Too Hard, Too Soft, Just Right ... Goldilocks and Three Research Paradigms in SE

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Abstract. This paper examines the spectrum of methodologies that can be utilized in research in general. The two primary categories, quantitative and qualitative, traditionally find use in particular discipline areas. This paper will examine the characteristics of common quantitative and qualitative methodologies and discuss how these can be applied to research in systems engineering. The result is a wide choice of methodologies covering both the functionalist (hard) and interpretive (soft) paradigms. The broad focus of systems engineering, covering both hard (technical) and soft (socio-technical) approaches, will be shown to benefit from a broad appreciation of the full range of research methods. The paper discusses the predisposition to quantitative methods that dominates engineering thinking and argues for the inclusion of qualitative research methods in the toolkit of systems engineering researchers.

Introduction

Purpose. There are a number of ways that the methods used to execute research can be categorized and understood. Research is frequently understood in terms of the nature of the data collected, and the manner in which those data are analyzed. This gives rise to the fundamental classifications of quantitative and qualitative research methods. Alternatively, research can be understood by examining the philosophical basis that underpins the research. The positivist paradigm (Neuman, 2000), for example, emphasizes experimental investigation and observation as the only legitimate sources of worthwhile knowledge, while interpretive paradigms focus on human perceptions, values, beliefs and interests (Jackson, 2000). Perhaps the most effective approach to understanding research is to ask the question “what is the purpose of research?” The commonly cited core purpose of research (for example, Leedy and Ormrod, 2001) is to increase understanding or knowledge. This is achieved through the acquisition and analysis and interpretation of relevant data.

Whether that purpose is shaped by a particular problem or is conducted for its own sake, viewing research as an exercise in increasing understanding and knowledge makes it possible to select the most effective way of increasing that commodity. This top-down approach defers the questions of how the research will be executed until later in the process. As is the case in systems engineering, focusing on the functional aspects of the task first is more likely to deliver a solution that best fulfils the need, rather than shaping the need to fit the choice of solution.

Once a problem situation is seen in this way, as a problem to be solved through the acquisition and analysis of data, the top-down approach suggests that the purpose of research can be stated more explicitly. Research, in relation to its purpose, is of three kinds (Sekaran, 2000):

- Exploratory – where understanding and knowledge are increased, through the acquisition and analysis of narrative data, so that a problem can be better comprehended, or more deeply understood. The typical goal of exploratory research
is the building of a tentative explanation for the problem situation, based on the
acquired data. Research conducted for this exploratory purpose is usually qualitative
in nature and is characterized by an inductive logic approach. This is exemplified by
questions such as “what kind of systems engineering methodology would best suit the
acquisition of a new main battle tank?” or “what problems exist in the configuration
management of a fleet of commercial aircraft?” or “what factors are associated with
the failure to deliver large, complex systems on time and within budget?”

• Descriptive – where understanding and knowledge are increased, through the
acquisition and analysis of numerical data, for the purpose of ascertaining and
describing the characteristics of the variables of interest in a given problem situation.
Research conducted for descriptive purposes is usually quantitative in nature and is
characterized by a deductive logic approach. This is exemplified by questions such as
“which of these factors, X, Y and Z, is most strongly associated with the failure to
deliver a large, complex system on time?” or “what percentage of employees in
company X is engaged in systems engineering tasks?”

• Experimental - where understanding and knowledge are increased, through the
acquisition and analysis of numerical data, for the purpose of explaining the nature of
observed relationships between variables, or, establishing the differences among
groups, or, establishing the relationship of two or more factors in a situation.
Research conducted for experimental purposes is usually termed quantitative research
and is characterized by deductive logic. This is exemplified by experiments to test
hypotheses such as “factor X causes large, complex systems projects to be delayed by
50%” or “an increase in factor A causes an increase in factor B in a given system”.

This paper advocates an approach to systems engineering research that is driven from the top
donw. The key step in defining and executing a research task is therefore to define the purpose of
the research in relation to one of the three types defined in this section.

Research in Systems Engineering. The ‘hard’ scientific framework on which systems
engineering is based means that the discipline is predisposed towards the application of
‘traditional’ (Neuman, 2000) or positivist research methods. These methods are quantitative
in nature and emphasize numerical methods and theory testing as the means for solving problems
and gaining knowledge. In other words, there is an unconscious bias towards research whose
purpose is descriptive or experimental. At the same time, however, the top-down approach
makes it clear that there is a whole class of research that addresses problems and knowledge
acquisition that may be regarded as ‘soft’ in nature. These ‘exploratory’ problems may be
dismissed by systems engineers as sitting outside the scope of traditional engineering endeavor,
yet their role in the general progression of understanding and scientific knowledge is undisputed.

