8th Conference on Systems Engineering Research
March 17-19, 2010, Hoboken, NJ

Paper #1569270883 (For final camera ready papers use the ID number provided to you in your letter of acceptance)

Towards a framework of research methodology choices in Systems Engineering

Ricardo Valerdi
Massachusetts Institute of Technology
rvalerdi@mit.edu

Samantha Brown
BAE Systems & Loughborough University
Samantha.F.Brown@baesystems.com

Gerrit Muller
Buskerud University College
Gerrit.muller@gmail.com

Abstract

Systems engineering researchers are repeatedly faced with a series of choices related to *what* to study. But there is another important parallel consideration that involves decisions about *how* to perform a study. This paper focuses on the latter by exploring specific questions related to research methodology choices in systems engineering.

These questions include: (1) why is methodology important in systems engineering? (2) what is the difference between methodology and method? (3) what methodological choices exist and which choices are better than others? (4) how do you connect theory, methodology and domain?

We view methodological choices as a set of dilemmas that the researcher must reconcile and we discuss reasons for methodological choices in systems engineering. We propose connections between theory, methodology and domain and provide implications for researchers given these discussions.

Introduction

In its most basic sense, science is the journey of discovery. The process of scientific research is seen as “Generating knowledge about what you believe the world is.” [Lee 2008]. Basic research tells us something we didn’t know before whereas applied research provides the answers to a specific problem as well as contributing to theory. In the context of this paper, systems engineering research is taken to be that which aims to advance the discipline of systems engineering in traditional or new domains. It specifically excludes both research which simply takes systems engineering data as an input to answer questions in another discipline (where methodology would be determined by the considerations of that discipline), and product development which might follow a systems engineering process but does not seek to enhance the process or the understanding thereof (where the systems engineering process itself defines the steps to be taken):

Included Examples of SE research:

- Analysing SE performance, based on established processes and heuristics, and

potentially theory from other disciplines in order to propose improvements
- Analysing SE performance, based on established processes and heuristics, and potentially theory from other disciplines in order to explain certain phenomena
- Applying SE to new domains in order to develop theories about how its application differs

Excluded examples:
- Understanding the factors affecting life expectancy of systems engineers
- Adherence to a systems engineering process in the development of a new vehicle.
- Modelling and demonstration of the reliability of a component

These definitions of research help differentiate the topics that can be considered to be within our intellectual domain. A second view is that research is a series of interlocking choices, in which we try simultaneously to maximize several conflicting desires [McGrath 1981]. This view frames the research process not as a set of problems to be "solved," but rather as a set of dilemmas to be "lived with". The dilemmatic view of the research process evaluates the set of methodological choices available to systems engineers and provides strengths and weaknesses of each.

In this paper we adopt the dilemmatic view of research, which should not be confused with cynicism; instead it should be seen as skeptical since it questions the assumptions of many choices we often make automatically.

Motivation

According to Checkland [1981], if systems engineering aspires to the status of a serious scholarly discipline "it will have to show that within the subject there is a cycle of interaction between the formulation of theory relevant to serious problems or concerns, and the testing of that theory by the application of methodology appropriate to the subject matter…[I]t will lead to ideas from which we can formulate two kinds of theory, substantive theories about the subject matter … and methodological theories concerning how to go about investigating the subject matter." [Checkland 1981, p7].

Choice of methodology affects not only the way in which the research is conducted, but also:
- the way in which the data are analysed
- the way in which validity is demonstrated
- the type of knowledge contribution that can legitimately be claimed
- the applicability of that knowledge to other contexts

Consequently, methodology must be addressed in the early stages of a research program. It is not adequate for it to be treated as an afterthought or – worse – ignored completely.

