Paper # 25

Empirical Research in Systems Engineering: Challenges and Opportunities of a New Frontier

Ricardo Valerdi
MIT
77 Massachusetts Ave., Cambridge, MA 02139
rvalerdi@mit.edu

Heidi L. Davidz
The Aerospace Corporation
15049 Conference Center Drive, CH3-230
Chantilly, VA 20151
Heidi.L.Davidz@aero.org

Abstract

This paper aims to advance the pedagogy of systems engineering by identifying opportunities and challenges in empirical research in the field. After an introduction to how empirical research could be further utilized in systems engineering, this paper discusses challenges faced when conducting empirical research in systems engineering, threats to validity associated with systems engineering data collection, and considerations for empirical mixed-methods research. Two recently completed systems engineering empirical studies are used to illustrate specific examples. Finally, suggestions are given on how a professional society might provide additional support for researchers completing empirical research in systems engineering. The goal is to describe how the increased use of empirical methods can be used to enrich the quality of research results to enhance the position of systems engineering as a widely recognized academic field. Utilizing well-grounded, valid theory improves understanding of systems engineering phenomena and advances the maturity of the field.

Introduction

As the systems engineering field continues to evolve, increasingly complex systems and organizations introduce challenges to understanding system behaviors. While many systems engineers have formal training in classical engineering disciplines, the problems faced by the field are both technical and social in nature. Though many engineers understand how to properly study inanimate objects in the natural sciences, the study of social phenomena requires another set of inquiry tools. In this paper, the fundamentals of the scientific process are reviewed in the context of systems engineering together with challenges and considerations of performing this type of work.

CSER 2007, Stevens Institute of Technology, ISBN - 0-9787122-1-8
PROCEEDINGS CSER 2007, March 14-16, Hoboken, NJ , USA

For purposes of this paper we favor the term "field" over "discipline" because the former encompasses the research, education, and practice of systems engineering. For a more detailed discussion on the distinction between the two terms the reader is encouraged to read the Dixit and Valerdi (2006) paper on systems engineering professionalism.

Most of our discussion in this paper is motivated by fundamental concepts that other fields take for granted. Namely, there are three key underlying principles of the scientific process: (1) empiricism, (2) objectivity, and (3) control (Singleton 1999). This paper will begin by addressing the concept of empiricism in the context of systems engineering and the present challenges. Objectivity will be discussed by reviewing potential threats to validity that may exist when doing research. Control is discussed throughout the paper but emphasized in a discussion on considerations for empirical mixed-methods research.

Fundamentals of Empirical Research

Though the goal of science is to develop theory, science is based on empirical observations. Singleton and Straits (1999) state that, "The foremost characteristic of scientific inquiry is that it is based on empiricism. Empiricism is a way of knowing or understanding the world that relies directly or indirectly on what we experience through our senses." They go on to say that "the only admissible evidence for or against a scientific hypothesis or theory must be observable, directly or indirectly, through some tangible manifestation."

Figure 1 shows the scientific process where scientists observe and record facts, make empirical generalizations of what they see, generate theories to describe what they see, compose predictive hypotheses to test the theories, and test the hypotheses with the observations. Where the research begins in the process is arbitrary. Some research studies use empirical observations to generate theory, and other research studies test existing theories using empirical data. The horizontal line in the figure separates the world of theory from the world of real observations.

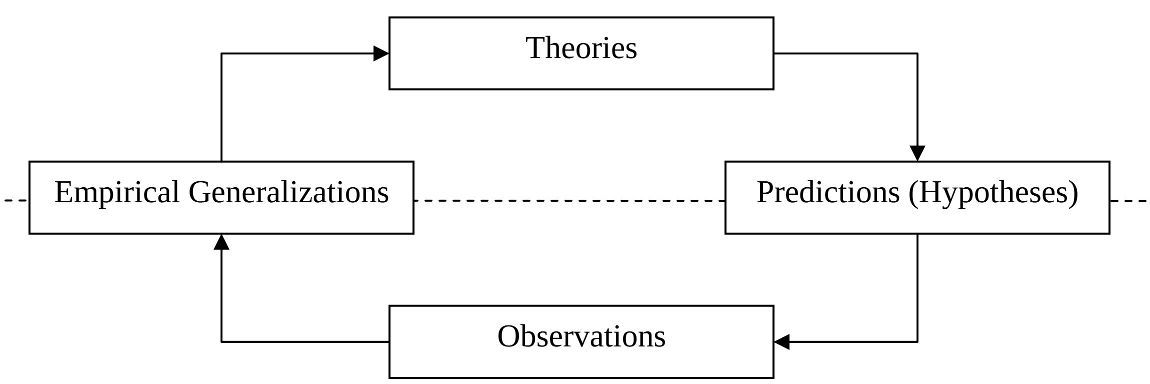

Figure 1: The scientific process (from Singleton and Straits 1999)

As an example, a recent systems engineering research study collected observations on how engineers develop systems thinking (Davidz 2006). The observations were primarily in the form of interviews, and as the interview data were processed, empirical generalizations of systems thinking development mechanisms emerged. Further analysis led to theories about how systems thinking develops in engineers. From the theories that were developed, predictions may be made. Though the study concluded with theories on systems thinking development, follow-on work is planned to complete the cycle shown in Figure 1.