The scientific method (Leedy and Ormrod, 2001) makes a clear progression from inductive
theory-building to deductive theory-testing as exemplified by the reputed experiences of Sir
Isaac Newton. Newton is reported to have observed a falling apple in his garden and from this
proposed a theory of gravitation as an attempt to explain his observations (inductive logic – a
specific case leads to a generalization). Subsequent experiments provided support for his theory
by examining other falling objects (deductive logic – a generalization is applied to new specific
cases). It is entirely conceivable that Newton might have engaged in qualitative research as a
means to better understand what he had observed – to develop his theory of gravitation. This
would not have involved tests or numerical data, rather it would have involved asking questions
to which there are not numerical answers – “why does the apple fall?” for example. Only when
he had developed his theory was he in a position to ask quantitative questions - “how fast does the apple fall?”, “how long does the apple take to fall from a given height?”

This paper proposes that all three purposes, exploratory, descriptive and experimental, play a legitimate role in systems engineering research. There are relevant questions and problems in systems engineering activities that are examples of each. If descriptive and experimental methods are seen as quantitative then there is a clear role for these in traditional, ‘hard’ systems problems, while the growing recognition of ‘soft’ systems concepts and approaches (Checkland, 1993) lends weight to the case for developing skills in exploratory research methods that are typically regarded as qualitative in nature.

This paper now adopts a bottom-up approach to the application of research methods and examines the toolbox of off-the-shelf methods that are widely recognized and used in quantitative and qualitative research. This approach has two purposes. This first is to provide a summary of extant methods to be matched to the three general paradigms (exploratory, descriptive and experimental). The second is to pave the way for a determination of the applicability of these methods to problems in systems engineering in order to identify any possible ‘profile’ of systems engineering research. For example, it may emerge that a specific subset of methods (either qualitative or quantitative) is widely used in typical systems engineering problems, and that it is possible to define a typical profile of systems engineering research. This paper will stop short of defining this profile, but future work will examine what such a profile might be.

**Descriptive (Non-Experimental) Methods**

**Introduction.** The chief characteristic of descriptive (non-experimental) research is that, while it is quantitative in nature, and therefore gathers numerical data, it does not employ techniques of control that are found in experimental research. Thus it observes existing conditions rather than creating conditions artificially, and is limited to ascertaining and describing the characteristics of the variables of interest in a given situation. As the general name of these methods suggests, their purpose is to describe the characteristics of phenomena. There is broad scope for this form of research in systems engineering, both at the level of system design/analysis as well as at the level of the management and control of systems engineering processes.

**Correlational Research**

**Introduction.** This method examines the extent to which one variable is related to one or more other variables. A correlational study answers questions about the nature and extent of associations between variables. Thus the question ‘are smoking and cancer related?’ can be investigated in a correlational study.

Correlational studies measure at least two variables for each subject in the study. For example, a correlational study might be conducted to investigate the nature of any relationship between ‘chronological age’ and ‘reading grade level’ in a group of children (Leedy and Ormrod, 2001). The degree of any correlation between the two variables is computed, using descriptive statistical techniques, as a correlation coefficient (r). A strong positive correlation (r = +1.00) between these two variables indicates that as age increases, reading grade level also increases in a linear fashion. A strong negative correlation (r = -1.00) indicates that as age increases, reading grade level decreases in a linear fashion. No correlation (r = 0.00) indicates that the two variables are independent, that is, there is no discernible relationship, positive or negative, between the two variables.
A further example of correlational research is given by an Army study, described in Wortman and Loftus (1985), attempting to correlate the number of motorcycle accidents a person had with a range of personal variables. The study showed that the strongest positive correlation for an individual was found between the number of motorcycle accidents suffered and the number of tattoos that they had.

This example also serves to illustrate the weakness of correlational research – it cannot establish cause and effect relationships. In other words, having tattoos does not cause a rider to have motorcycle accidents, nor does having an accident cause the rider to get a tattoo. Similarly correlational research cannot say that smoking causes lung cancer. Such relationships, if they are believed to exist, must be established through experimental research.

Correlational research is, however, useful, and widely used, in a range of circumstances. These vary from situations where a controlled experiment is not feasible, for example where it is not possible to exert control over the system of interest, to situations where the researcher may only wish to establish a link, whatever its nature. Correlations also give the researcher the ability to make predictions on the basis of the strength of the correlational. For example, a strong negative correlation exists between tone deafness and musical ability. Thus the researcher can predict that if a given person is tone deaf it is likely that they will have a low musical ability. Because very few correlations are perfect (r = +1.00 or r = -1.00) it is possible that the prediction will prove incorrect, however useful generalizations can be made the stronger the correlation.

**Observation Studies**

**Introduction.** The term observation must be used with caution when describing an ‘observation study’ because, in truth, the term applies to all research. All forms of research are fundamentally based on the observation of phenomena in some sense. Observation studies have come to mean forms of research undertaken in a descriptive paradigm that ‘observe’ sentient beings, typically humans, but also animals, and record actions, behaviors and interactions of these conscious entities. Observations, in the present context, are quantified in some manner, for example by counting the frequency of occurrence of a certain behavior. Alternatively quantification may take the form of a numerical rating of a behavior to record factors such as the intensity or duration of the behavior. Observation studies are typically of two kinds: (a) participant observation, and (b) non-participant observation.