Differentiating between Methodology and Method

Lack of discipline in terminology is a problem in systems engineering research, with many researchers using the terms interchangeably to refer to the procedure followed [see Brown 2009]. This makes it difficult to (1) compare research results across studies, (2) communicate results to sponsors, and (3) share results with other disciplines. However, if advances are to be made in SE research methodology, it is necessary to clearly define the two and to respect those definitions. To quote Jackson (p43) [2003]:

> "The distinction between methodology and methods is crucial here. Methodology is a higher order term that refers to the logical principles that must govern the use of methods in order that the philosophy/theory embraced by the approach is properly respected and

> appropriately put into practice. Methodology is not detachable from the philosophy/theory of the particular systems approach, or, therefore, from the approach itself. Methods, however, concerned as they are with achieving more specific procedural outcomes, are detachable and can be used in the service of other systems approaches with varying degrees of success and failure".

For example, methodology can be the holistic systems thinking approach that many systems engineering researchers employ. On the other hand, method refers to the specific approach taken by the researcher such as the measurement instruments, the (statistical) analysis techniques or the modelling techniques that the researcher may choose to apply. Both methodology and method are important but it is often the case that method is the primary consideration in systems engineering researcher.

Why isn't method enough? From an early age, students of science learn to describe the method used when undertaking an experiment in the laboratory. As they progress, they will refer to the physical law or chemical process that they are observing as the "theory", applying different 'laws' or equations to different parts of the experiment. Although seldom discussed in its own right, an overarching scientific methodology guides the collection of empirical data under appropriately controlled conditions and the use of those observations to reinforce or falsify the theory.

A similar situation persists in systems engineering. It is our view that we are lacking both fundamental systems engineering theories and an overarching methodology for the discipline. As a result, much existing systems engineering research has followed an approach best described as 'atheoretical pragmatism', combining techniques from different strands of management science and systems practice to build up a tool kit through a process of trial and error, but drawing superficially (if at all) from any recognisable theoretical position [Midgley 1997]. The methods used for data collection and analysis, whilst potentially valid in their own right, lack any formal connection to the knowledge which the researcher believes may be derived from the work.

Methodological Choices

The selection of an appropriate research methodology is complicated by a myriad of considerations. Systems Engineering as a discipline stretches from physical science at one extreme to social science at the other (and others may argue that there are other dimensions too that don't fit on this one-dimensional scale). As a consequence, systems engineering research faces an equally diverse range of possibilities regarding an appropriate research methodology. Are all equally correct, or equally wrong? Clearly not: it depends on the circumstances. In an attempt to guide researchers away from atheoretical pragmatism, this paper now explores some of the issues underpinning the selection of an appropriate research methodology.

Methodological Choices as a set of dilemmas. Examples of research methodologies that are applicable to systems engineering[1] are discussed from the viewpoint of the social sciences. According to McGrath [1981] there are at least eight readily distinguishable research strategies:

1. Laboratory experiments
2. Experimental simulations
3. Field experiments
4. Field studies
5. Computer simulations
6. Format theory
7. Sample surveys
8. Judgment tasks

[1] For a more detailed classification of systems engineering methodologies, see [Ferris 2009].

Systems engineering researchers tend to favour strategies that are "field" oriented rather than "lab" oriented because of the people-centric nature of our discipline. Furthermore, there is a preference towards " simulation" over "experimental" since there are not many ample opportunities to study systems engineering phenomena *in situ.* Lastly, there are strong preferences towards "empirical" over "theoretical" which is a reflection of the results-oriented approach of engineers [Valerdi & Davidz 2009].

Despite the choice of strategy, it is an explicit choice of methodology that is often not made fully informed. A common situation that we are trying to avoid is the one where the methodology is chosen first before the problem is identified. This can be referred to as the atheoretical pragmatism view of "having a hammer looking for nail" where there is more interest in applying a specific methodology without consideration of whether it fits the problem at hand. There is a clear bias in methodological choices in our discipline that is driven by three traditions:

