

Design of Experiments as Applied to Systems Engineering Return on Investment

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Abstract

Research has shown that there is a quantifiable correlation between the amount, types and quality of systems engineering efforts used during a program and the success of the program. Continuing research into systems engineering return on investment (SE-ROI) is exploring the optimal nature of these selections using a Design of Experiments (DOE) method. The project expects to achieve practical results in the form of (a) statistical correlation of SE methods with project success, to understand how much of each SE method is appropriate under what conditions, (b) leading indicators that can be used during a project to assess the project's expected future success and risks, and (c) identification of good SE practices that are appropriate to generate success under different conditions. The ongoing SE-ROI project aims to quantify the correlations by gathering data on current and completed programs. Each program acts as a single data point for the statistical research. This paper describes the statistical methods and their applicability to research in systems engineering. To achieve the desired results in a reasonable number of data points (programs), data must be taken simultaneously on multiple practices, multiple

success measures, and multiple characterization parameters. Statistical separation of these different correlations requires care in both the design and use of the data. DOE methods have long been used in many fields, including industrial/organizational psychology as a basis for understanding team development and project management. This paper shows how the same methods can apply to the key issues of systems engineering.¹

SE-ROI Research

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 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.

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Only a few studies have been reported that systematically quantify the value of systems engineering to programs. The author continues to research the literature for such information. (Honour 2004) reported seven directly applicable projects. Summarizing the findings of 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)
- Parametric cost estimation of systems engineering is possible. (Valerdi 2003)

The findings, however, are not conclusive. Each research project was undertaken for limited goals, and each project reflects the limitations of its goals and its available data. The types of development programs reported varied; 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 any specific system development program might not be appropriate.

The information so far is not directly usable. 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.

The Systems Engineering Return on Investment (SE-ROI) project (Honour 2006b) gathers empirical information to understand how systems engineering methods relate to program success. In particular, the project expects to achieve three practical results:

1. ***Statistical correlation of SE methods with program success***, to understand how much of each SE method is appropriate under what conditions.
2. ***Leading indicators*** that can be used during a program to assess the program's expected future success and risks based on SE practices used.
3. ***Identification of good SE practices*** that are appropriate to generate success under different conditions.

Design of Experiments

Design of Experiments (DOE) is a statistical technique developed in the early 1900s by Sir Ronald A. Fisher to improve the quality and rigor of statistical information, particularly in the case of multiple source factors. DOE is built on the foundations of analysis of variance, in which the variance of response to each source factor can be mathematically calculated and treated. It is based in five primary areas of experimental design (Wikipedia 2007):

- *Randomization*, the purposeful process of making the source factors random,
- *Replication*, repeating the creation of a phenomenon, so that the variability of the phenomenon can be estimated,
- *Blocking*, the arrangement of experiments in groups (blocks) which are similar to one another.
- *Orthogonality*, the independence (or perpendicularity) of the source factors,
- *Factorial experiments*, the use of experiments that vary multiple factors at the same time.

The methods of DOE are to carefully design the entire statistical experiment prior to collecting data. Replicated measurements are made over a carefully randomized, simultaneous variation in multiple independent source factors. Usually, the variation is structured in blocks to reduce the impact of confounding factors (those outside the control of the experiment).

Example. (Attributed to Harold Hotelling in Chernoff 1972) The estimated weights (θ) of eight objects are to be determined using a pan balance that can discern the difference in weight (Y) between the two pans. There is a random error in the measurement apparatus. Average measurement error is zero, and there is a variance of σ^2 on each measurement. Errors on different weighings are independent.

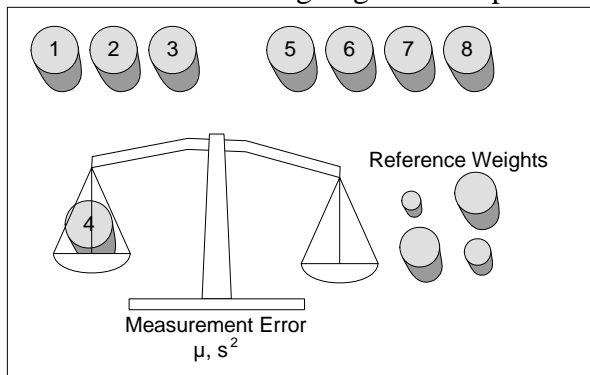


Figure 1. Example: Non-DOE. Eight measurements of one object each.