**Participant observation.** In this form of quantitative research, the observer enters the research setting, whether an organization, group, community, and becomes part of that organization. For example, the researcher may be an employee in the company where the observations are made.

**Non-participant observation.** This form of quantitative research shares the characteristics of participant observation, with the exception that the researcher does not become a part of the culture in which the observation takes place. The non-participant observer may literally sit in a corner, for lengthy periods, and merely watch and record the behaviors of interest. It may be argued that it is strictly not possible to have true non-participant observation. This can be linked to factors such as “reactivity” and “experimenter expectancy” (Leedy and Ormrod, 2001) and mirrors the limitations found in physical measurement that underpin Heisenberg’s Uncertainty Principle (Rae, 1986). In effect, the observer will always ‘disturb’ that which he or she observes, to some degree. In the case of a non-participant observation study of factory
workers, for example, the workers may change their behavior for one of several reasons, even though the researcher does not interact with them. They may be aware that they are under observation as part of a research study, and may even know the general nature of the researcher’s hypothesis, for example that better lighting will result in higher productivity. In such cases the workers may change their behavior and improve their productivity, exhibiting “reactivity”, also commonly known as the Hawthorne Effect (“discovered” in a study into work and productivity conducted at Western Electric’s Hawthorne Works in Chicago, USA).

**Systems engineering applications.** Observation studies can be used as the means for gathering data to support correlational research of the type described in the previous section. For example, to study the effectiveness of system engineering in a particular company, non-participant observation may be used to record the impact of the introduction of SE practices in the workplace.

**Survey Research and Developmental Studies**

These forms of research offer a variety of descriptive techniques with potential application across the systems engineering domain. For reasons of brevity they are considered only in summary.

**Descriptive surveys.** These involve questionnaires or structured interviews. Questionnaires typically utilize carefully constructed questions with a range of possible answers, created in such a way as to facilitate the creation of quantitative data. An example of this would be the use of a five-point Likert scale (named after Dr Rensis Likert who developed the technique in the 1920’s) ranging from “completely disagree” to “completely agree”. Such scales make it possible to quantify the answers of survey respondents and allow the application of descriptive statistics to the data.

**Cross-sectional studies.** This methodology, in conjunction with longitudinal research (see below), is also known as a developmental methodology. In this approach, numerical data that describe some time-varying characteristic or variable for the group (or sample) under investigation are gathered at the same time.

**Longitudinal studies.** By contrast, a longitudinal study gathers data at various points in time. Typically this form of study tracks a group of subjects over time, measuring the characteristic or variable of interest at regular times.

**Systems engineering applications.** Survey research is commonly used to study logistics supportability issues for new systems, or systems that are under development. This is typically found in military systems development as operational suitability testing, and is practiced widely by test and evaluation professionals.

**Experimental Methods**

**Introduction.** The chief characteristic of experimental methods, in contrast to descriptive research, is the use of controlled settings to establish and explain the nature of relationships between variables. Like descriptive methods, experimental research is concerned with numerical data. Experimental methods deliberately and carefully manipulate the conditions of a situation under investigation in order to test carefully formulated theories (hypotheses) about that
situation. Because of the element of control that is characteristic of experimental methods, they are frequently associated with laboratory settings, and the deliberate formulation of sample groups.

**Pre-experimental**

**Introduction.** Pre-experimental designs cannot show cause-and-effect relationships for one of two reasons. Either there are flaws in the manipulation of the independent variable (that which the researcher manipulates), or there are flaws in the formation of the groups or samples that are used. It is important to note that these deficiencies are not necessarily deliberate, but may be the result of unavoidable restrictions that exist in the research problem space. In such a situation the researcher may have no choice other than to use a pre-experimental design, but must do so in the knowledge that the capacity for the method to provide reliable and usable data is limited.

**One-shot experimental case study.** This design applies an experimental treatment to a single group or sample and then measures the dependent variable. For example a sample of a new composite material is subjected to a chemical treatment and its thermal conductivity is measured. The weakness of this design is that no control has been exerted over the particular sample used, and no knowledge of the thermal conductivity of the material prior to treatment was obtained. Thus any change to thermal conductivity cannot be ascribed conclusively to the chemical treatment. Indeed it is not known that a change has actually taken place.

**One-group pre-test/post-test design.** This design improves on the previous by adding a test of the dependent variable prior to treatment. Thus the thermal conductivity in the previous example is measured before the chemical treatment is applied. After treatment the thermal conductivity is again measured. The weakness of this design is that the lack of control means that factors other than the chemical treatment cannot be ruled out as the source of the change in thermal conductivity.