For instance, the empirical observations showed that systems thinking is developed primarily through experiential learning. From this theory, a prediction may be made that a training program based on experiential learning will outperform a training program based of classroom courses. To test this prediction, a back-to-back comparison may be made where two groups of equivalent students are subjected to two alternative training programs and the resulting systems thinking development is measured. By testing the predictions with observations, the full cycle will be complete.

This is a basic example of how empirical research can be used to develop and test theories in systems engineering. However, some uses of the word “empirical” and “empiricism” do introduce confusion. The empirical method is not sharply defined and is often contrasted with the precision of the experimental method, where data are derived from the systematic manipulation of variables in an experiment. Some of the difficulty in discussing the empirical method is from the ambiguity of the meaning of its linguist root: *empiric*. The term empiric is derived from the ancient Greek for experience, *έμπειρία*, which is ultimately derived from *έν* in + *πε ρα* trial, experiment (Oxford 1989). The empirical method is a broader classification, and the experimental method is a subset of this. In an experiment the different "trials" are strictly manipulated so that an inference can be made as to causation of the observed change that results such as in experimental drug testing. This contrasts with the broader category of the empirical method, which is aggregating direct or indirect observations

Adding further confusion is another connotation of “empiric.” Strict empiricists are those who derive their rules of practice entirely from experience, to the exclusion of philosophical theory. The Oxford dictionary refers to an empiric as "one who, either in medicine or in other branches of science, relies *solely* upon observation and experiment" (Oxford 1989). In this case, an empiricist can be someone who conducts an experiment but without using a hypothesis to guide the process, i.e., strictly by the trial-and-error method. This is counter to the hypothetico-deductive method, where the manipulation of the variable in an experiment is dictated by the hypothesis being tested.

As fields evolve, theoretical methods drive collection of empirical data. “The empirical method is necessary in entering hitherto completely unexplored fields, and becomes less purely empirical as the acquired mastery of the field increases. Successful use of an exclusively empirical method demands a higher degree of intuitive ability in the practitioner (Bridgman & Holton 2000). This emphasizes the importance of both theory and empirical observation.

Importance of Empirical Research to Systems Engineering

As the field of systems engineering seeks to develop valid, proven theories about systems engineering phenomena, empirical research is critical. As Singleton and Straits state, "appeals to authority, tradition, revelation, intuition, or other nonempirical ways of knowing which may be acceptable in other endeavors (such as theology and philosophy) cannot be used as scientific evidence" (Singleton 1999). For us to better understand the phenomena in systems engineering, it is essential to develop test systems engineering theories using actual observations. Furthermore, appeals to revelation and intuition keep systems engineering in the realm of philosophy, not science.

If systems engineering is to advance, it is important to utilize a full, rigorous scientific process. Theories should be based in evidence and substantiation. Whether empirical methods are used to build theory or test theory, it is essential to ground the systems engineering field in empirical observations. The importance of employing a full, rigorous scientific process in systems engineering is not just the concern of systems engineering researchers. Exemplary understanding of systems engineering phenomena comes from exemplary development of systems engineering theory. However, the lack of attention being given to empirical systems engineering delivers a loud message about the challenges faced by empirical researchers in systems engineering.

Challenges of Empirical Research in Systems Engineering

Multiple challenges hinder the collection of empirical observations in systems engineering. Four of these challenges are discussed below: (1) the relative immaturity of the field, (2) the lack of appreciation for empirical research, (3) the lack of access to data, and (4) the lack of accepted metrics. Though significant, these challenges also pose numerous opportunities to participate in shaping an evolving and influential field.

Relative Immaturity of the Field. Systems engineering can be traced back to Bell Labs in the 1950s (Auyang 2004) but was not defined as a formal field until the early 1990s with the creation of the National Council on Systems Engineering. Relative to other engineering fields, this puts systems engineering at a disadvantage because there are fewer universities offering systems engineering programs, fewer professionals with systems engineering degrees and fewer formally trained researchers contributing to the systems engineering body of knowledge. Fortunately, systems engineering is growing, but it has not yet reached the same magnitude compared to the "Big Four" engineering disciplines of Civil, Computer, Electrical, and Mechanical Engineering which together account for approximately two-thirds of engineering bachelor degrees awarded in the U.S. (Online Guide to Engineering Schools 2006). This difference in magnitude is an indicator of the number of resources available to these disciplines. In contrast, an emerging field such as systems engineering faces a lack of large repositories of data that can be shared among researchers, limited research networks, and more limited financial resources for research in the field. As a result, students and researchers wishing to pursue systems engineering empirical studies must spend extra time to identify colleagues, find financial resources for the research, negotiate data access, gain research methods training, and break new theoretical ground.

