Elements of a Framework for the Engineering of Complex Systems

Stephen C Cook, Joseph E Kasser and Timothy L J Ferris

Systems Engineering and Evaluation Centre
University of South Australia
Mawson Lakes Campus
Mawson Lakes, Australia, 5095
Stephen.Cook@unisa.edu.au

Abstract

The engineering of complex systems is becoming an increasingly important field of study. As a consequence, teaching and research programs are appearing at universities throughout the world. The appearance of these offerings emphasises the need for a coherent and consistent framework that defines the discipline in terms of its Area of concern (A), Methodology (M), and Framework of ideas (F). This paper seeks to identify a number of elements of that fit within these three components. We use the recent ISO/IEC 15288 standard to define the breath of the field (A), and the writings of Hitchins to define the scope. We deduce that there are two rather different areas of concern: (1) the engineering of actual complex systems, and (2) the engineering organisations that undertake (1). Then we introduce systems thinking as the principle concept around which to build the framework of ideas (F). Subsequently, we introduce Total Systems Intervention as a way of identifying suitable systems methodologies (M) to tackle the areas of concern and posit that systems engineering is well suited to engineering the product systems whereas the second area of concern is better served by conventional systems interventions. Having reached this point we enrich our framework of ideas by incorporating elements from the philosophical doctrine of pragmatism and from social theory. We then revisit our methodological basis, and assert that pluralist approaches will be necessary for the two areas of concern, and propose that current practice can be considered to be an imperialist multimethodology. This is a first paper on this topic and we recognise that much more research is needed to synthesise these initial ideas into a well-reasoned framework.

Introduction

Systems engineering, the creation of large complex, technical systems, has been a recognised activity for over fifty years. Over most of this time, systems engineering has been considered as a practice-based activity rather than a discipline in its own right. This perception has been changing over the last 15 years since the genesis of professional societies such as the International Council on Systems Engineering (INCOSE). There are now over 100 postgraduate programs in the field catering to an ever-growing demand (Fabryky, 2003). The Education and Research Technical Committee of INCOSE has been establishing a body of knowledge for systems engineering (Leibrandt, 2001) that can be used to inform teaching at universities and training needs within a workplace-based employee competency framework. The authors have contributed to this work (Kasser and Massie, 2001) and have accepted the challenge to work as part of an international working group to establish a framework for research into the discipline of systems engineering. This paper collects some of the initial elements of that framework and discusses their contribution.

Checkland and Holwell (1998), state that there are three elements necessary to describe any piece of research:

- **The Area of Concern** (A), which might be a particular problem in a discipline (area of study), a real-world problem situation, or a system of interest.
- **A particular linked Framework of Ideas** (F) in which the knowledge about the area of concern is expressed. It includes current theories, bodies of knowledge, heuristics, etc as documented in the literature as well as tacit knowledge.
- **The Methodology** (M) in which the framework is embodied that incorporates methods, tools, and techniques in a manner appropriate to the discipline that uses them to investigate the area of concern.

Figure 1 extracted from Checkland and Holwell (1998), illustrates the relationship between these three elements and how undertaking the methodology creates new knowledge about all three elements. These same three elements can also be used to characterise a discipline because they encompass the key aspects of a discipline: a specific area of study (A), a literature (F), an agreed methodology (M), given that there is a working community of paid scholars and/or practitioners, (Kline, 1995, p3).

The paper investigates each of the three elements in turn and opens by defining the areas of concern. We have elected to take an iterative approach to discussing the linked framework of ideas and the methodologies. On the first pass we introduce systems thinking as an underpinning ideology upon which to assemble a framework of ideas. This is followed by a discussion on methodological options for the areas of concern based on the concepts of Total Systems Intervention (TSI) posited by Flood and Jackson (1991). Next we revisit the framework of ideas and examine the contributions that pragmatism and social theory can provide. The paper concludes by suggesting that an alternative methodological taxonomy wherein systems engineering resides at the same metamethodological level as TSI.