**Static group comparison.** In an attempt to improve the design a control group can be added. This is a group, or sample that is similar to the treated group of sample, but which does not receive the treatment. In the static group design, however, no pre-testing is used which fails to establish if the samples had the same properties prior to treatment. In addition, no formal mechanism is used to select the two samples, or groups. Thus while differences in the thermal conductivity of the two sample may be observed after the chemical treatment of one, this cannot be ascribed conclusively to the treatment itself. The difference may have been pre-existing.

**True experimental**

**Introduction.** The key improvement adopted in true experimental designs is that assignment of the groups or samples is truly random. This minimizes the extant differences between experimental and control groups and increases the likelihood that observed differences are the result of the experimental manipulation of independent variables. In all cases both experimental and control groups are used, as well as pre-testing and post-testing.

**Pre-test/Post-test control group design.** In this design, assignment to experimental and control groups is formally randomized. The control group is isolated from the experimental treatment. In this way a high degree of confidence can be placed on the fact that observed differences in the dependent variable are the result only of the applied treatment and not of other factors. In this way, randomly selected samples of the composite material in the previous example are used to
create experimental and control samples. The thermal conductivity of both samples is measured prior to treatment. The experimental sample is subjected to the chemical treatment while the control sample is not. In all other ways the conditions to which the samples are subjected are kept as similar as possible. After treatment the thermal conductivity of both samples is again measured. There is now a much stronger case for ascribing any observed differences in thermal conductivity of the two samples to the action of the chemical treatment, and nothing else. This makes it possible to establish a cause-and-effect relationship – chemical treatment of composite material X causes an increase in thermal conductivity, for example.

**Solomon four-group design.** To eliminate the possible action of effects such as reactivity (the Hawthorne effect) the previous design can be improved with the use of additional groups that are not pre-tested. This increases the ability of the researcher to make generalizations beyond the immediate samples or groups used in the experiment. This form of experiment is more commonly found in research involving sentient entities, such as humans, who exhibit a capacity to behave in a reactive way. The danger posed by reactivity is that humans will change their behavior as a result of pre-testing, for example by experiencing an increased motivation to do well in the experimental treatment. To eliminate this possibility, four groups are used. Two control groups are formed, but one is not pre-tested. Similarly, two experimental groups are formed, but one is not pre-tested.

**Post-test-only control group design.** In some situations pre-testing is difficult or impossible. In the case of phenomena that only occur once, typically physical phenomena, a post-test only design may be used. Similarly there may be situations, like those described in the Solomon four-group design, where pre-testing is undesirable. In these cases a post-test only design can be used. While outwardly similar to the pre-experimental static group design, post-test only control group design utilizes properly constituted and controlled samples or groups.

A number of refinements to these design are possible, however the examples listed here illustrate the basic parameters required for formal, controlled experimentation, leading to accurate and useful hypothesis testing in research.

**Quasi-experimental**

These designs acknowledge the limitations that are sometimes imposed on the research by circumstances outside the researcher’s control. Random assignment of samples or groups may not be feasible, while other conditions may preclude the use of true experimental designs. The key factor is that the researcher is aware of the limitations and does not form conclusions that are unwarranted.

Four examples of quasi-experimental design are listed:

- Non-randomized control group pre-test/post-test design.
- Time-series experiment.
- Control group, time-series design.
- Equivalent time-samples design.

Each is limited by the lack of random assignment, however each differs from pre-experimental design in the greater degree of formality and control that is still imposed. Each still suffers from the weakness that a source other than the applied treatment may be the cause of the observed effect.
Factorial

The primary purpose of a factorial design is to permit the simultaneous investigation of more than one independent variable. In effect this means that two or more different treatments are applied to the samples or groups in the experiment. To maximize the usefulness of the findings, the same considerations of random assignment and control are used. Four two independent variables this gives rise to four parallel groups. The first group or sample receives both treatments, with or without pre-testing. The second group or sample receives treatment T1, the third receives only treatment T2 and the fourth group or sample receives no treatment (as control group). In this way it is possible not only to observe differences resulting from either treatment alone, but also difference arising from the interaction of the two treatments.

Systems engineering applications. Experimental research is a classic technique at the core of the developmental test and evaluation phase of complex systems. The main thrust is to explore cause-and-effect relationships in order to finalise design configuration. An application area is, for example, flight test of military aircraft.

Causal-Comparative Methods

Also known as ex post facto (after the fact) research, causal comparative designs recognize the impossibility, in some situations, of manipulating a variable. While it is feasible and possible to apply a chemical treatment to a composite material, it is not feasible, particularly ethically, for example to introduce a virus into a human population, or to ask parents to abuse their children. For this reason causal-comparative designs look back in time at conditions that have already occurred and attempt to gather data to examine the effect that these pre-existing conditions have had on other variables. Essentially the design compares groups or samples for a dependent variable (for example, thermal conductivity) and attempt to identify what caused the observed effect (was it caused by chemical treatment, heat treatment or something else). Thus the design lacks the controls that give true-experimental methods their strength; however the design works within an acknowledged, and unavoidable, set of limitations. Causal-comparative designs are commonly found in medical research where the constraints regarding the application of potential harmful treatments are most obvious.