Challenges exist in the development of systems engineering as a recognized profession. The problem space in which systems engineering operates is very broad, many principles are borrowed from other disciplines which gives the profession a lack of identity, and there is no empirical paradigm in systems engineering that can serve as the foundation for theory building (Dixit & Valerdi 2006). Aggravating this are the approaches driven by industry demands that are agile and practitioner oriented.

The closest discipline to systems engineering that has recently experienced a similar maturation is software engineering. Software engineering methods grew out of the realization that hardware engineering methods were inadequate for software development. Eventually, software researchers began to use mixed-mode approaches and have evolved to the development of a research community around the Empirical Software Engineering Journal and the International Software Engineering Research Network due to the persistence of its founding editor Vic Basili of the University of Maryland (Basili 2005).

Lack of Appreciation for Empirical and Social Science Research. Since many engineers were classically trained in a positivist, quantitative research paradigm, many have not thought more deeply about the scientific process and the need for empirical substantiation for theory.

First, the systems engineering field was initially driven by practitioners who may not be versed in the scientific process for both social and technical systems. The need for evidence and the need to substantiate theory have been undervalued in systems engineering.

Second, systems engineers often lack a familiarity with social science research methods. Though empirical data may come from either technical or social sources, many systems engineering problems are socio-technical issues. If systems engineers are not familiar with social science methods, empirically-based socio-technical research can be difficult. Instructors, courses, books and journals on research methods and empiricism often reside in academic departments outside of engineering. Researchers must also learn how to deal with some issues that social science researchers take for granted such as validity and reliability, which are discussed in the next section. Unfamiliarity with social science approaches leads to larger investment in the early stages of research because of the need to identify and incorporate research methods from other fields. This leaves less time to write about the findings and implications of the work.

In addition, classical engineering training also promotes a mindset that engineering research is only valid when it is quantitative. Both qualitative and quantitative research can be valid or invalid. Theory can be grounded and substantiated by both qualitative and quantitative observations. Knowledge of the scientific process and research methods enables one to distinguish the quality and usefulness of research, whether it is quantitative or qualitative.

Finally, classical engineering training does not discuss the difference between the objects of study in natural science versus social science. In natural science, the objects of study are inanimate and cannot interpret themselves or the surrounding environment. Singleton and Straits say that “The natural scientist can invoke interpretations without regard to how the objects of study may interpret their own worlds.” This is called the positivist or natural science model (Singleton 1999). However, in social science, the objects of study are humans who have the ability to interpret both themselves and their environment. Thus, the interpretive model says that it is essential to capture the subject’s frame of reference, since identifying only the external causes of phenomena may lead to erroneous interpretations. Though, for some social science research questions, the subject's view of social reality is not needed. More detailed contrasts between these research approaches are discussed in the management literature (Weber 2004, Singleton 1999). The important point is that methodological approaches become more complicated when the object of study is not an inanimate object. Since systems engineering empirical research often extends into this space, research methods beyond classical engineering training may be needed.

Lack of access to data. The systems engineering laboratory is a real world space which makes empirical research more challenging. Due the large projects and enterprises studied in SE, controls and control groups are difficult to utilize because of the potential interference with projects in progress. Both the natural sciences and the social sciences affect SE, and the SE field requires the scientific use of qualitative and quantitative data. The complexity of the problems in SE makes research difficult.

Researchers need laboratories to observe and manipulate the variables which only exist where systems are being realized. Industry needs to understand how to do a better job at systems engineering. The leads to a need for synergistic relationships where industry provides academia access to real data and academia provides industry with new SE insights. Empirical work is also more expensive than unfounded theory, and researchers must show the value of their work to those providing the financial resources.

Though there are considerable challenges to move from the current state, establishing an academia, government, and industry empirical research engine for systems engineering will enhance the theories being used in systems engineering practice. The integration of billion-dollar systems will then draw from a strong base of substantiated theory rather than trial and error and heuristics.

Lack of accepted metrics. The lack of accepted metrics in systems engineering makes it difficult to measure quality of SE research constructs. The core of systems engineering standards and *de facto* standards – IEEE 1220 (1998), ANSI/EIA 632 (1999), EIA 731 (2002), ISO/IEC 15288 (2002), and CMMI (2002) – have been around for less than a decade which makes the definition of systems engineering somewhat immature. MIL-STD-499A (1969) and MIL-STD-490A (1985) were the first standards that mentioned systems engineering but define systems engineering in a much narrower way. Popular systems engineering textbooks by Blanchard & Fabrycky (1981) and Sage (1992) have not been around for much longer compared to textbooks in the "Big Four." The lack of convergence in metrics and definitions makes valid research difficult.

