capabilities (in order of correlation strength): product architecture, trade studies, technical solution, integrated product teams, requirements engineering, and others. In this survey, respondents anonymously answered a large number of questions about systems engineering activities and program results. The capability categories were assembled from related survey questions, statistically combined in the correlation process. Program success was also assembled from related survey questions. The results advance our knowledge of which SE activities appear to have the greatest effect, but still present some of the same limitations due to the anonymous nature of the surveys.

Another recent approach to quantifying the value of SE was presented in (Boehm 2008). In this work, the authors examined the existing data in the COCOMO software cost estimation model for indications about the ROI of systems engineering. Some results were found in the "Architecture and Risk Resolution" (RESL) factor, which tracks a portion of what is considered to be SE activity that precedes a software development. As shown in Figure 7, there is a strong positive correlation of the RESL factor to the size of the project that indicates this SE activity. Large software development programs require a significantly larger addition of effort for architecture and risk resolution.

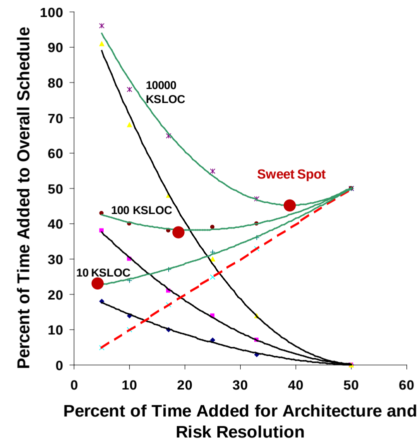

Figure 7. Greater SE Activity for Larger Software Programs

SE-ROI Research Program

Preparation for the current SE-ROI work started immediately after the publication of the author's 2004 results and has been reported in several publications. The plan for the SE-ROI research was published in (Honour 2006a) and is summarized below.

Interview Method. The SE-ROI project implemented a comprehensive and detailed gathering of information from real programs. The research obtained data from 51 programs in 16 different developing organizations. Data obtained through the interviews falls in three basic classes:

- Program success, measured in technical, cost, schedule, and subjective terms.
- Systems engineering effort, measured in labor cost against the program total cost, as a total and in each of eight categories of SE activity.
- Program characterization values (size, complexity, quality) that parameterize the expected correlation of systems engineering effort with program success.

Standardization of the data required using a structured interview process so that the interviewer could perform a consistent interpretation of the native program data into common definitions. The interviewer needed to be a senior individual with extensive program management and systems engineering experience, unbiased, and capable of probing beyond the initial question to get at the true data. The principal investigator fulfills these qualifications and performed all interviews for consistency. Many of the interview principles were selected using the pattern established by (Valerdi 2004).

Standard forms for the interviews were important and needed to reflect the best perceived *a priori* organization of SE practices to be tested. An early step in the research, therefore, was to define and obtain broad review on an ontology sufficient to provide useful and widely-accepted categorization of systems engineering activities. The ontology and resulting categorization was reported in (Honour/Valerdi 2006). Following the development of this categorization, the project developed and tested interview data sheets to obtain the necessary data (Honour 2006b). The interview data sheets were further reviewed through conference publication and detailed peer/supervisory review.

Program Access. The research is based on real programs, for which data can be both proprietary and difficult to obtain. Data obtained from programs is obviously proprietary to the parent organizations, including key business parameters of technical success, cost, schedule and risk. Therefore, all interview data is maintained by the principal investigator in accordance with proprietary data agreements with the participating organizations. These protections were necessary to obtain access to the required data.

Basic Demographics

SE-ROI interviews occurred from 2007 through 2009.

Table 1 displays the primary demographics of the data, including funding methods, cost and schedule compliance, and systems engineering content.

Table 1: Basic Demographic Data

Characteristic	ValueSE Data Set	SE-ROI Data Set
Number of organizations	Unknown	16
Number of data points	44	48[2]
Funding method	Unknown	39 contracted, 9 amortized
Program total cost	\$1.1M - \$5.6B Median \$42.5M	\$600K - \$1.8B Median \$14.4M
Cost compliance	(0.8):1 – (3.0):1 Median (1.2):1	(0.6):1 – (10):1[3] Median (1.0):1
Development schedule	2.8 mo. – 144 mo. Median 43 mo.	2 mo. – 120 mo. Median 35 mo.
Schedule compliance	(0.8):1 – (4.0):1 Median (1.2):1	(0.3):1 – (2.5):1 Median (1.1):1
Percent of program used in systems engineering effort, by cost	0.1% - 27% Median 5.8%	0.1% - 80%[4] Median 17.4%
Subjective assessment of systems engineering quality (scale of 1 poor to 10 world class)	Values of 1 to 10 Median 5	Values of 1 to 10 Median 7

The data on which this report is based comes from two different data sets, obtained using different methods.

- "Value of Systems Engineering" data includes 44 program data points obtained during 2001-2004 as a part of the prior project (Honour 2004). This data was obtained through

[2] (Table 1, "Number of data points") Three of the 51 interviews resulted in incomplete data.
[3] (Table 1, "Cost compliance") One amortized program had a highly excessive 10:1 overrun in cost, likely due to poor estimation of effort. The next largest cost overrun is 3:1.
[4] (Table 1, "Percent … systems engineering effort") There were four outlier points with very large SE content at 80%, 51%, 48% and 46%. All other programs have SE content at less than 31%. All four outlier programs were systems with highly unusual characteristics.

voluntary, anonymous surveys using a simple data sheet.

- "SE-ROI" data includes 48 program data points obtained during 2007-2009 as a part of the SE-ROI project. This data was obtained using interviews guided by the interview data sheet designed for SE-ROI.