Areas of Concern

The systems concept is widely used to provide insight into complex problem situations. This

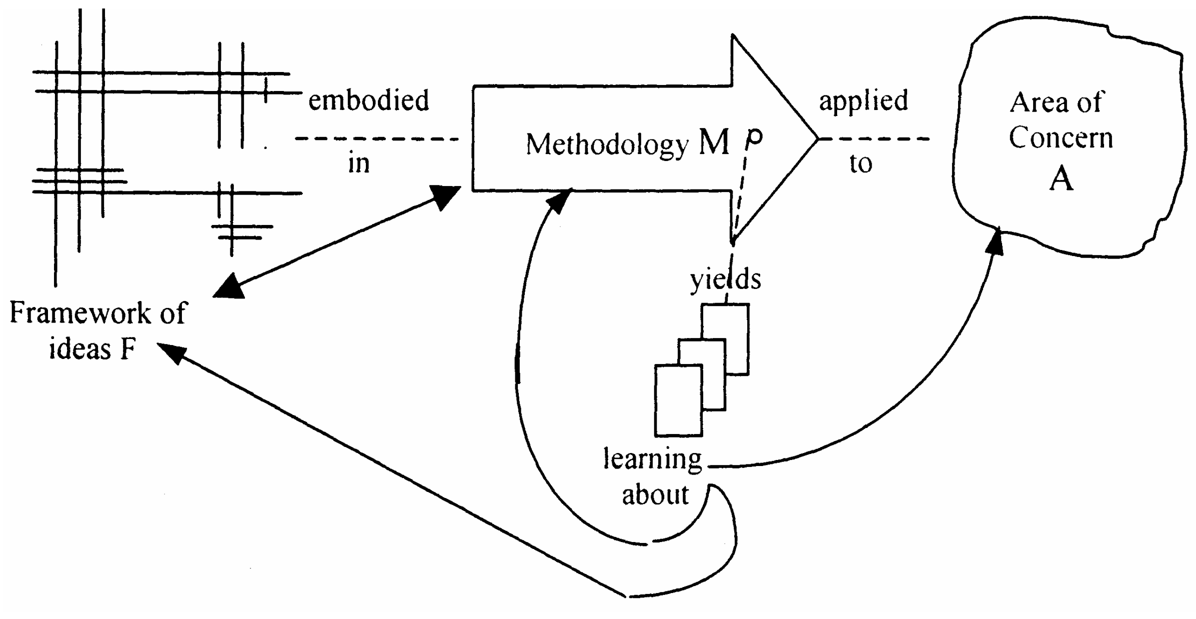

Figure 1. Elements relevant to any piece of research (Checkland and Holwell, 1998: p 13).

paper is concerned with the range of systems ideas and systems methodologies that comprise the field that we term the *engineering of complex systems*. We use the term *engineering* in the sense of both "the design and manufacture of complex products" and "calculated manipulation or direction (as of behaviour) as in social engineering" (Merrim-Webster, 2003). More explicitly, we are interested in the creation, evolution, and operation of complex socio-technical systems, in which people play a major role, and the social systems that undertake these activities. The sections below define the area of concern more completely using the ISO/IEC 15288:2002 standard for systems engineering processes and Hitchins' five-layer model (Hitchins, 2003).

Standards framework

The recently released ISO/IEC systems engineering standard (ISO/IEC 15288:2002) is the newest and highest level systems engineering standard to be published. The standard (ISO/IEC 15288:2002: p 1):

> "concerns those systems that are man-made and may be configured with one or more of the following: hardware, software, humans, processes (e.g. review process), procedures (e.g. operator instructions), facilities and naturally occurring entities (e.g. water organisms, minerals)."