Threats to Validity

The classification of a paper as "research" does not necessarily mean that the findings are valid or generalizable to all contexts. It is important for both researchers and practitioners to understand the importance of research validity. Researchers should take steps to enhance the validity of their work, and practitioners should critically analyze the validity of a research study prior to incorporating the findings in their specific context. Complete disregard for research validity yields limited research findings which may lead to invalid application of research results.

Validity is a key challenge in conducting empirical systems engineering research because there is little emphasis placed on it and the standard of proof in systems engineering has not been established. There are inconsistent standards for valid research in systems engineering, which leaves plenty of room for unproven results. Fortunately, a discussion of the importance of research validity is included in a recent introduction to the Systems Research Forum Journal published by Stevens Institute of Technology (Sage 2006). This is a positive step, but considerations of these threats will take time to enter the research mainstream in systems engineering.

The basic validity tests that should be applied to systems engineering research include: construct validity, convergent validity, discriminant validity, internal validity, and external validity. These are discussed below.

Construct Validity. In the study of systems engineering, construct validity is a unique concept. When it comes to research design and methods, there are often serious obstacles for addressing validity of the parameters, or constructs, being measured because the ambiguity of terminology makes it hard to compare experimental variables across organizations. For example, the definition of a requirement varies greatly across organizations due to diverse business and sometimes cultural practices.

The complexity of contemporary systems also makes it hard to isolate variables, to standardize treatments, and to identify control cases. Many of the systems studied are also one-time systems, which makes it difficult to replicate much less generalize the results. In order to increase the validity and proper applicability of research results, issues of construct validity should be addressed in systems engineering research studies.

Convergent Validity. The first issue is convergent validity. If two people are asked to rank a set of ten people they both know on the quality of their systems engineering prowess, would the two people agree on their rankings? If people cannot converge on an understanding of quality of systems engineering, then the construct is not valid. Selecting systems engineering "experts" for a study may be risky. Although there are increasing efforts to measure goodness or quality of systems engineering at the individual, group, and organizational levels of analysis, the majority of the measures of systems engineering quality are currently subjective measures (Davidz, 2006). For a study to have convergent validity, there must be convergence on the meaning of the construct of interest. This is extremely difficult in the field of systems engineering.

Discriminant Validity. Another problem is discriminant validity. If people are asked to rate an individual on quality of systems engineering, are they indeed rating systems engineering prowess, or are they rating another construct, such as leadership, creativity, openness, or eminence in the engineering field? If it is not possible to discriminate between systems engineering prowess and these other constructs, then the study lacks discriminant validity.

Internal Validity. Another concern is internal validity. Internal validity is when a study can plausibly demonstrate the causal relationship between treatment and outcome (Robson 2002). This is when a study rules out extraneous variables that may be responsible for the observed outcome. Studies eliminate rival explanations by neutralizing prior differences through randomly assigning subjects to treatment and control groups and by treating the treatment and control groups exactly alike (Singleton 1999). Internal validity can be a serious problem when studying systems engineering. The complexity and breadth of systems makes it difficult to isolate extraneous variables. The time frame required to develop systems may be too long for a controlled intervention. Different combinations of treatments and events makes it hard to draw valid comparisons.

External Validity. There are difficulties with systems engineering and external validity as well. As stated by Singleton and Straits, "External validity is basically a problem of generalizability, or what the experimental results mean outside of the particular context of the experiment" (Singleton 1999). The research sample and setting must be representative of the population of interest in order to have external validity. Systems are linked to contexts, which is a problem if the research results are then applied to a context for which the research study was not designed. In addition, external validity may be a problem if one seeks to generalize from what people say in a survey to what people actually do, since there is a notorious lack of relation between attitude and behavior (Robson 2002). There are things that can be done to help external validity, including adequate sampling, sampling randomly, replicating results in a diverse setting, using multiple methods, and using field research.

Considerations for Empirical Mixed-Methods Research

To overcome validity challenges, researchers often utilize a combination of research methods. For example, in an empirical mixed-methods approach, a researcher might utilize a combination of surveys, interviews, qualitative analysis, and quantitative analysis. A study on the factors affecting systems engineering resource estimation (Valerdi 2005) and a study on the development of senior systems engineers (Davidz 2006) are two recent examples which used empirical methods for studying systems engineering topics. Performed as doctoral dissertation research projects, both studies utilized social science research methods to study difficult human-intensive problems in the practice of systems engineering. The Valerdi dissertation was comprised of 3 Delphi survey rounds of 40 people each on systems engineering effort. The Davidz study on "Enabling Systems Thinking to Accelerate the Development of Senior Systems Engineers" used data from 205 one-hour interviews and 188 twenty-minute surveys in 10 companies. Performing these systems engineering empirical studies resulted in multiple lessons learned regarding research design, construct development, data acquisition, and data analysis. These are discussed in the following sections.