An earlier publication (Honour 2009) presented interim demographics with 30 interviews completed. While interviews have now been expanded to 51, the basic demographics from that prior work are still valid. See the prior work for indications of the business domains and breadth of data sources used in this work.

Basic Measures

Correlations in this research are primarily between SE effort and program success. There are nine quantitative measures for SE effort and four quantitative measures for program success.

Systems Engineering Effort. The primary measure of SE effort is the percent of the program effort that was used to perform SE activities. Among several different possible measures, the author chose to use the cost ratio based on its importance to program success and pre-program costing. In addition, as described in the early work by (Mar/Honour 2002), the cost ratio is further modified by the respondents' subjective assessment of the quality of the SE effort (SE Quality, or SEQ). This redefined the (normalized) systems engineering effort (SEE) as

SEE = SEQ * SE Cost / Actual Cost

Further adjustment was made to SEE for the front-end efforts. Each interview reported on the "level of definition at start," on the following scale. Figure 8 shows a response histogram.

- Poorly-defined user problem
- User problem well defined.
- Meta-system architecture diagrammed
- System mission/operations defined
- Performance-based requirements documented
- Complete system technical requirements documented.
- System architecture diagrams completed to next-level components
- Technical requirements allocated to next-level components

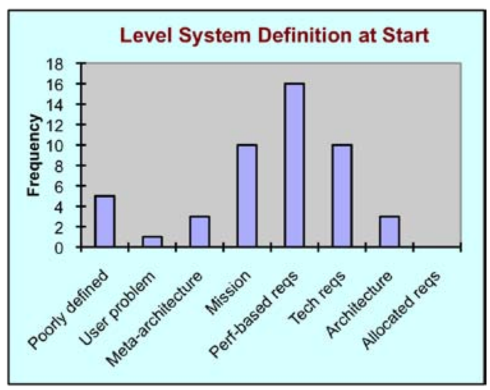

Figure 8. Start Definition of Interviewed Programs

Because many programs started at later points in the SE definition, the SEE was further modified to correct of the missing front-end data. The correction averaged the percent expended within each of the early stages, then added that amount to programs that did not perform the stage.

Systems Engineering Activities. Also of interest is the spread of the SE effort across eight defined categories of SE activity. For each activity, a similar normalized ratio of activity cost to program total cost is used as a measure of the level of activity. Figure 9 shows a histogram of the level of effort applied within each of the eight categories. Those categories are:

- <u>MD - Mission/Purpose Definition</u>. Includes (a) describing the mission and (b) quantifying the stakeholder preferences. Usually done in the language of the system users rather than in technical language, often performed by marketing groups or a contracting agency before involving systems developers.

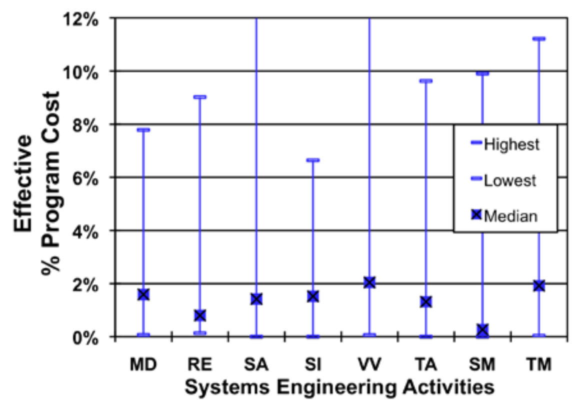

Figure 9. SE Activities Histogram

- <u>RE - Requirements Engineering</u>. Creation and management of requirements, formal technical statements that define the capabilities, characteristics, or quality factors of a system. May include efforts to define, analyze, validate, and manage the requirements.

- <u>SA - System Architecting</u>. Synthesizing a design for the system in terms of its component elements and their relationships. Diagrams depict the high-level concept of the system in its environment, the components of the system, and the relation of the components to each other and to the environment. Process usually involves generation and evaluation of alternatives, then defining the components by the use of allocated requirements.

- <u>SI - System Implementation</u>. Systems engineering effort to support creation of a first functioning or prototype system that meets the defined mission or purpose. Specific system-level efforts include system integration and transition to use.

- <u>VV - Verification and Validation</u>. Verification is the comparison of the system (or developmental artifacts) with its requirements through the use of objective evidence. Validation is the comparison of the completed system (or artifacts) with the intended mission.

- <u>TA - Technical Analysis</u>. Multi-disciplinary analysis focused on system emergent properties, usually used either to predict system performance or to support decision trade-offs. Includes functional analysis, predictive analysis, and trade-off analysis, except when inseparable from requirements engineering or system architecting. Also includes 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.

- <u>SM - Scope Management</u>. Technical definition and management of acquisition and supply issues. Defining technical contractual relationships both upward (development contract or marketing definition) and downward (subsystem or component definition/control).

- <u>TM - Technical Management/Leadership</u>. Efforts to guide and coordinate the technical personnel toward the appropriate completion of technical goals. These tasks encompass elements of program planning, technical progress assessment, technical control, team leadership, inter-discipline coordination, providing common language and goals, risk management, configuration management (when performed as part of leadership), and interface management.