1. **Positivist tradition**. Engineers and physical scientists often (though not always) prefer to define the theory first and then find cases that help validate the theory. The opposite approach, known as interpretivist, would be to have no theory defined and allow the observations or data to surface a theory that can subsequently be tested. We are not advocating against the positivist approach but simply pointing out that most researchers do not recognize that they are positivists and are therefore overlooking possible limitations of the approach. One of these being the rigidity in which hypothesis testing is done.
2. **Method based tradition**. This is simply known as the "copycat" approach that stems from replicating someone else's method. The danger in re-using methods outside the original context comes from transferability of *methodology* from one context to another. It also assumes that the other person selected the correct methodology for their study which may be unintentionally flawed. Researchers need to make their own methodological decisions based on the context of their study and the underlying theory that motivates it.
3. **Directed tradition**. This can also be referred to as the "my supervisor told me" approach. This is clearly a more difficult discussion to have since research supervisors give advice based on a series of factors such as their personal specialty, the context in which the research sponsor is supporting the work, the availability and form of the data, and the intellectual traditions of the academic department, university or country.

Recognizing the existence of these traditions, we propose some approaches that can help mitigate some of the risks in selecting a methodology blindly:

a. Recognising the theoretical assumptions implicit in:
    i. The problem context
    ii. The research question
b. Refining the research question to align with the theoretical assumptions
c. Using the higher-order concept of methodology to translate the philosophy/theory into practical application, i.e. the method – different models, tools and techniques – to be used

Connecting theory, methodology and domain

Given these approaches, it is logical to consider the question: how *should* our research methodology be selected?

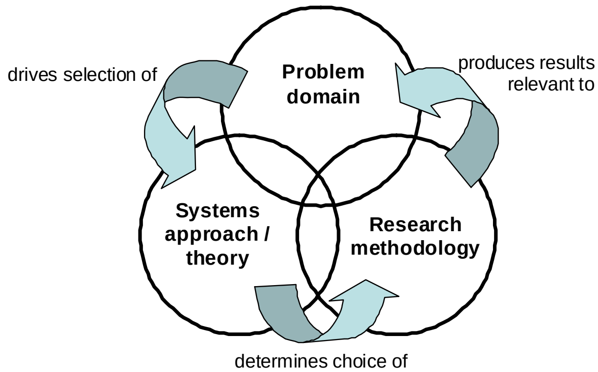

Figure 1. Connecting theory, methodology and domain.

Figure 1. shows the connections between research or problem domain, systems approach or theory and the research methodology to be used. The main principles are that:

- The theory being used should be consistent with the problem domain and context
- The research methodology used should be consistent with the theory upon which it is based
- The research output – the answer to the research question - should be relevant in the problem domain