Systems engineering applications. This method can be found in research that examines the root causes of the failure of complex systems, particularly where the nature of the system precludes the use of experiments. A case in point is the investigation of accidents in nuclear power plants.

Characteristics of Qualitative Research

One of the main difficulties in discussing qualitative research methodologies, particularly with systems engineers, is that the term qualitative is viewpoint-dependant, or as Denzin and Lincoln (1998) point out, it (qualitative research) is “many things to many people”. Qualitative research, as explained by Leedy & Ormrod (2001), is useful for answering problems or questions about the complex nature of systems, usually with the distinct purpose of describing or understanding the viewpoint of the people intimately involved within the system of interest. However the outcome from qualitative research is usually a hypothesis, or possibly a ‘best-guess’ answer or explanation, in contrast to the tested hypothesis outcome from quantitative research (Leedy & Ormrod, 2001; Cropley, 2002). Qualitative methodologies exist solely to describe the nature of a
complex system rather than quantifying the system’s characteristics. Little effort is therefore expended in qualitative research in addressing the causal factors of observed phenomena.

**Strengths of qualitative research.** The greatest weakness of quantitative research, namely the inability to account for the self-determining nature of the people in a system of interest, is conversely, the main strength of qualitative research. In accounting for the human aspects, qualitative research emphasizes (Cropley, 2002) discovery, broadly-defined goals, open research questions, emergent conditions, the generation of hypotheses, and credibility. Generally, qualitative methodologies will be based upon non-experimental designs with analysis techniques to extract the meaning of the ‘narratives’ collected in natural settings, therefore concentrating on the people searching for the intention and purpose of their behavior (Cropley, 2002).

**Perceived weaknesses of qualitative research.** In introducing qualitative research methods to psychology and education students, Cropley (2002) admits three possible weaknesses of qualitative research, which would seem to strike a note with most systems engineers:

1. *Arbitrariness* – the dependence of qualitative research on the researcher’s creativity and ideas on research design;
2. *Lack of proof* – the deficiency of objective and/or statistical procedures;
3. *Banality* – stating the obvious, repeating what common sense or common knowledge already explains.

**Adding value to the obvious.** Cropley (2002) went to reasonable effort to describe the differences between ‘scientific’ qualitative research and ‘non-scientific’ observation of the obvious. In essence, he states that the differences lie in how the methods are used (as opposed to what the methods are or how much they are used.) These differences are summarized in Table 3.

<table>
<thead>
<tr>
<th>Factor</th>
<th>Qualitative Research</th>
<th>Non-Scientific Observation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Organization of observations</td>
<td>conscious, systematic, goal-directed</td>
<td>casual, informal</td>
</tr>
<tr>
<td>Awareness of distorting factors</td>
<td>acute awareness</td>
<td>little or no awareness</td>
</tr>
<tr>
<td>Record keeping</td>
<td>formal, systematic, usually written or electronic</td>
<td>casual recollection, will include distortions</td>
</tr>
<tr>
<td>Analysis</td>
<td>distinguishes between supported conclusions and speculations</td>
<td>little or no separation between systematic conclusions and own bias</td>
</tr>
<tr>
<td>Generalizing</td>
<td>keenly aware of limits of generalizing – usually stated as suggestions for further study</td>
<td>willing to generalize</td>
</tr>
<tr>
<td>Communication</td>
<td>aim is to describe their procedures and the basis of their conclusions</td>
<td>aim is to persuade others to accept their views, vague details</td>
</tr>
</tbody>
</table>

**Table 2: Differences between qualitative research and observation (after Cropley, 2002)**

In noting these differences, we can understand that qualitative research does add value to our understanding of a system, in comparison with the merely stating of the obvious or the application of common sense. However, there remains the need to address the perceived
weaknesses of qualitative research to ensure the research maintains the required level of scientific rigor.

**Basic principles of qualitative research.** The strengths of qualitative research for systems engineering may be displayed in basic principles adapted from those proposed by Cropley (2002):

1. *Investigate intentions* – The research problem must be framed to investigate the intentions and purposes of the people in the system of interest, asking ‘why, how, what kind?’

2. *Inductive philosophy* - Proceed from specific cases (individual participants) to generalizations for the whole system of interest. This is achieved by recording the participants’ narratives, describing what they have said in systems engineering terms and concepts, then explaining what this means for the system of interest (possibly in the form of a hypothesis).

3. *Collect narratives* – The main method of data gathering should be the collection of narratives (via interview or questionnaire), to allow participants to describe their experiences and interactions in the system of interest in their own words. The researcher then has the task of interpreting the narratives.