One method (not DOE) is to weigh each object separately in one pan as shown in Figure 1, using reference weights to measure the difference between the object and the empty pan. One measurement is taken for each object so that $\theta=Y$, and the resulting variance for the estimated weight of each object is σ^2 , the same as the measurement variance.

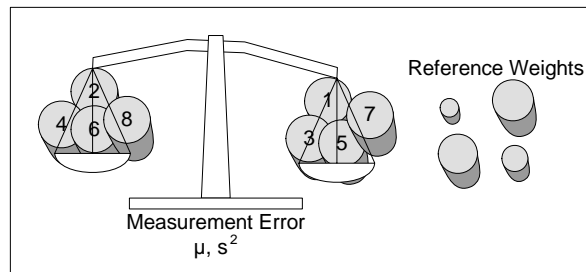


Figure 2. Example: DOE. Eight combined measurements, each using all eight objects.

A DOE method to obtain the same weights is to make a series of eight measurements as shown in Figure 2 (the same number of weighings) but with all eight objects included in each weighing, purposefully varying their positions in the pans to carefully randomize the effects, as in Table 1. Each measurement purposefully includes the effects of all the objects. Note that the variations in placement follow a logical sequence to place each object in each pan half the time. (With eight objects, there are only seven degrees of freedom, so object 8 remains in the left pan for all measurements.)

Table 1. DOE Example Experiment

Weighing	Left Pan	Right Pan
1 st	12345678	None
2 nd	1238	4567
3 rd	1458	2367
4 th	1678	2345
5 th	2468	1357
6 th	2578	1346
7 th	3478	1256
8 th	3568	1247

In a full DOE experiment, the sequence of the weighings might be (a) randomized to reduce the impact of confounding factors that

might be hidden by the sequence, or (b) blocked to reduce the impact of confounding factors that might vary during the measurement. Choice of randomization or blocking is made by considering the likely confounding factors.

In this experiment, the estimated weight of object 1 is given by:

$$\theta_1 = \frac{Y_1 + Y_2 + Y_3 + Y_4 - Y_5 - Y_6 - Y_7 - Y_8}{8}$$

However, because object 1 is involved in all 8 weighings rather than only a single weighing, the experimental variance for θ_1 (and each of the other estimated weights) is now $\sigma^2/8$. This clearly shows that the DOE method provides a more accurate answer, even though all measurements combine the effects of all objects..

Benefits. DOE provides several benefits in statistical analysis:

- Ability to handle multiple source factors simultaneously.
- Ability to consider interactions among the multiple source factors.
- Inclusion of multiple factors in sequential measurements, thereby increasing the statistical accuracy of the results.

Drawbacks and Cautions. It is apparent from the example that DOE requires more design time than a simple measurement. Careful thought must be given to the impacts of the measurements, the sequences of measurement, and the possible confounding factors. DOE also assumes independence of the source factors, that they can be controlled independently of each other without cross-fertilization of the sources. (It does not require independence of the impacts on the experiment; in fact, DOE is intended specifically to handle such combined effects.)

SE-ROI Project Design

The SE-ROI project is a three year project to obtain information about the ROI of SE using DOE methods. Data is gathered through the use of controlled interviews, guided by a specific interview data sheet to obtain the specific measurement values desired. Based on the background work of literature research, the primary hypotheses of the SE-ROI project are (Honour 2006b):

- There is a quantifiable correlation between the amount, types and quality of systems engineering efforts used during a program and the success of the program.
- For any given program, an optimum amount, type and quality of systems engineering effort can be predicted from the quantified correlations.