Program Success. The data structuring of the research interviews was designed to allow four different measures of program success:

- Cost Compliance. Degree of compliance with planned cost is measured by the ratio of actual cost to planned cost.
- Schedule Compliance. Degree of compliance with planned schedule is measured by the ratio of actual program duration to planned program duration.
- Overall Success. The success of the product/program as perceived in the viewpoint of the stakeholders, measured by a single subjective assessment on a scale of 1-to-5 allowing 0.5 scores.
- Technical Quality. The technical quality of the product system is measured by the quantified compliance with the stakeholder Key Performance Parameters (KPPs) as described in (Browning/Honour 2005). The scale used for compliance is translated linearly from the original KPP values to a scale of 0=failure; 1.0=threshold acceptance; 2.0=highest objective. All KPPs are then combined using a weighted sum. Estimation of actual performance, stakeholder threshold/objective values, and weights was done in each interview from the viewpoint of the stakeholders.

Systems Engineering versus Program Success

This section shows the statistical correlations observed in the data between the total SE Effort (SEE) and the four defined program success measures.

Figures 10 and 11 show the correlation between SEE and cost/schedule compliance. This is an extension of the data reported in (Honour 2004), which is repeated on this graph as the small red data points. The larger blue data points are the SE-ROI data. The relationship observed in 2004 is still evident, for levels of SEE less than about 12%, although there are fewer such programs in the SE-ROI data set. However, the SE-ROI data also now provides more information for programs with greater SEE. The relationships now show an obvious optimum at about 15% SEE. A similar relationship is seen in Figure 12, demonstrating the correlation to overall subjective success.

The trend lines on the graphs show that the interview data conforms to and extends the same trends as the 2004 data, thereby corroborating both methods. The addition of the SE-ROI data provides a much better estimation of the optimum point of SE effort, although still confirming that the optimum appears to be between 15% and 20% of the total program cost.

It should also be noted, however, that there is a wide variation. This is to be expected, because program success depends on many factors other than SE activity. Those other confounding factors (e.g. program management, stakeholder changes, personnel quality, etc.) cause many variations that SEE cannot control. See the "Future Work" section for a discussion of how the correlations are being improved by consideration of the many characterization parameters.

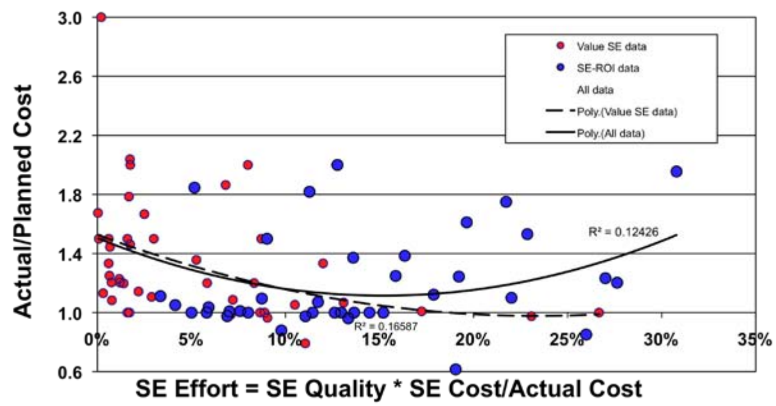

Figure 10. Correlation of SE Effort to Cost Compliance

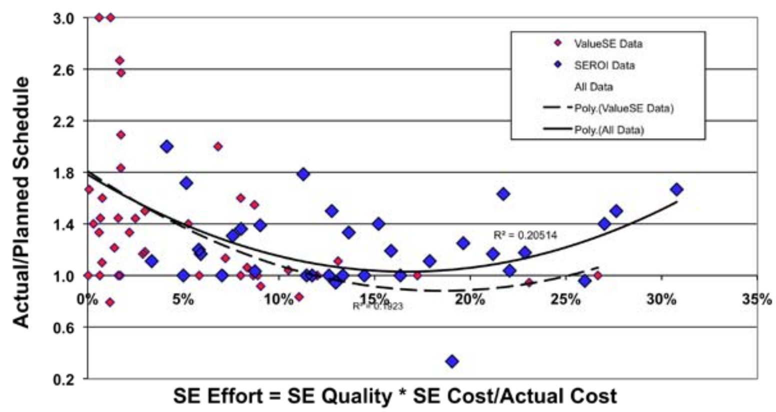

Figure 11. Correlation of SE Effort to Schedule Compliance

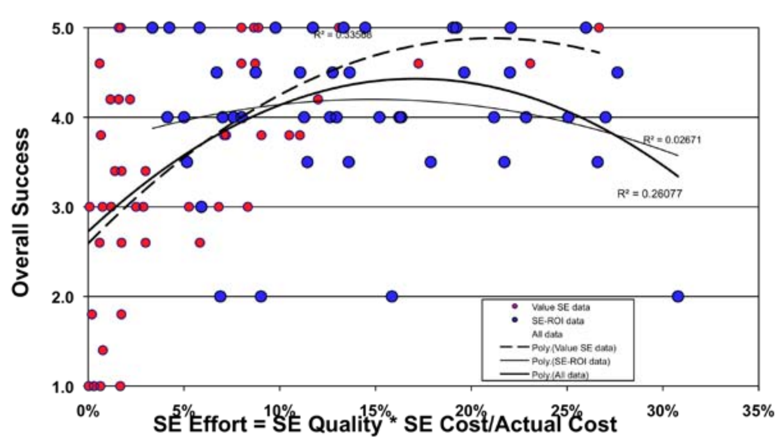

Figure 12. Correlation of SE Effort to Subjective Success

The fourth program success measure shows an unexpected result. As seen in Figure 13, there is little to no apparent correlation between SEE and the defined measure of technical quality that is based in meeting the stakeholder KPPs. Programs appear to randomly fall within the threshold (=1.0) and objective (=2.0) levels, without relation to the level of SEE. In its raw form, this chart could be interpreted as indicating that SE effort has little effect on the quality of the product system.