Levels and Units of Analysis. In order to clearly define the research construct of interest, a researcher must understand the unit of analysis and the level of analysis for the study. Four standard levels of analysis in social science are individuals, groups, organizations, and environments. For example, a researcher might study the individual systems engineer, the team in which systems engineers work, a systems engineering organization, or systems engineering in the broader sector. In systems engineering, many research constructs are driven by multi-level interactions, which complicates the research design.

Once the researcher has decided on the level of analysis, the unit of analysis must be defined. A unit of analysis is the entity being described or analyzed during a research study. A typical unit of analysis could be an individual person, a social role, a relationship, a social grouping like a family, an organization, a city, or even a social artifact like a book (Singleton 1999).

In order to increase the validity of the results, a study should compare equivalent units. For example, if a researcher chooses the individual level of analysis, special care should be taken to distinguish between a systems engineer in the aerospace sector, a systems engineer with twenty years of experience in the same sector, a systems engineer for product-centric systems, and a systems engineer for system-of-systems. Since the definition of “systems engineer” varies, it may be difficult to define a unit of analysis that is comparable across multiple organizations and contexts.

Pilot Interviews. Pilot interviews are a method to gain more information about the research construct of interest. In pilot interviews, the researcher studies a small sampling of individuals, often in a more informal nature. Many research constructs in systems engineering lack rigorous theoretical development, so exploratory work might be needed to better define the research construct of interest. Pilot interviews provide an opportunity for this type of exploratory work, and pilot interviews also help to give academic studies grounding in real world practice. In addition, pilot interviews may also be conducted to develop and refine research instruments such as surveys.

Sampling. There are many resources available to assist the researcher in the design of the sampling method, and it is important for the researcher to understand the implications of the sampling method used. For example, if convenience sampling is used, where the respondents are the nearest and most convenient subjects, the research findings may not be representative or generalizable. This is a problem for systems engineering empirical research, since for many of the research constructs of interest because of the extensive one-of-a-kind development efforts that take place as in the case of the Hubble Space Telescope. Moreover, it might not be possible to have a random sample of respondents because of the necessary expertise for answering certain questions. Non-response bias may also be a serious problem, since those who do not participate may differ significantly from those who do participate in the study (Robson 2002). As an example, if there is a systems engineering research study where only a small number of systems are studied, convenience sampling is used, and there is non-response bias, a practitioner should be cautious about utilizing the research results since the findings may not be representative or generalizable for the practitioner’s context.

Survey. After an appropriate sample of respondents is chosen for a survey, there are multiple resources available to assist the researcher in the design of a survey instrument. The survey instrument should be designed to help achieve the goals of the research and answer the research questions (Robson 2002). Researchers should keep the length of a survey instrument as short as possible, since respondents are more likely to participate if the survey is short and since it is unprofessional to waste the respondent’s time with poorly written and unnecessary questions. There are open-ended questions where respondents answer in their own words and closed-ended questions where a respondent chooses a response from those provided (Singleton 1999). Although data analysis is easiest for closed-ended questions, the lack of convergence of definitions in systems engineering drive empirical researchers to open-ended questions so respondents can further explain the meaning of their responses. The difficulty of analyzing open-ended questions is another challenge for empirical research in systems engineering. For example, a closed-ended survey question may be "How many requirements does this system have?" whereas an open-ended questions may be "What documentation did you use to obtain the number of requirements?"

Interviews. The interview is a common approach where a researcher directly asks questions of the respondent. Though costly and time consuming, interviews can provide rich data for research studies. The degree of structure varies, since a researcher might use a fully structured interview, a semi-structured interview, or an unstructured interview. Particularly in the divergent field of systems engineering, semi-structured and unstructured interviews are useful since this gives respondents room to elaborate on their perspectives. However, data analysis is more difficult for semi-structured and unstructured interviews. Sampling issues must be addressed when choosing interview participants.

Data Analysis Tools. Since many systems engineers have classical engineering training, they may not be aware of tools for analyzing qualitative and quantitative empirical data. Tools for qualitative data management and analysis assist the empirical researcher in making sense of qualitative data by linking documents and data from multiple interviews and by enabling quantitative data analysis methods like content analysis. For example, in the Davidz dissertation, a qualitative data analysis tool was used to assist in the content analysis of the interview transcripts. During content analysis, ideas and concepts from the interviews were "coded" into what are called "nodes." The software program tracked the nodes and allowed the researcher to organize the nodes into hierarchies. The frequency analysis of the node hierarchy was then exported to a quantitative statistical data analysis tool to perform statistical analysis on the data. The results could then be statistically compared across companies, across control groups, and across an extreme case sample. Though full details of the data analysis are in the dissertation, this example shows that qualitative and quantitative empirical data analysis tools can be quite useful for systems engineering empirical studies.