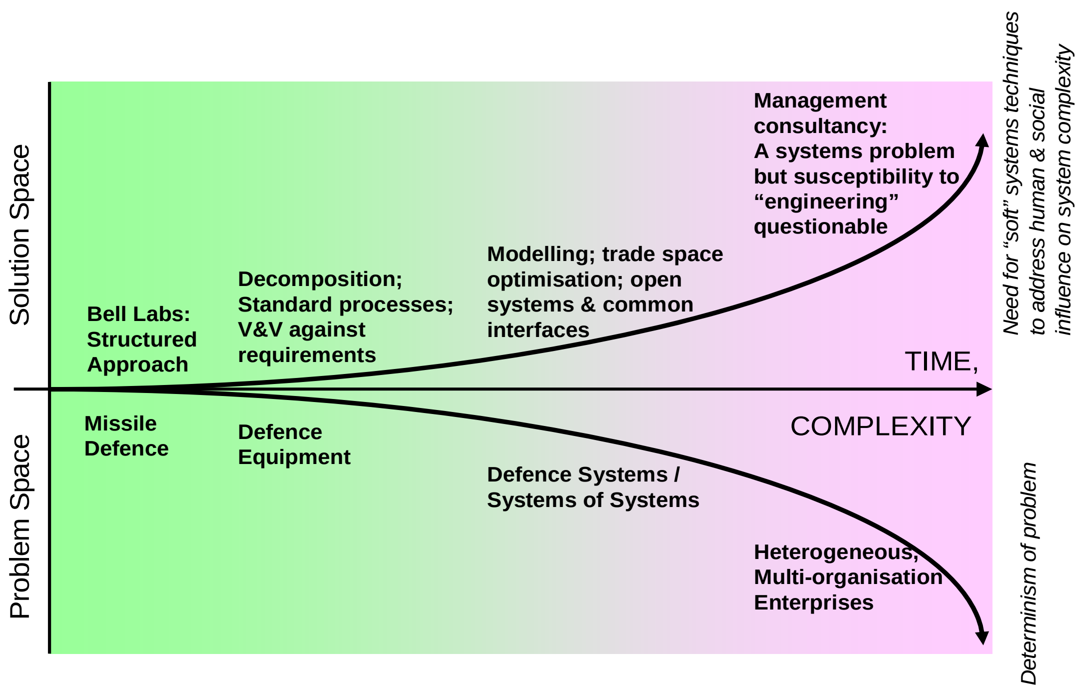

Figure 2. Types of Systems Engineering (in Defence).

Using the problem domain to determine the systems approach /theory

Figure 2 identifies the different types of systems engineering which have evolved in a defence environment in the 1950s, although the principles are equally applicable in other domains. It illustrates that as problems become more complex, the most useful systems principles and approaches change, reflecting an increasing need for softer approaches.

With time, and increasing complexity, we are moving towards the right hand side of the graph in Figure 2. Not in everything – some problems still sit in the green area - but increasingly, we need different systems techniques, approaches, theories (solutions) to solve our systems problems.

Selecting methodology based on systems approach

At the lefthandside of Figure 2, experimental methodologies are appropriate for the conduct of SE research, but as we move to the right it becomes more difficult, more susceptible to issues of validity and ethicality.

At the lefthandside, ‘human issues’ in the system relate to, for example, ergonomics and cognitive capabilities. At the righthandside there is a need to deal with social issues such as trust.

For example in “project” oriented domains “product” oriented theories might not make sense. The methodology might be based on the number and type of stakeholders. A methodology that is appropriate for projects with projects specific stakeholders might be inappropriate for products, where many stakeholders are only known in abstract terms (e.g., User, Operator).

Implications for Researchers

Our discussions on methodology and methods in systems engineering have a number of implications for researchers. To begin with, we see the blurred intellectual boundaries between the “hard” and “soft” approaches as opportunities for systems engineering. The one difficulty is that most systems engineers tend to use hard approaches mainly due to their academic training. Rather than advocating for the focus to shift to soft approaches, we would like to push the systems engineering research community to consider hybrid approaches that leverage joint strengths, but do so within a framework which is philosophically consistent. This requires a significant amount of risk and experimentation but one that we see as a worthwhile venture.

Another important implication in the implementation of new methodologies and methods in systems engineering is the standard of proof in our discipline. There are dramatically different expectations about what is accepted as rigorous research across engineering and the social sciences. In psychiatry, for instance, the gold standard is a double-blind placebo-controlled study. While this makes perfect sense for testing the effects of a new drug, it is impractical for systems engineering researchers. Testing the effects of a new systems engineering technique or tool unfortunately cannot be done in a laboratory where a control group and treatment group are used because systems engineering is an activity performed in the context of a product or service with a client that is willing to pay for it. Such efforts are not tangible things that can be analyzed as objects to be inspected and described, but rather they interact with their users and stakeholders in a complex manner, where the introduction of the system perturbs the pre-existent situation, resulting in a need for sophisticated methodologies to analyze and predict outcomes of system creation and deployment [Ferris, Cook & Honour 2005]. These conditions limit the possible methodologies and methods that can be employed.