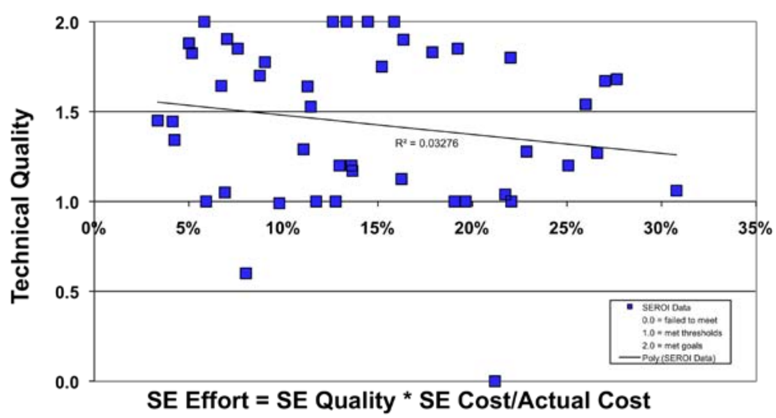

Figure 13. Correlation of SE Effort to Technical Quality

As noted earlier, the "technical quality" measure is obtained by identifying the quantifiable KPPs that matter to the stakeholders (e.g. aircraft range, satellite reliability, ship displacement, signal throughput, etc.), with acceptable (threshold) and objective levels for each. The actual values obtained by the system product were then compared with the threshold/objective levels and translated linearly into the graph scale of 1.0 to 2.0. Lack of correlation appears to indicate that programs (and traditional SE processes) place their primary emphasis on minimum requirements compliance. Any higher quality is often attained only if it is occurs without significant effort. As a result, products developed using these traditional SE processes may have difficulty competing with higher quality products.

SE Activities versus Program Success

Unlike the prior works, the research has also gathered data to determine the correlation between eight subsidiary SE activities and the same program success measures. This section shows the statistical correlations observed in the data between the SE activities and the four defined program success measures.

Figure 14 shows the correlation graphs for each of the eight SE activities against cost compliance. There is an obvious correlation with each activity except mission definition (MD). The relationship for MD is poor because few of the interviewed programs had performed much MD effort; most programs started with the MD effort already completed elsewhere. Each of the other charts has a coefficient of determination (R^2) on the order of 5% to 20% - weak correlation, but understandable given the wide number of confounding variables that apply to program cost compliance. The graphs also roughly indicate the level of each activity at which cost compliance is optimized, measured in percent of total program cost expended in this activity.