Supporting the primary hypotheses requires the following basic types of data:

- **Program characterization data** such as program size, program type, development phases, bounding parameters, risk levels.
- **Program success data** such as cost/schedule compliance and technical quality measures.
- **Systems engineering data** such as hours expended on systems engineering tasks, quality of those tasks, specific nature of the methods and tools used,

Such data is not usually stored directly in customer or contractor databases. Program databases store some equivalent data, but the data is organized in accordance with program, customer, or contractor structures. Interpretation of the data is needed to convert it into a common structure. For these reasons, the only effective method to obtain data is through an interview process with the key individuals.

The expected form of data gathering is to use one day in a sponsoring organization to obtain data from four programs. Each interview lasts 1-1/2 to 2 hours. Preferred participants are the program manager, chief systems engineer, program administrative clerk, and the project principal investigator. If available, a second SE-ROI project individual is desirable to help probe at the data. The interview time is structured around the technical structure and data sheets previously developed, with the intent to obtain a full set of data at one sitting. Data is obtained to the best level available. In some cases, data may be directly available from the program records. In other cases, data might be interpreted by the key individuals from the program records. In still other cases, data relies on the memory of the key individuals.

SE-ROI as a DOE Study

The design of the SE-ROI project directly follows the methods of DOE, in which each program interview provides a single data measurement. The data elements to be gathered are discussed fully in (Honour 2006c); in this paper we select from those elements to emphasize the DOE nature of the research.

DOE Source Factors. The source factors to be varied in the experiment design are (1) the program characterization data and (2) the systems engineering data. These source factors are considered to be the independent variables to the experimental design.

Program characterization data (item 1) includes both subjective and objective information. Subjective information values depend on the perception of the interviewee, while objective information values can be independently verified by records or examination. Objective characterization data includes factors such as the following (among many others), all of which can be stated numerically based on program records or metrics:

- Number of system requirements
- Requirements volatility
- Number of system interfaces
- Number of developing organizations
- Number of formal test locations
- Planned cost/schedule

Subjective characterization data includes factors such as the following (among many others), all of which must be graded by the interview subject(s):

- Life cycle stage
- Requirements understanding
- Technology risk
- Personnel experience/continuity
- Lead system engineer experience level
- Process capability.

The responses to the subjective parameters are scaled and controlled by (a) written definitions clarified and standardized by the interviewers, and (b) a multiple-choice response scale previously used in the COSYSMO modeling effort (Valerdi 2004).

Systems engineering data (item 2) includes both objective and explorative information in eight activity areas previously defined as part of a common ontology of systems engineering. (Honour 2006a) Those activity areas are

- Mission/purpose definition
- Requirements engineering
- System architecting
- System implementation
- Technical analysis
- Technical management/leadership
- Scope management
- Verification/validation

Within each activity area, the objective information includes the total work effort in man-hours and the total costs expended. It is recognized that, while the responses are numerical, some interpretation by the subject(s) will be necessary, with definition clarification by the interviewer(s), to obtain similar data from each program.

Within each activity area, the explorative information includes (a) the methods used by the program to perform that activity, (b) the tools used, and (c) any metrics gathered by the program in that area. The explorative information is not planned as part of the DOE research, although if sufficient consistency is obtained from programs it may become part of the experiment in post-interview analysis. The purpose for the explorative information is to gather information for qualitative discovery purposes, thereby to formulate new hypotheses about systems engineering. In particular, the explorative information will yield “best practices” and “leading indicators” that can be correlated with the program success data. This explorative nature of qualitative research is described well in (Cropley 2002).

DOE Result Phenomena. The phenomena to be measured in the SE-ROI experiment are the program success data. The program success is considered to be the dependent variable in the experimental design.

Program success data is objective in nature, although some subjective interpretation will be necessary to obtain comparable data from all programs. A “program” is controlled to be the sequence of developmental activities that results in a prototype system. Success data includes:

- Originally planned and final program cost, adjusted for any scope changes during the program.
- Originally planned and final program schedule, adjusted for scope changes.