The range of methodologies and methods available to systems engineering researchers is also limited by the education provided by doctoral programs. The reality is that most doctoral advisors do not teach research methods, as observed in the discussions among INCOSE's Systems Engineering & Architecting Doctoral Student Network [Rhodes & Valerdi 2007]. Even the ones that do tend to emphasize their own preferences. This leads to one of two outcomes. One is that doctoral students simply accept what is provided and proceed with their research plan with a single perspective. This alternative may lead to the shortest path to the dissertation but may be inappropriate for the problem domain being addressed. Furthermore, it is counterproductive to pursue research in a way that ignores the methodological considerations we have posed. The other alternative is that students look for research training beyond their home departments. This alternative seems the most innovative and one that can potentially lead to the ultimate objective: a better domain-approach-methodology fit. However, a new issue emerges based on the application of methodologies from other disciplines. It is more difficult to implement, especially for doctoral students in engineering, because the degree is being sought in an engineering school not a social science school. As discussed previously, the standard of proof varies widely based on research traditions and the temperament of the doctoral advisor. Solid justification must be provided for the choice of methodology and method and the doctoral committee could be supplemented by an external faculty member that can assist with the methodological considerations.

Further along the research life cycle, there are important implications for journal editors and reviewers. In order for new methodologies and methods to promulgate our discipline we must not only allow, but also encourage, the application of new research perspectives. In a practical sense, we may not have the expertise to be able to evaluate such work but over time this may be less of an obstacle as new research momentum builds to areas beyond the hard engineering sciences.

References

Brown, S.F., "Naivety in Systems Engineering Research: Are We Putting the Methodological Cart Before the Philosophical Horse?" 7th Annual Conference on Systems Engineering Research, Loughborough University, 2009.

Checkland, P. (1981), *Systems Thinking, Systems Practice,* Chichester, UK: Wiley.

Ferris, T.L.J., "On the Methods of Research for Systems Engineering," 7th Annual Conference on Systems Engineering Research, Loughborough University, 2009.

Ferris, T.L.J., Cook, S.C., Honour, E.C., "Towards a Structure for Systems Engineering Research," 15th INCOSE Symposium, Rochester, NY, July 2005.

Jackson, M.C. (2003), *Systems Thinking: Creative Holism for Managers*, Chichester, UK: Wiley.

Lee, N. & Lings, I. (2008), *Doing Business Research: A Guide to Theory and Practice,* London, UK: Sage

Midgley, G. (1997), "Mixing Methods: Developing Systemic Intervention" in Mingers J.C. & Gill, A. (eds) *Multimethodology: The Theory and Practice of Combining Management Science Methodologies*, Chichester, UK: Wiley, pp 249-290.

Rhodes, D. and Valerdi, R., "Enabling Research Synergies Through a Doctoral Research Network in Systems Engineering," *Systems Engineering, 10(4),* 348-360, 2007.

Valerdi, R., Davidz, H., “Empirical Research in Systems Engineering: Challenges and Opportunities of a New Frontier,” *Systems Engineering*, 12(2), 169-181, 2009.

Biography

Ricardo Valerdi is a Research Associate at the Massachusetts Institute of Technology. He holds a PhD in Systems Engineering from the University of Southern California and BS/BA in Electrical Engineering from the University of San Diego. He serves on the Board of Directors of INCOSE as Treasurer.

Samantha Brown is currently on sabbatical studying for an Engineering Doctorate (EngD) in Systems Engineering at Loughborough University, UK, sponsored by BAE Systems. She holds a Bachelors degree in Mechanical Engineering, Masters degrees in Gun Systems Design and Engineering Management, is a Chartered Engineer and a Fellow of the Institution of Mechanical Engineers. She has over 20 years defence-industry experience, and is the incoming President of the International Council on Systems Engineering (INCOSE).

Gerrit Muller received his Master’s degree in Physics from the University of Amsterdam in 1979. He worked from 1980 until 1997 at Philips Medical Systems as a system architect, followed by two years at ASML as a manager of systems engineering, returning to Philips (Research) in 1999. Since 2003 he has worked as a senior research fellow at the Embedded Systems Institute in Eindhoven, focusing on developing system architecture methods and the education of new system architects, receiving his doctorate in 2004. In January 2008 he became a full Professor of Systems Engineering at Buskerud University College in Kongsberg, Norway.