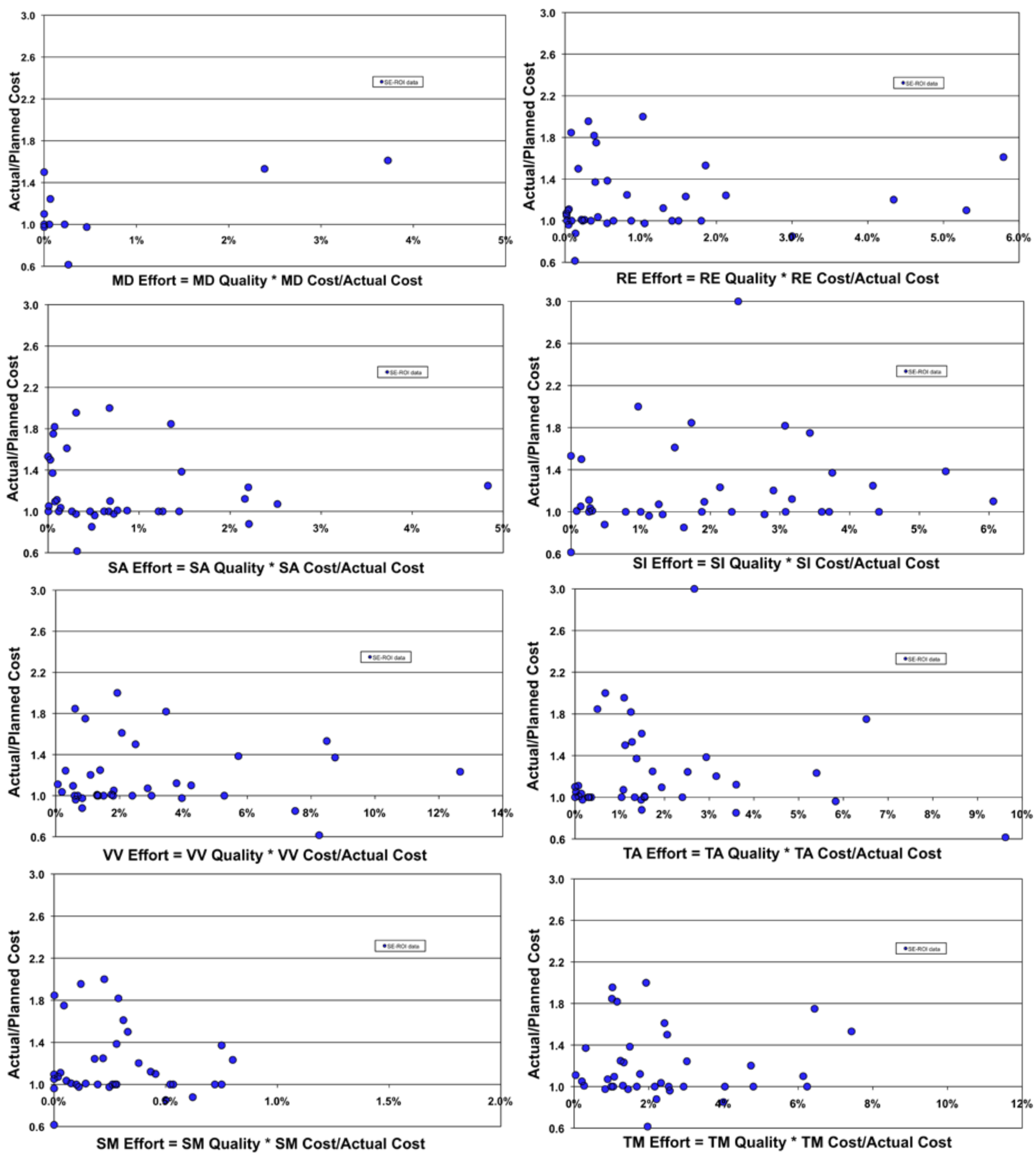

Figure 14. Correlation of SE Activities to Cost Compliance

Figure 15 shows the correlation graphs for the eight SE activities against schedule compliance. Again, there is an obvious correlation with each activity except MD. As for cost compliance, the correlation levels are weak but distinctive.

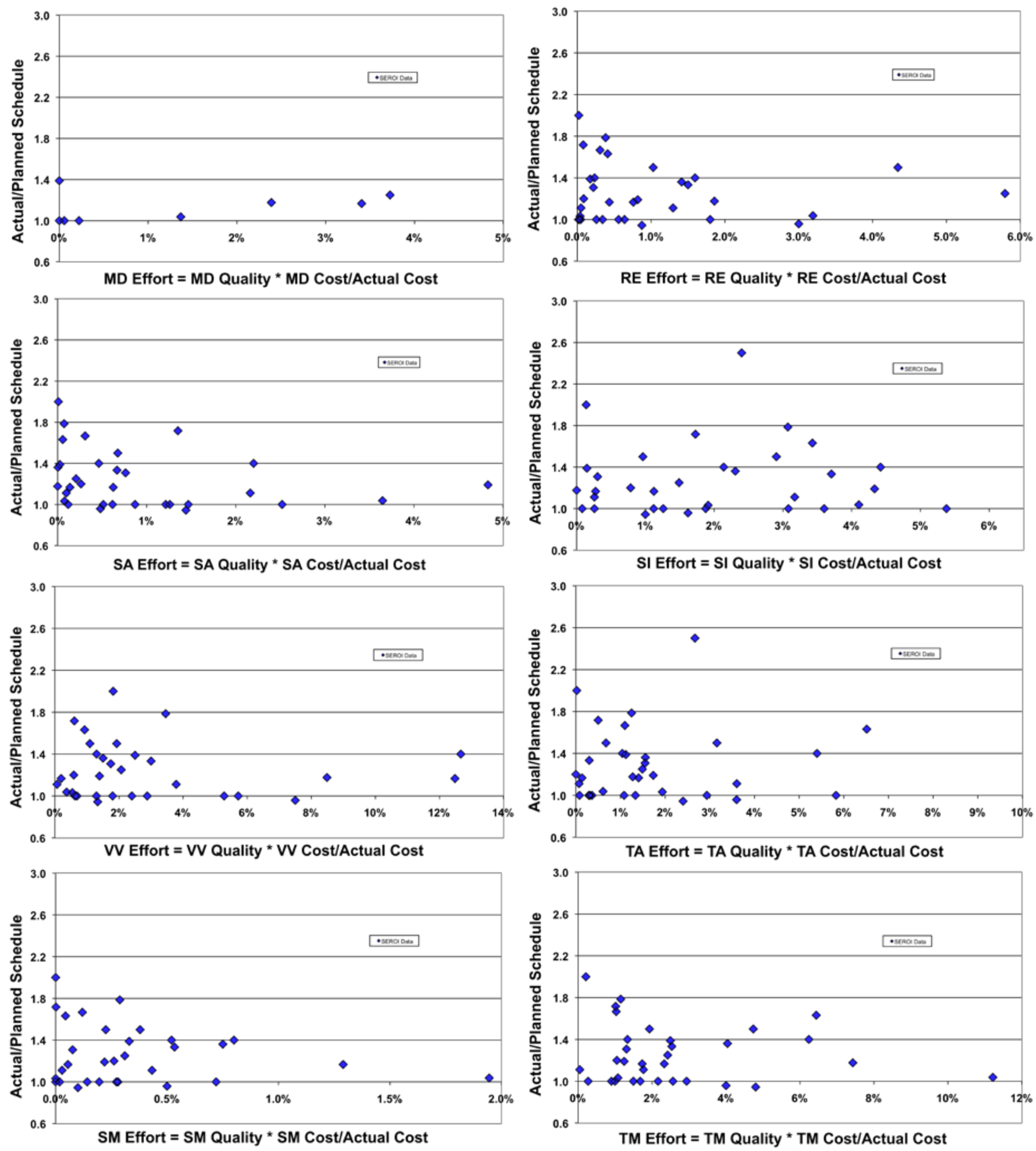

Figure 15. Correlation of SE Activities to Schedule Compliance

Figure 16 shows the correlation graphs for the eight SE activities against overall success. In this case, there is an obvious weak correlation with all eight activities.