It states in the introduction that it is intended to be used in one or more of the following modes (ISO/IEC 15288:2002: p vii, authors' emphasis):

> "**By an organization** – to help establish an environment of desired processes. These processes can be supported by an infrastructure of methods, procedures, techniques, tools and trained personnel. The organisation may then employ this environment to perform and manage its projects and progress systems through their life cycle stages. In this mode this International Standard is used to assess conformance of a declared, established environment to its provisions.
>
> **By a project** – to help select, structure and employ the elements of an established environment to provide products and services. In this mode this International Standard is used in the assessment of conformance of the project to the declared and established environment.
>
> **By an acquirer and a supplier** – to help develop an agreement concerning processes and activities. Via the agreement, the processes and activities in this International Standard are selected, negotiated, agreed to and performed. In this mode this International Standard is used for guidance in developing the agreement."

The standard, as its name implies, is concerned with processes where the definition of a process is given therein as a (ISO/IEC 15288:2002: p 4):

> "set of interrelated or interacting activities which transform inputs into outputs."

ISO/IEC 15288, in common with other recently released systems engineering standards, limits itself to *what* processes are applicable to the practice of systems engineering. It does not cover *how* these processes are to be performed or which methods, tools, procedures, or techniques are to be employed. Figure 2 shows the processes described in the standard and the four groupings into which they are categorised.

The importance of ISO/IEC 15288:2002 is that it encompasses all the activities in the earlier standards (such as ANSI/EIA-632, IEEE 1220:1998, MIL-STD-499B) and importantly explicitly adds the enterprise processes that (ISO/IEC 15288:2002: p8-9):

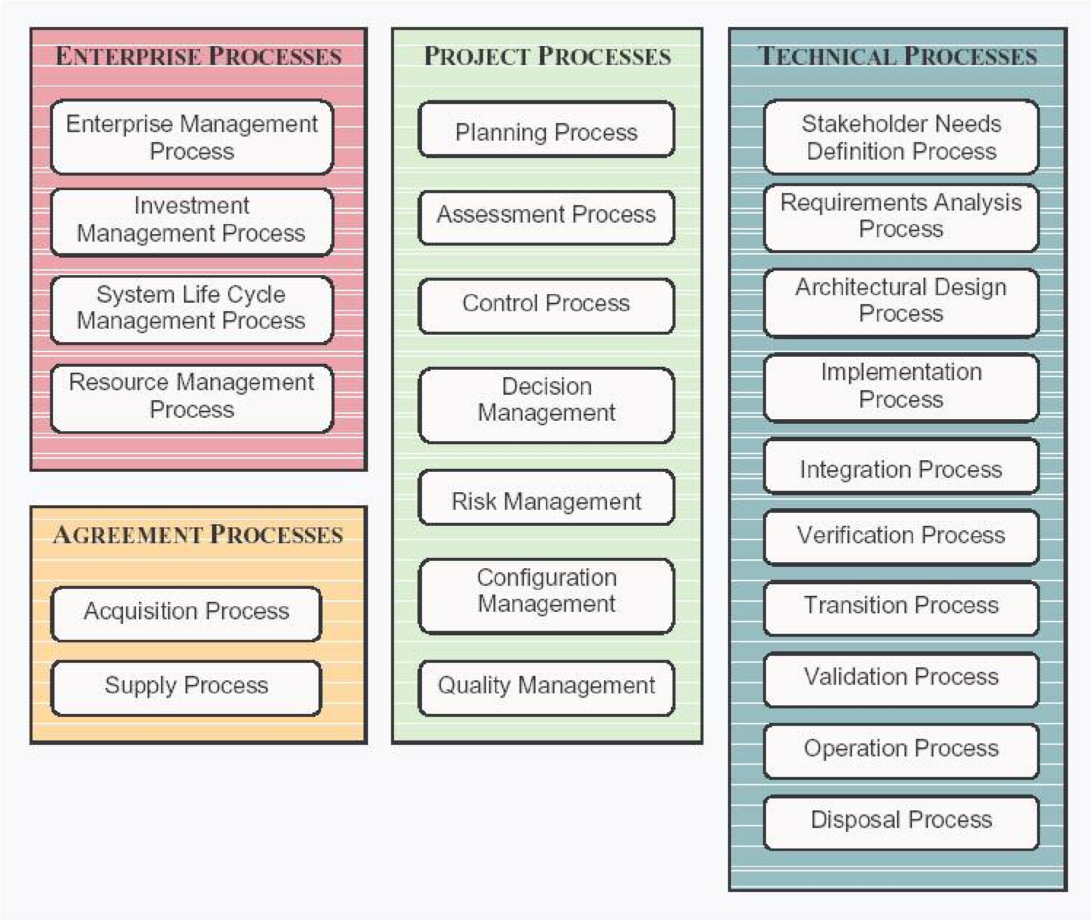

Figure 2. The system life cycle processes (ISO/IEC 15288: 2002: p61).