4. *Partnership* – The researcher must form a partnership with participants in order to reconstruct their experiences and interactions, and to be able to understand them fully. This differs from the *quantitative* research approach of treating participants dispassionately as ‘subjects’.

**Qualitative Research Methods**

By its very nature, qualitative research is not open to a prescriptive list of methodologies. However, five common qualitative research methodologies are outlined below and their applicability to systems engineering research discussed. These methodologies are summarized in Table 2.

**Case Study**

A case study is a useful methodology for learning more about a phenomenon which is not well understood or about which little is known (Lee & Ormrod, 2002). The phenomenon might be a person’s complexity, a project or program, or a system, and the case study may concentrate on a single case (say a senior manager or a specific process) or consider multiple cases chosen because of they are different in key aspects, in order to make comparisons. The individual, program or process is studied in detail for a specified period, and the case study may be used to investigate how the subject changes over time (perhaps as the result of interventions or environmental changes.) Although case studies can be either qualitative or quantitative in their approach, the emphasis remains on studying one unit or case in detail, using whatever data collection methods seem appropriate (Punch, 1998).

In conducting a case study, the researcher must spend a significant amount of time on-site with the participants. The initial period is spent reviewing records, manuals, audio-visual and other materials in order to ‘read into’ the problem space and know what questions to ask in subsequent interviews, focus groups and informal interactions with the participants. During the case study, the researcher must also record the context in which the case is found (Lee &
Ormrod, 2001) in order to comprehend the extent to which the subsequent results may be generalized to other situations. In considering the context, the researcher should heed the advice of Leedy and Ormrod (2001) and Harris (2001, 2002) to note the physical environment, the historical, economic and cultural factors bearing on the situation, and learn the organizational culture and internal politics affecting the participants.

The strengths of a case study is that it provides detailed knowledge of the subject matter and promotes the partnership with the participants; however its weakness (particularly single case studies) is that the applicability of the results to other situations is unknown.

**Systems engineering applications.** The case study is a useful methodology for consultants and researchers investigating systems engineering organizations, management practices or processes.

<table>
<thead>
<tr>
<th>Methodology</th>
<th>Purpose</th>
<th>Focus</th>
<th>Data Collection Methods</th>
<th>Application to SE Research</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case Study</td>
<td>To understand one (or a small number)</td>
<td>one case within its natural</td>
<td>observation, interviews, documents, audio-visual material</td>
<td>organizational management, SE practices or processes</td>
</tr>
<tr>
<td></td>
<td>person or situation in great detail.</td>
<td>setting</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ethnography</td>
<td>To understand how behaviors reflect</td>
<td>one case-site in which a group</td>
<td>participant observation, interviews with ‘informants’,</td>
<td>organizational culture, concept analysis of</td>
</tr>
<tr>
<td></td>
<td>the culture of the group.</td>
<td>shares a common culture</td>
<td>document/artifact collection</td>
<td>socio-technical systems</td>
</tr>
<tr>
<td>Phenomenological</td>
<td>To understand an experience from the</td>
<td>a particular phenomenon as it</td>
<td>in-depth unstructured interviews, sampling of 5 – 25</td>
<td>successful systems houses, systems engineers’</td>
</tr>
<tr>
<td>Study</td>
<td>participants’ point of view.</td>
<td>is typically lived and</td>
<td>people</td>
<td>experiences</td>
</tr>
<tr>
<td>Grounded Theory</td>
<td>To derive a theory from data collected</td>
<td>human actions and interactions, and how they result and influence each other</td>
<td>interviews, other data sources</td>
<td>ways that systems engineers work, interactions between groups</td>
</tr>
<tr>
<td>Study</td>
<td>in a natural setting.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Content Analysis</td>
<td>To identify the specific characteristics of a body of material.</td>
<td>any form of communication (verbal, visual or behavioral)</td>
<td>identification and sampling of specific material, coding in terms of predetermined characteristics</td>
<td>systems engineering standards, organizations’ policies &amp; procedures, trends in the body of knowledge</td>
</tr>
<tr>
<td>Historiography</td>
<td>To interpret past events and search for root causes.</td>
<td>a single past event within a ‘constellation’ of events</td>
<td>chronology, timeline continuum, space graph, ex post facto reconstruction</td>
<td>historical record, root causes of complex problems.</td>
</tr>
</tbody>
</table>

**Table 3: Characteristics of Common Qualitative Research Methodologies (after Leedy and Ormrod, 2001)**

**Ethnography**

Ethnography is the direct description of a group which shares a common culture, in contrast to the case study methodology in that the *entire* group is examined rather than a particular
individual or event (Leedy & Ormrod, 2001). Ethnography was first used in anthropology to examine large cultures, but is now used in many disciplines to study cultures of much smaller groups, including sub-cultures. Ethnographical studies concentrate on the everyday behavior of the people, focusing on their language, interactions, rituals and practices in order to identify the cultural norms, patterns and social structures which affect the group’s behavior. The methodology allows great flexibility in the research design, and so may be overwhelming for a novice researcher who may be easily distracted by irrelevant detail.