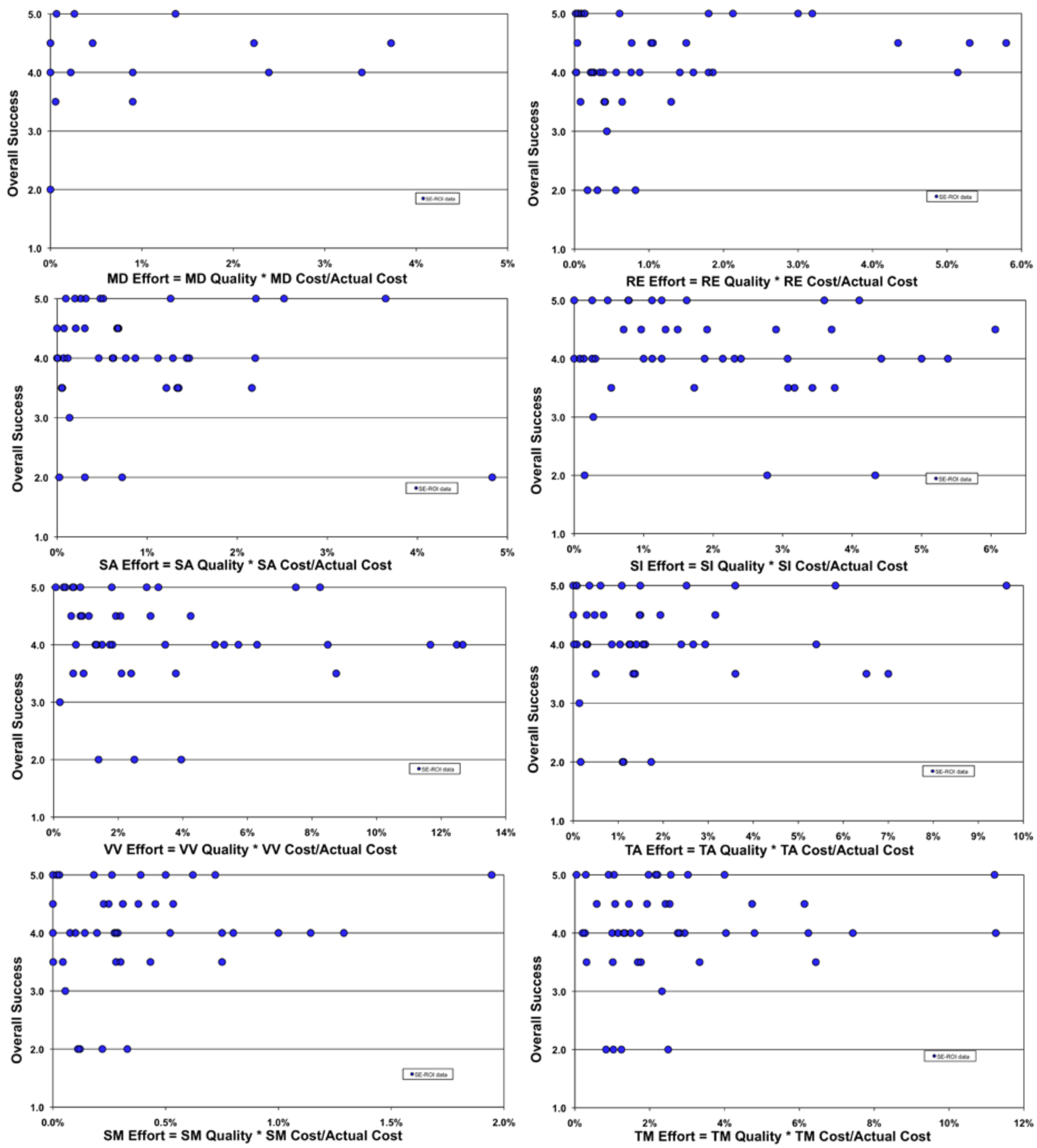

Figure 16. Correlation of SE Activities to Overall Success

Figure 17 shows the correlation graphs for the eight SE activities against technical quality. As with the total SEE, however, the correlation appears to be nearly non-existent for all SE activities.