- Originally planned and final labor hours, adjusted for scope changes.
- Threshold, goal, and achieved values for the top 4 to 8 key performance parameters (as viewed by the users).

The interviewers will also gather any other success measures stated by the subject(s), in an explorative manner.

Randomization. DOE is based on careful randomization of the source factors, to obtain controlled variation with samples that are representative of the true population. In a classic DOE research, the source factors would actually be controlled during measurement.

One of the key difficulties for SE-ROI, however, is that each measurement is based on a program. Creating the “data point” usually required several years and millions of dollars of cost, while developing a prototype system. It is not feasible to perform a classic scientific experiment against a control, because it is too costly to select source factors such as “personnel experience” and then initiate several development programs with varying values of the factor. This has always been the primary deterrent to measurement of the value of systems engineering. In addition, there is an extreme difficulty to control confounding factors during an experiment. Confounding factors arise because SE work is always done in a context where there are multiple people doing the project. The question is always present as to the extent of influence arising from factors such as individual quality, or the teamwork quality of the people in each of the experimentally separated teams.

DOE provides a solution to this difficulty, in that the source factors only need to be randomized, not necessarily controlled. Randomization is achieved in SE-ROI by obtaining interviews from a wide variety of real programs. Programs are selected for their variation in the source factors, such as programs with planned cost from high (~\$1B)

to low (~\$1M), with technology risk from “very high” to “very low,” with number of system requirements from many (thousands) to few (dozens). The search for applicable programs is continuing, with programs to be selected from many different domains across the United States and internationally.

In practicality, it is also difficult to gain access to programs due to the proprietary nature of the data requested. Therefore, programs are actually selected as targets of opportunity, gathering interview data from any that are available, while constantly seeking programs that can fill in the missing variability in the desired source factors. This is not a difficulty for the DOE randomization, however, because the programs selected for analysis will be an appropriate subset of the total. Subsets will also be selected to explore segmentation of the data by source factors or by explorative factors as opportunity arises.

Replication. The DOE concept of replication is implemented in SE-ROI by the use of interviews from many programs. Each program is a replication of the “experiment,” consisting of the development of a prototype system. The source factors vary in each repetition of the experiment, because each prototype system development is different. This allows SE-ROI to explore the variability in the phenomenon by measuring the variation in success factors as correlated to the variation in source factors.

Blocking. A significant difficulty for SE-ROI is in the control of confounding factors. This is normally achieved in DOE by blocking of the experiments so that variability in the source factors can be achieved while confounding factors have little opportunity to change. Because SE-ROI is obtaining data after each experiment (program) is performed, it has no control over the time frame of performance except through selection of data subsets.

This is not a trivial issue, because there are many confounding factors in the experiment.

While the experiment is designed to measure the ROI of SE, many other factors, outside the control of the experiment, also affect the program success factors. Some such confounding factors include program management effectiveness, level of definition at program start, political influences, technology difficulties, semi-random events, and changes in the program scope or system need.

SE-ROI intends to accept these confounding factors as given. They will result in greater variation in the program success factors than might otherwise be desirable. They will also reduce significantly the measures of correlation during analysis. To the extent possible, the explorative factors in the interviews will be used to evaluate subjectively the statistical dependency of the confounding factors with the SE source factors. If possible, such dependency will be calculated into the correlation analysis.

Orthogonality. DOE normally assumes independence of the source factors: if one source factor is varied, other source factors are not affected. This independence is mostly true for the source factors selected in SE-ROI. “Lead system engineer experience level,” for instance, is largely independent of “number of requirements.” (Even in this example, however, it is true that more experienced leaders are sometimes assigned to projects with greater number of requirements.)

As with the confounding factors, however, this independence is sometimes violated in the source factors selected. A lower level of “requirements understanding,” for instance, can be expected to result in a higher degree of “requirements volatility.”

This statistical dependence is even more evident in the subjective parameters than in the objective parameters. During an interview, subject(s) answer questions from the interviewers. As the interview proceeds, there is a natural tendency to base later answers on the answers already provided.