Ethnography requires prolonged engagement with the group of interest in their usual environment, yet the researcher must have and maintain sufficient detachment to be objective in their perception of the group’s culture and practices. For this reason, researchers should avoid conducting an ethnographical study in organizations with which they have a prior relationship.

Systems engineering researchers should note however that Creswell (2003) recommends researchers should get a solid grounding in cultural anthropology before venturing into the field to conduct an ethnographical study, which may very well be beyond the capabilities and resources of most systems engineers.

**Systems engineering applications.** Limited application, but may be useful for gaining insight into a specific customer-organization’s culture (and therefore their user’s needs) during concept analysis of complex socio-technical systems. An example might be conducting an ethnographical study in order to understand the culture of a firm in order to architect its management information system.

**Phenomenological Study**

Phenomenological study explores people’s perception of an event rather than describing the event external to them. This methodology is especially useful for gaining understanding of the complexities of particular, intact culture. It allows considerable flexibility in the choice of methods used to obtain information about culture (Leedy & Ormrod, 2001). A phenomenological study is focused on answering the question, what is it like to experience that? The usual driver for a researcher to consider a phenomenological approach is a recent, intimate personal experience which has sparked the researcher’s interest in the related phenomenon and a wish to better understand how others experience it. As Leedy and Ormrod (2001) summarize, “by looking at multiple perspectives on the same situation, the researcher can then make some generalizations of what something is like from an insider’s perspective.”

Creswell (2003) outlines the usual method in a phenomenological study is for the researcher to carefully select 5 to 25 individuals whom have had direct experience of the phenomenon of interest, then to conduct lengthy, unstructured interviews with them. These interviews take on a ‘partnership’ feel and are more like a conversation as the researcher and the participant strive to get to the ‘heart of the matter’ with the researcher allowing the participant to do most of the talking. In analyzing the data form these interviews, the aim is to identify common themes in the participants’ experiences. The researcher analyses the data by (Leedy & Ormrod, 2001; Creswell, 2003):

1. Sorting the relevant information into small phrases or sentences which reflect a single, specific thought.
2. Grouping these phrases into categories that reflect the various meanings or aspects of the experienced phenomenon. These categories are described as “meaning units”.
3. Looking for divergent perspectives, to consider how the different participants experienced the same phenomenon.

4. Constructing a composite or overall description of the phenomenon as people typically experience it.

**Systems engineering applications.** The usefulness of phenomenological studies in systems engineering research is likely to be limited. They will be extremely applicable to researching the culture of successful systems houses or how leading systems engineers’ experiences can be used to mentor upcoming systems engineers.

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**Grounded Theory Study**

Grounded theory studies are used to develop a theory, usually regarding people’s actions and interactions. A prescribed procedure is set for the collection and analyzing of the data, and for the construction of a theoretical model from the data. The term ‘grounded’ refers to the theory which emerges from such a study which has been ‘grounded’ in data collected directly from the real world rather than from the research literature (Leedy and Ormrod, 2001).

The usual method is to use constant comparison that is, analyzing the data immediately to refine subsequent data collection (Leedy and Ormrod, 2001). Data is collected from interviews, observations, records, audiovisual material and documents, so long as these sources include the voices and viewpoints of the people being studied. The data is analyzed for commonalities suggesting a small set of themes or categories to reduce the data. The themes or categories are then further analyzed for interconnections, to determine the conditions giving rise to the category, the context, the strategies people use to manage it, and the consequences. The categories are then refined in constant comparison, until a story line describing what happens in the phenomenon of interest develops. A theory based on this data set is then developed, (in the form of a statement, hypothesis or model), in order to explain the connection between conditions and actions in the phenomenon of interest.

**Systems engineering applications.** Grounded theory study would be a very useful methodology for research into the ways that systems engineers work or for investigating interactions between groups in a systems engineering process.

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**Content Analysis**

Leedy and Ormrod (2001) define content analysis as “a detailed and systematic examination of a particular body of material for the purpose of identifying patterns, themes or biases.” The focus of content analyses is people’s communications, as opposed to their perspectives or interactions. The forms of communications of interest to a content analysis may include documents, mass media, art, music, and audiovisual material. Content analyses are not necessarily a stand-alone research methodology, as they might be incorporated in a larger, quantitative study. This is feasible since one of the main data analysis steps in a content analysis is to determine the frequency of each characteristic found in the study material, with statistical methods being employed if required (Leedy & Ormrod, 2001).

Content analysis is systematic in the approach to research, typically involving identification of the specific body of communications material to be investigated, deciding whether the entire body should be studied or randomly sampled, definition of the characteristics or qualities to be examined (specific examples might be used), then evaluation of each piece of material. A single
judge is appropriate if the evaluation required is objective in nature, otherwise a small team of evaluators is used to form a composite evaluation (Leedy & Ormrod, 2001).