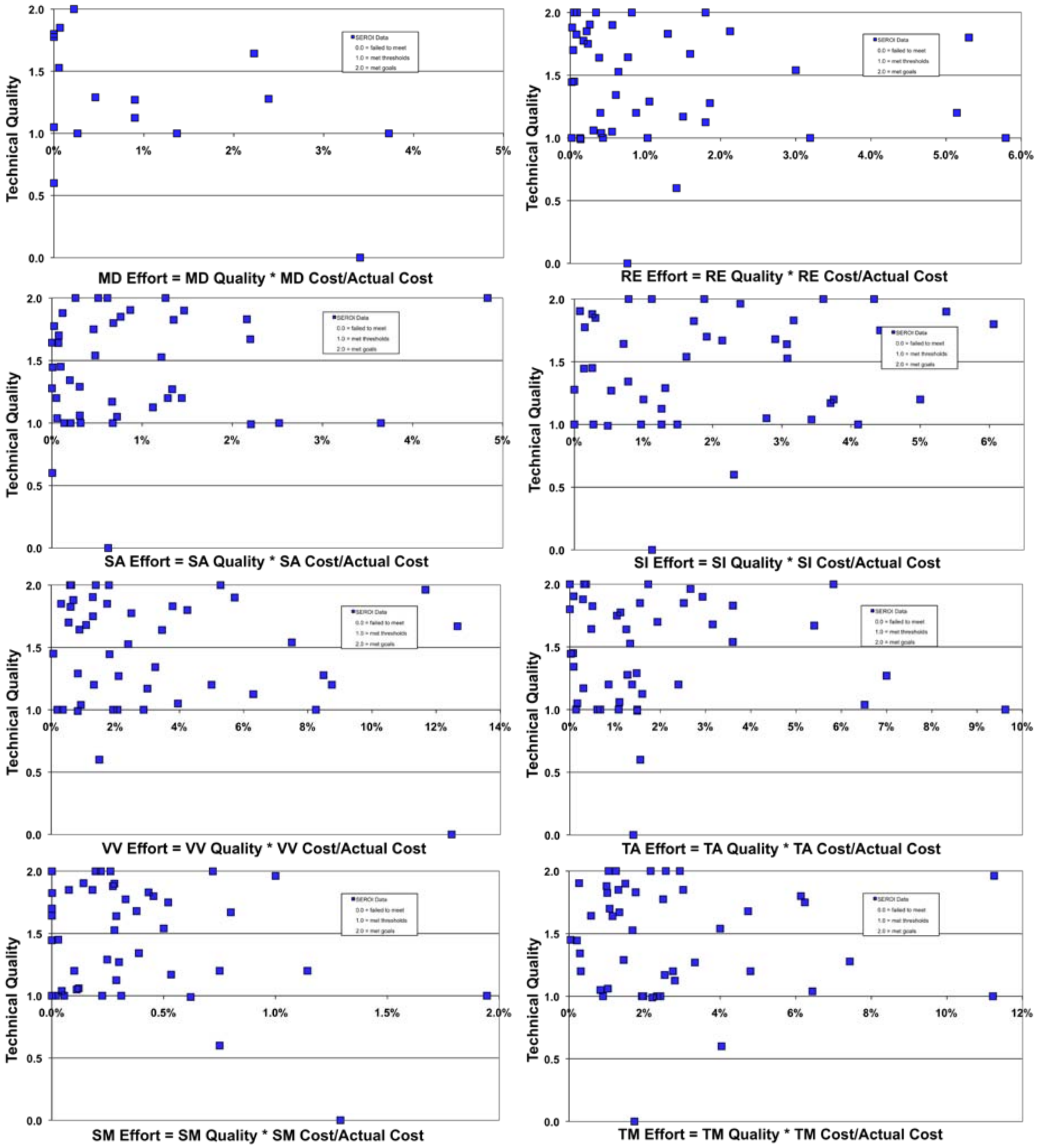

Figure 17. Correlation of SE Activities to Technical Quality

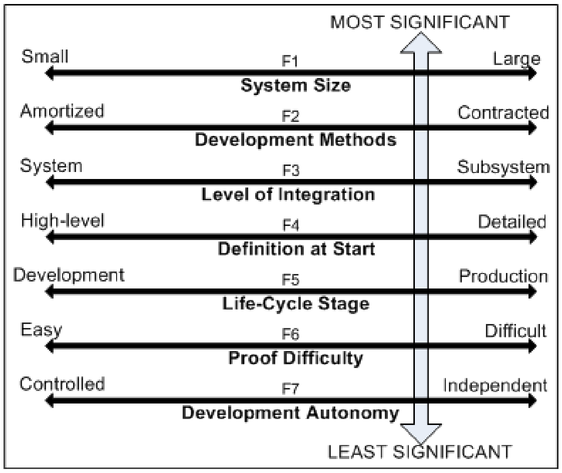

Figure 18. Quantitative Factors

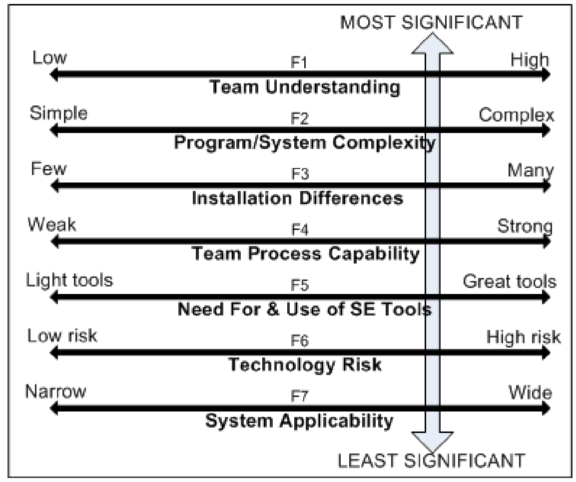

Figure 19. Subjective Factors

Further Work

The SE-ROI program obtained a wealth of data about the 51 programs interviewed. In addition to the results presented using SE activities and success measures, the interviews also obtained 45 characterization parameters concerning the programs, teams, and product systems. The work presented in (Honour 2010) correlated those characterization parameters with each other to create a useful set of 7 size parameters and 7 subjective parameters that effectively characterize each program. Those parameters are shown in Figures 18 and 19. Each parameter has a specific, quantifiable definition based on the original 45 parameters and a rigorous mathematical transformation created through Principal Component Analysis.

Statistical analysis of results is still proceeding, adding in the effects of the program characteristics. That analysis is also beginning to provide quantified statistical correlation levels for the relationships shown herein (i.e. coefficients of determination and correlation coefficients). Initial indications are that the program characteristics, when applied to the correlations, improve the correlative factors from R^2 levels of 4-15% (as shown in Figures 10-17) to levels nearing 70%. Figure 20 provides one example of this improvement, in which the SEE levels have been consistently modified for all programs by multiplicative factors based on the 14 parameters.

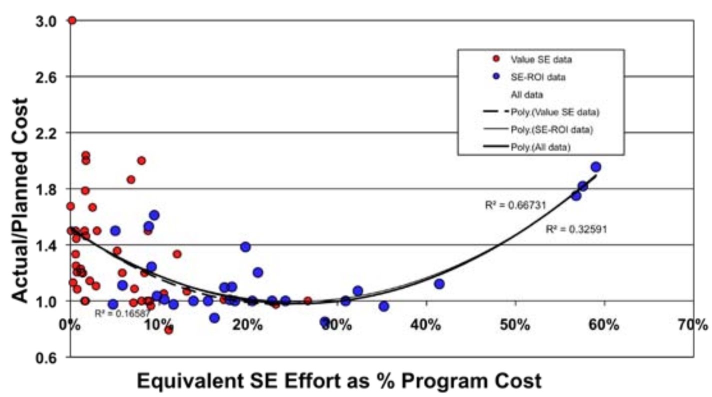

Figure 20. Improved Correlation by Application of Characterization Parameters to SE Effort

Further work continues on this secondary correlation analysis. As a result, the parameters will be used to determine the appropriate level of SE effort to apply in each activity; i.e. given “this” set of parameters, then the optimum level of each SE activity should be "that." This statistical analysis will be reported in future works.