Legal Regulations. Legal restrictions are another obstacle for researchers conducting empirical research in systems engineering. Some companies require researchers to sign a non-disclosure agreement. Non-disclosure agreements are much easier to get approved when companies have the researcher sign the company's own internal template. For the Davidz dissertation, the researcher was in negotiations for over a year with one organization due to non-disclosure agreement problems. In this case, the researcher had to negotiate between the participating company's non-disclosure agreement, the non-disclosure agreement for the researcher's funding agency, and the university lawyers. When these non-disclosure agreements are provided, the data collector must ensure that there are no clauses requiring the destruction of the data after a certain period of time. The data collector must also ensure that there are no intellectual property clauses that jeopardize publication plans. Often researchers will use company information in aggregate form such as providing summaries of the data only when multiple organizations are included in the analysis so no individual company results are identifiable in research publications.

Some organizations also have committees that regulate the use of humans as experimental subjects based on Federal Law. For example, at MIT, all research involving human subjects must be approved by the Committee on the Use of

Humans as Experimental Subjects (COUHES). These types of committees may require researchers to have each respondent sign an approved document granting consent to participate in the research study. Negotiating the restrictions and regulations of these types of committees is another challenge for the empirical researcher, particularly if the study involves sensitive information, such as personality test results.

When U.S. defense contractors are the subject of systems engineering research studies, additional restrictions may be imposed. For example, many contractors do not permit recording devices in their facility. It might not be possible to tape-record interviews at the facility, so interview notes might need to be taken by hand or on a laptop. Lack of an exact transcript introduces error, which might be mitigated by sending the typed interview transcript back to the respondent. However, in cases where the respondent has been promised anonymity from their management for responses, sending the typed interview transcript back to the respondent puts the respondent's comments on the internal company email system. Management may then access the interview transcript, which may be undesirable if the researcher is soliciting a candid response.

Further Guidelines. There is a rich literature available on guidelines for empirical studies in software engineering which is has many similarities to systems engineering. For more information, the reader is directed to papers by Basili, et al (1986), Kitchenham, et al (2002), Sjoberg, et al (2005), and Jedlitschka & Pfahl (2005), and a book by Juristo & Moreno (2001). These guidelines are helpful for designing controlled experiments, developing and testing theories, and reporting results from empirical studies.

Role of a Professional Society

There are opportunities for the International Council on Systems Engineering (INCOSE) to provide additional research methods support for doctoral students and researchers performing systems engineering research.

SE Research Methods Tutorials. Particularly at the Conference on Systems Engineering Research (CSER) or as part of a workshop for the Systems Engineering and Architecting Doctoral Student Network (SEANET), there could be a series of tutorials on "Systems Engineering Research Methods." There could be a two-part tutorial with the first part focusing on "Quantitative Research Methods for Systems Engineering Research" and the second part on "Qualitative Research Methods for Systems Engineering Research." One cannot properly cover research methods in short sessions like this, but these sessions could be beginning guidance to: (a) make people aware that rigorous methods exist and (b) guide people to proper follow-up resources. Another alternative is to have "Systems Engineering Research Methods" tutorials at other INCOSE conferences and at the local chapters.

SE Research Task Force. The INCOSE Academic Forum could form a Systems Engineering Research Task Force. Working with the established position of the INCOSE Head of Research and Education, INCOSE Journal Editors, and Systems Engineering Conference Technical Chairs, the task force could place more emphasis on research methods through the following actions: (a) monitor the quality of the research methods in INCOSE papers/presentations, (b) coordinate the INCOSE offerings of tutorials and courses in SE research methods, (c) develop a research methods section on the INCOSE website to guide students and researchers to available books, experts, and other resources, (d) provide critical feedback to doctoral students during SEANET sessions, (e) certify SE doctoral programs. Although it is the onus of individual universities and doctoral committees to demand academic rigor, something needs to be done to raise the benchmark across the systems engineering field for all those conducting systems engineering research.

SE Research Crits. In civil architecture school, they have "crits" which are critical design reviews where students pin-up their work on boards and the professors and class provide critical feedback on their work which considerably enhances the design and the end-product. Perhaps INCOSE could sponsor a series of regional crits where doctoral students and researchers present their work at different stages and willing volunteers critique it. This could possibly be done: (a) at SEANET, (b) before or after INCOSE conferences, (c) before or after INCOSE regional meetings, or (d) by a web-enabled program.