> "manage the organization's capability to acquire and supply products or services through the initiation, support and control of projects. They provide resources and infrastructure necessary to support projects and ensure the satisfaction of organizational objectives and established agreements."

In many people's minds, the term systems engineering immediately conjures up the mental model of the activities associated with substantial defence or aerospace projects such as the design of a new aircraft. The inclusion of the enterprise processes in the ISO standard reflects the recognition of the actual breadth of systems engineering practice and helps present a more complete process framework.

Hitchins' five-layer model of Systems Engineering

Hitchins (2003) proposes the following five-layer model for systems engineering to try and encompass the scope and diversity of activities that systems engineering embraces.

- **Layer 5** - Socioeconomic, the stuff of regulation and government control.
- **Layer 4** - Industrial Systems Engineering, or engineering of complete supply chains/circles. Many industries make a socio-economic system. A global wealth creation philosophy. Japan seems to operate most effectively at this layer.
- **Layer 3** - Business Systems Engineering - many businesses make an industry. At this layer, systems engineering seeks to optimize performance somewhat independent of other businesses.

- **Layer 2** - Project or System Layer. Many projects make a Business. Western engineer-managers operate at this layer, principally making complex artifacts.
- **Layer 1** - Product Layer. Many products make a system. The tangible artifact layer. Many engineers and their institutions consider this to be the only "real" systems engineering.

Hitchins states that the layers form a "nesting" model, in that many products make a project, many projects make a business, many businesses make an industry and many industries make a socio-economic system. He goes on to say that these statements are only approximate since a socioeconomic system has more in it than just industries and a business comprises more than just projects, and so on. Hitchins' model is useful because it:

- Gives an appreciation of the scope of activities that fall within the term *systems engineering*.
- Illustrates how each activity fits within the layer above and as such emphasizes both the open system view of the engineering of complex systems, and the hierarchy of systems engineering activities.
- Indicates that the ISO/IEC 15288 processes can be applied to various levels of complexity, in particular, those beyond Layer 2 engineering projects[1].

For the purposes of teaching systems engineering and illustrating where certain activities fit within the scope of both systems engineering and the system life cycle, we map Hitchins' model onto a two-dimensional space defined by system scope on the vertical axis, and life-cycle timeline on the horizontal axis (Kasser and Massie, 2001). Activities can then be mapped onto this space to indicate where they fit with respect to these two dimensions as shown in Figure 3.

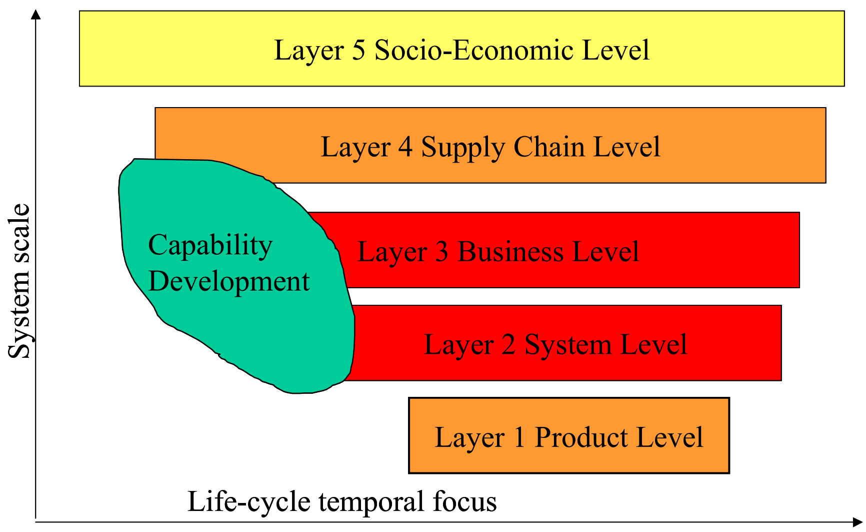

Figure 3. A graphical depiction of Hitchins' five-layer model showing the scale of the layers and their relative positioning (Cook et al, 2003).