This human behavior makes DOE less applicable and less reliable when applied to subjective data.

SE-ROI will partially handle the dependence of subjective data by varying the sequence of the questioning during interviews. Each subject will still have dependence in their answers, the later answers being dependent on the earlier answers. For different subjects, however, the dependence will operate in different sequences, thereby reducing the overall level of dependence.

Factorial Experimentation. The design of SE-ROI certainly includes the concept of factorial experimentation. The many source factors are coupled with the phenomena of program success factors. The research analysis is testing the hypothesis of correlation among these factors.

Summary

The SE-ROI project is exploring information that is key to an understanding and applicability of systems engineering. The field has long been lacking knowledge of its true value to programs, relying instead on heuristic and subjective perceptions of value. As a result, metrics are not available to inform managers how much and what kind of systems engineering is appropriate for any given program.

To obtain this information, SE-ROI is designed to use as much statistical rigor as can be available within the practical issues of real programs. Using the DOE paradigm, the project achieves randomization of the multiple source factors while replicating the “experiment” of developing a prototype system. The method presents some difficulties in independence of the source factors and in the inclusion of confounding factors, but demonstrates that DOE can be applied to the measurement of key systems engineering information.

References

- Ancona and Caldwell, “Boundary Management,” *Research Technology Management*, 1990.
- Barker, B. “Determining Systems Engineering Effectiveness,” *Conference on Systems Integration*, Stevens Institute of Technology, Hoboken, NJ, 2003
- Chernoff, H., *Sequential Analysis and Optimal Design*, SIAM Monograph, 1972.
- Cropley, A., *Qualitative Research Methods*, Zinatne, 2002.
- Frantz, W.F. “The Impact of Systems Engineering on Quality and Schedule – Empirical Evidence,” *NCOSE International Symposium*, St. Louis, MO 1995
- Frantz, W.F. “The Impact of Systems Engineering on Quality and Schedule – Empirical Evidence,” *NCOSE International Symposium*, St. Louis, MO 1995
- Honour, E.C. and Valerdi, R, “Advancing an Ontology for Systems Engineering to Allow Consistent Measurement,” *Conference on Systems Engineering Research*, University of Southern California, Los Angeles, CA 2006
- Honour, E.C., “Understanding the Value of Systems Engineering,” *Proceedings of the 14th International INCOSE Symposium*, Toulouse, France, 2004.
- Honour, E.C., “A Practical Program of Research to Measure Systems Engineering Return on Investment (SE-ROI),” *Proceeding of the 16th International INCOSE Symposium*, Orlando, FL 2006
- Honour, E.C., “Gathering Data to Measure Systems Engineering Return on Investment (SE-ROI),” *Proceedings of the Systems Engineering, Test & Evaluation (SETE) Conference*, Melbourne, VIC 2006
- Kludze, A.K., “The Impact of Systems Engineering on Complex Systems,” *Conference on Systems Engineering*

Research, University of Southern California, Los Angeles, CA 2004.

Miller, R., S. Floricel, D.R. Lessard, The Strategic Management of Large Engineering Projects, MIT Press, 2000.

Valerdi, R., Reiff, J.E., Roedler, G.J, Wheaton, M.J., "Lessons Learned From Collecting Systems Engineering Data," *Conference on Systems Engineering Research*, Los Angeles, CA, 2004.

Wikipedia contributors, 'Design of experiments', *Wikipedia, The Free Encyclopedia*, 5 January 2007, 22:55 UTC, <http://en.wikipedia.org/w/index.php?title=Design_of_experiments&oldid=98747804> [accessed 11 January 2007]

Biography

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 37 years of systems experience. He is currently a doctoral candidate at the UniSA SEEC. 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, the founding chair of the INCOSE Technical Board, and a past director of the Systems Engineering Center of Excellence. He was selected in 2000 for Who's Who in Science and Technology and in 2004 as an INCOSE Founder. Mr. Honour provides technical management support and systems engineering training as President of Honourcode, Inc., while continuing research into the quantification of systems engineering.