SE Journal. The Systems Engineering journal should require discussions about validity and research methods. This will lead to higher expectations for SE literature and SE research studies. These higher expectations will not only yield a stronger journal which will be cited by other fields, but it will also yield more reputable and accurate research results which can be adopted by industry. For the quality of SE research to be enhanced, it is important for researchers to have access to proper training and methods resources. This is the role of the university, but for an emerging academic field like SE, it is important for INCOSE to take leadership on this, or it might not happen.

Data Collection. Results from the SEANET survey (Rhodes & Valerdi 2006) showed that the second most important item, when thirty doctoral students were asked how INCOSE could help, was to facilitate data access with industry and government.

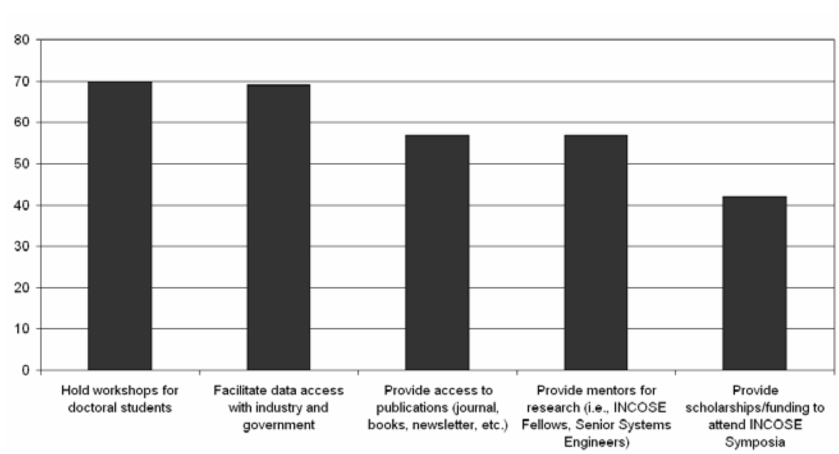

Figure 2. What INCOSE Can Do to Help Doctoral Students (Rhodes & Valerdi 2006)

Next Steps, Key Questions, and Conclusions

As Basili (1996) stated: In most disciplines, the evolution of knowledge involves learning by observing, formulating theories, and experimenting…it is used to create and communicate our basic understanding of the discipline.

We see a similar path for systems engineering. In order to move along this path we must develop theories supported by an empirical base. Though there are multiple challenges to conducting systems engineering empirical research, professional societies such as INCOSE can assist in enabling these studies. Expanded use of empirical research in systems engineering can lead to well-grounded, valid theory which helps both academics and practitioners better understand systems engineering phenomena. This is a new frontier for exploration which will surely yield many great opportunities for researchers and practitioners to work together.

Next Steps. In the immediate future we need to promote the collection of empirical data for systems engineering studies, analyze and synthesize this data into models and theories, and collaborate to evolve systems engineering into a mature discipline. This will generate more confidence in the specification of variables, data collection, models, and hypotheses in the pursuit of overall validity of our studies. Eventually, the goal should be to build decision support systems based on the best empirical evidence available so that the systems engineering community can make better decisions.

Key Questions. After a reflection of the challenges and opportunities available in empirical systems engineering research there are fundamental questions that remain unanswered but provide a useful roadmap for future work. These include:

1. Is it feasible to propose and validate theories in subdisciplines of systems engineering?
   a) Which subdisciplines should exist?
   b) Do we need general laws first or specific laws?
   c) Could we give an example of a theory in systems engineering that is based on empirical data?
2. If we agree that empirical systems engineering researchers should pursue theory building:
   a) What is the sufficient amount of empirical data needed to propose an initial theory?
   b) when is a study considered to be representative in order to be generalizable?
   c) To what extent should we depend on the replication of fundamental experiments in systems engineering for a theory to be considered valid?
   d) What are the relevant sources of variation in systems engineering experimentation?
3. What kind of guidelines are needed to apply, propose and validate theories in empirical systems engineering?
4. To what extent should we depend on theories from other disciplines (management science, system dynamics, project management, software engineering) before we develop our own?
   a) How close should a theory in another discipline be in order to be used in or adapted to systems engineering?

Despite the number of unanswered questions, we believe that we have made progress towards an empirical basis for systems engineering. It is still a long road ahead with potential roadblocks and detours but with the help of the research and practitioner communities we can work towards a more mature understanding of our field.

References

Basili, V. R., Weiss, D. M., “A methodology for collecting valid software engineering data.” *IEEE Transactions on Software Engineering,* vol. SE-10, no. 6, pp. 728-738, Nov. 1984

Basili, V. R., Selby, R., Hutchens, D., “Experimentation in Software Engineering,” *IEEE Transactions on Software Engineering,* vol. 12(7): 733-743, July 1986.