Threats to Validity

This work is part of a rigorous doctoral research program and is being handled in accordance with strict statistical methods. Nonetheless, there are always threats to the validity of any statistical work. The following threats have been largely controlled as part of the research method, but may still have residual effects:

- Divergent SE definitions exist. The ontology developed in (Honour/Valerdi 2006) created a central set of definitions that spanned across most of the divergence.
- Participants may not have understood the ontology, but the use of a single principal investigator to perform the interviews contributed to a standardization of definitions.
- Programs report SE activities differently, sometimes placing efforts into categories far distant from SE. The principal investigator helped the interview participants to translate the project data from its original structures into the common structure of the research.
- Projects have many different temporal, life-cycle, and technical bounds on their scope. At the outset of each interview, the participants worked to define a consistent scope for the project to be interviewed.
- Scope changes often occur on development programs, including most of the interviewed programs. During the scope definition for each interview, the participants agreed to answer all questions as if the decided scope had been the original scope. The answers, therefore, represented a consistent scope even when the original data did not.
- Many confounding variables exist, which cause all the correlation charts to exhibit significant scatter. The statistical correlations in the future work, based on the characterization parameters, promise to reduce the scatter significantly.
- Subjectivity exists in many of the data elements, with human opinion prevalent throughout the work. The interviews were obtained across a sufficiently broad base of organizations and business domains that much subjectivity has been balanced, yet some pervasive human opinions may still be evident.
- SE is often restricted to aerospace organizations. The business domains interviewed in this effort include both aerospace and commercial efforts, although aerospace work still dominates. See (Honour 2009) for an indication of the demographic spread.

The following threats have been mostly uncontrollable and likely still have some effect on the data and results:

- Organizations self-selected to take part in the research. It can be expected that the results contain some skew in favor of organizations that are aware of and practice SE methods.
- Organizations selected the programs that were made available for interview. The demographics indicate that the selected programs used more SE activity than many of the 2004 surveyed programs.
- Participating organizations have all been at low to moderate levels of maturity, with no

organizations higher than CMMi level 3.

- All participating projects used traditional SE methods. No projects were operating using significant Lean or Agile methods.

Conclusions

The results in this paper represent a major step forward in the work advanced over more than a decade by Dr. Brian Mar, Dr. Ricardo Valerdi, Dr. Barry Boehm, Joseph Elm and his associates at the National Defense Industries Association, the author, and others. This work provides specific quantified measures that show the relationship between systems engineering effort and program success. Specifically, the following relationships appear to be valid:

- There appears to be a significant correlation between all eight systems engineering activities and the success level of programs.
- Systems engineering activities seem to have little effect on the technical quality of the product system, as measured by KPPs in the viewpoint of the stakeholders.
- The most successful programs, as measured in cost compliance, schedule compliance, and overall subjective success, appear to expend about 15%-20% of the development program cost in systems engineering efforts.
- The most successful programs, measured in the same three areas, also seem to have optimum values for the eight defined systems engineering activities. When considered individually, the optimum value for each activity is:
    - Mission Definition – 1%
    - Requirements Engineering – 2.5%
    - System Architecting – 2.5%
    - System Implementation – 3%
    - Technical Analysis – 4%
    - Technical Management – 4%
    - Scope Management – 1%
    - Verification & Validation – 7%
- Further statistical work significantly improves the correlations by correcting the level of SE effort using factors derived from the program characterization parameters. This future work promises to provide a quantified method to determine the optimum level of SE effort based on the *a priori* knowledge of the program characterization.

As with any empirical work, the statistical correlation cannot indicate the causality relationships. Such relationships can only be inferred from the theory of operation of the values, and then proven by direct experimentation. In this case, systems engineering is certainly an influencing and causal factor in program performance through its leadership of other engineering efforts during a development. From this leadership role, it can be inferred that the results herein demonstrate a significant Return on Investment for SE effort.

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Biography

Eric Honour was the 1997 INCOSE President. He has been in international leadership of the engineering of systems for over 15 years, part of a 41-year career of complex systems development and operation. He was the founding Chair of the INCOSE (International Council on Systems Engineering) Technical Board in 1994 and served as Director of the Systems Engineering Center of Excellence (SECOE). He was selected in 2000 for Who's Who in Science and Technology and in 2004 as an INCOSE Founder. He is on the editorial board for *Systems Engineering*. He has been a systems engineer, engineering manager, and program manager at Harris Information Systems, E-Systems Melpar, and Singer Link, preceded by nine years as a US Naval Officer flying P-3 aircraft. He has led or contributed to the development of 17 major systems, including the Air Combat Maneuvering Instrumentation systems, the Battle Group Passive Horizon Extension System, the National Crime Information Center, and the DDC1200 Digital Zone Control system for heating and air conditioning. Mr. Honour now heads Honourcode, Inc., a training and consulting firm offering effective methods in the development of system products. Mr. Honour has a BSSE (Systems Engineering) from the US Naval Academy, MSEE from the Naval Postgraduate School, and is a doctoral candidate at the University of South Australia based on his ground-breaking work to quantify the value of systems engineering.