**Systems engineering applications.** Content analysis would be useful for examining systems engineering standards, organizations’ policies and procedures, or researching trends in the systems engineering body of knowledge.

**Historiography**

Historiography is the interpretation of historical events, and is more than a mere chronology (i.e. the recording of events in the order in which of they occurred). Chronology may be an initial step in a historiographical study, as the listing of the events in their chronological order is a useful data collection and analysis step, but the meaning and significance of the events still need to be interpreted. Indeed, a focus of historiography is the understanding of the significance of a specific event on within the “constellation of events” (Leedy & Ormrod, 2001).

Historical data may be analyzed by presenting it as a chronological listing, a timeline continuum or graphically. A timeline continuum offers easier understanding of the historical time involved in the period of interest, as the dynamics and rhythms of the events become obvious by their clustering on the timeline. A historical graph (such as map showing locations of the events) is useful for interpreting the historical space or spatial dimension to the events.

**Ex post facto research.** Historiography may be used to search for the root cause for a phenomenon, a kind of ‘rewinding’ of historical events. Such a process of beginning with a phenomenon and retreating through time to identify the causal factors is called *ex post facto* research (Leedy & Ormrod, 2001).

**Conceptual historical research.** Historiography may also be used to research the history of concepts, since ideas and concepts can influence history, people and events. Leedy and Ormrod (2001) consider this method, termed conceptual historical research, as quite distinct from conventional historical research. The focus in conceptual historical research is on the description of the ideas and their dynamics, rather than the description and interpretation of events.

**Systems engineering applications.** The usefulness of historiography in interpreting the history of systems engineering as a discipline is obvious. Ex post facto research may be a useful methodology for identifying and interpreting the root causes of the complex problems to be solved by systems engineering.

**Summary: Contrasting Methodologies**

The methodologies described in this paper can usefully be grouped according to six dimensions (Cropley, 2002). Table 4 illustrates these grouping and their correspondence to the purposes of research described previously.

<table>
<thead>
<tr>
<th>Purpose</th>
<th>Design</th>
<th>Setting</th>
<th>Data Collection</th>
<th>Data Type</th>
<th>Analysis</th>
<th>Generalization</th>
</tr>
</thead>
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<td>Descriptive</td>
<td>Non-experimental</td>
<td>Field</td>
<td>Instruments</td>
<td>Numerical</td>
<td>Statistics</td>
<td>Hypothesis testing (deduction)</td>
</tr>
<tr>
<td>Experimental</td>
<td>Experimental</td>
<td>Laboratory</td>
<td>Instruments</td>
<td>Numerical</td>
<td>Statistics</td>
<td>Hypothesis testing (deduction)</td>
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</tr>
<tr>
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<td>Non-experimental</td>
<td>Field</td>
<td>Narratives</td>
<td>Descriptive</td>
<td>Meaning</td>
<td>Hypothesis generation (induction)</td>
</tr>
</tbody>
</table>

**Table 4: Types of Research Projects**

Research projects in all disciplines, not least systems engineering, serve one or more of the three purposes listed in table 4. For research whose purpose is to ascertain and describe the characteristics of the variables of interest in a given situation, **descriptive** research methods are most appropriate. For research whose purpose is to engage in hypothesis testing to explain the nature of certain relationships, or, to establish the differences among groups, or, to establish the independence of two or more factors in a situation, **experimental** research methods are to be preferred. For research whose purpose is to better comprehend a problem or obtain a deeper understanding of a problem area, and as a basis for theory building, **exploratory** research methods are most appropriate.

It is highly likely that, in systems engineering, a combination of these methods may be used. Such a hybrid approach offers the best opportunity to address problems in systems engineering that derive from the hardware, software and human facets of complex socio-technical systems. A sound understanding of the characteristics of the common research methodologies is a prerequisite to the rigorous application of these techniques in solving complex problems.

**References**

Biography

Dr David Cropley is Director of the Systems Engineering and Evaluation Centre, University of South Australia. He has a Bachelor of Science (Hons) degree in Applied Physics with Electronics from the University of Salford, UK, a Graduate Certificate in Higher Education from the Queensland University of Technology and a doctorate in engineering from the University of South Australia. Prior to joining the University of South Australia in 1990, Dr Cropley served in the United Kingdom’s Royal Navy, in the West Indies and Middle East, between 1986 and 1990. His other interests are dictated by his wife and three young children.

Michael Harris is a senior research fellow with the Systems Engineering and Evaluation Centre, University of South Australia. His qualifications include a BSc (Hons) in physics and an MSc in military vehicle technology. Prior to joining the University in 1998, Michael was a project manager with CEA Technologies Pty Ltd, (an Australian electronics research and development firm), following 14 years service in the Australian Army. Michael’s other interests include coaching cricket, umpiring Australian football and running marathons.