Basili, V. R., “Editor’s Comments” *Empirical Software Engineering,* Vol. 1(2), 1996

Basili, V. R., “Empirical Software Engineering: Where are we headed?”, keynote given at the 27th International Conference on Software Engineering (ICSE 2005), during Foundations of Empirical Software Engineering - The Legacy of Victor R. Basili. May 2005.

Butcher, J. N. (Ed.), Personality Assessment in Managed Health Care: Using the MMPI-2 in Treatment Planning, Oxford University Press, 1997.

Bridgman, P. W., Holton, G., "Empirical method", in AccessScience@McGraw-Hill, http://www.accessscience.com, DOI 10.1036/1097-8542.231000, last modified: April 10, 2000.

Davidz, H., Enabling Systems Thinking to Accelerate the Development of Senior Systems Engineers, Massachusetts Institute of Technology, PhD Dissertation, 2006.

Dixit, I., Valerdi, R., “Challenges in the development of systems engineering as a profession,” working paper, 2006.

Ferris, T.L.J., Cook, S.C., Honour, E., “A structure for systems engineering research,” Systems Engineering/Test and Evaluation Conference, 27-29 October, Canberra, 2003.

Frenz, P., “The Nuts, Bolts and Duct Tape of Establishing a System Engineering Measurement Program,” INCOSE Symposium, Rochester, NY, 2005.

Friedman, G., Sage, A. P., “Case Studies of Systems Engineering and Management in Systems Acquisition,” Systems Engineering, Vol. 7., No. 1, 2004.

Jedlitschka, A., Pfahl, D., “Reporting Guidelines for Controlled Experiments in Software Engineering,” International Symposium on Software Engineering, 2005.

Juristo, N., Moreno, A. M., *Basics of Software Engineering Experimentation,* Kluwer 2001.

Kitchenham, B., Pfleeger, S., Pickard, L., Jones, P., Hoaglin, D., Emam, K., Rosenberg, J., “Preliminary Guidelines for Empirical Research in Software Engineering”, *IEEE Transactions on Software Engineering*, Vol. 28(8), 721--734, 2002.

Online Guide to Engineering Schools, http://www.engineering-colleges.info/Resources/about_disciplines.htm, 2006.

Oxford English Dictionary, 2nd edition, edited by John Simpson and Edmund Weiner, Clarendon Press, 1989, twenty volumes, hardcover, ISBN 0-19-861186-2

Rhodes, D., Valerdi, R., Systems Engineering & Architecting Doctoral Student Network Workshop Notes, April 2006.

Robson, C., *Real World Research*, Second Edition, Blackwell Publishers, 2002.

Rouse, B., Theory of Enterprise Transformation, *Systems Engineering*, 2005.

Sage, A. P., *Systems Engineering*, Wiley, 1992.

Singleton, R. A., Straits, B. C., *Approaches to Social Research*, Third Edition, Oxford University Press, 1999.

Sjoeberg, D. I. K., Hannay, J. E., Hansen, O., Kampenes, V. B., Karahasanovic, A., Liborg, N. K., Rekdal, A. C., “A Survey of Controlled Experiments in Software

Engineering," *IEEE Transactions on Software Engineering,* Vol. 31(9), September 2005.

Straub, D., "Validating Instruments in MIS Research." *MIS Quarterly*, Vol. 13, No. 2, pp. 147-169, Jun. 1989.

University of Miami Libraries, Research Methods in the Social Sciences: An Internet Resource List, http://www.library.miami.edu/netguides/psymeth.html

Valerdi R., The Constructive Systems Engineering Cost Model (COSYSMO), University of Southern California, PhD Dissertation, 2005.

Weber, R., The Rhetoric of Positivism Versus Interpretivism: A Personal View, *MIS Quarterly*, Vol. 28, No. 1, March 2004.

Biographies

Ricardo Valerdi is a Research Associate with the Lean Aerospace Initiative at MIT. He is currently the research lead for the Enterprise Cost and Metrics cluster. Ricardo received his doctoral degree in systems engineering from USC in 2005, where he developed the COSYSMO model for systems engineering cost estimation. Prior to his doctoral studies, Dr. Valerdi was a systems engineer at Motorola Radio Network Solutions Group.

Heidi L. Davidz is currently a Senior Member of the Technical Staff at The Aerospace Corporation in the Systems Architecture, Engineering and Cost Department where she provides support for National Security Space projects. She completed her doctoral degree in the Engineering Systems Division (ESD) at the Massachusetts Institute of Technology (MIT), where she was a Research Assistant in the Lean Aerospace Initiative (LAI). Prior to her doctoral studies, Dr. Davidz worked full-time at GE Aircraft Engines as a member of the Edison Engineering Development Program and as a Test Operations Engineer at Boeing Rocketdyne. She holds a B.S. in Mechanical Engineering from The Ohio State University.