For example, classical project-centric systems engineering covers Layer 2 completely. Shown in the figure is the centre of concern of capability development activities (these roughly correspond to the *investment management* and *resource management* processes in ISO/IEC 15288). The positioning of capability development in the figure illustrates that this activity is centred at the front of the business-layer lifecycle. Capability development also interacts with

[1] It has to be said that the INCOSE, project-centric Systems Engineering Body of Knowledge tends to emphasise this view despite the fact that it publishes many papers each year on activities above Layer 2.

the supply chain level because there is a need to ensure enduring support to future defence capabilities. And finally, it interfaces to Layer 2 through the acquisition projects it spawns[2].

Framework of Ideas

Checkland and Holwell (1998: p23-25) discuss the importance of a declared-in-advance epistemological framework (F) when undertaking interpretive research. Capra (1996) reinforces the importance of a declared-in-advance epistemological framework because he challenges objectivity in science and states that all assertions need to be coupled to an epistemological framework. Thus establishing an F is fundamental to the definition of a research topic or a discipline. We have chosen to start the discussion on the framework of ideas with a discourse on systems thinking.

Basic systems thinking

Systems thinking is concerned with the conscious use of the concept of wholeness when considering an entity (system) that exhibits properties that are greater than the sum of its components. It is the antithesis of Descartes' reductionism (the mainstay of the scientific community): the technique of breaking down problems and analysing them piecemeal. While it is recognised that the reductionist approach has value in relatively simple "clockwork" systems such as celestial mechanics, it is incapable of examining the very properties for which most designed systems are constructed: the emergent properties that are only observable at a whole-system level. Specifically, the scientific method cannot cope with complexity, real-world problems, and social phenomena. Systems thinking, which has its origins in organismic biology, control engineering, communications engineering, economics, philosophy and among other disciplines, arose to tackle problems of this type. Checkland (1981) states that systems thinking encompasses two pairs of core concerns[3]:

- Emergence and hierarchy
- Communication and control

Consider the concepts of *emergence* and *hierarchy*. In natural science, and in designed systems, there exists clearly defined levels of complexity and there are properties that are emergent at a particular level of complexity that cannot be reduced in explanation at lower levels. For example, a biological hierarchy might include cells, organs, organisms, groups of organisms, etc. Bio-chemical reactions are observed at the level of the cell whereas consciousness appears at the level of the organism. Any study of consciousness necessitates study at the level of the organism: nothing will be gained by dismembering the organism and examining its component organs. An example of natural hierarchies is given in Table 1 extracted from Checkland (1981) after Boulding (1956). It is noteworthy that the disciplines required to study the emergent properties of each of the layers of complexity are different.

[2] Such a representation is, of course, overly simplistic because aspects of the capability development processes also occur further down the life-cycle, thus a more accurate representation would be an overlay whose colour saturation represents the degree of effort applied at each point in the two-dimensional space.

[3] It is important to appreciate that system thinking is generic and broader than the areas of concern of this paper.

Table 1. An informal intuitive hierarchy of real-world complexity.
(from Checkland, 1981 after Boulding, 1956)

Level	Characteristics	Examples	Relevant Disciplines
1. Structures	Static	Crystals, bridges	Description, verbal or pictorial, in any discipline
2. Clock-work	Predetermined motion	Clocks, machines, the solar systems	Physics, classical natural science
3. Control mechanisms	Closed-loop control	Thermostats, homeostasis mechanisms in organisms	Control theory, cybernetics
4. Open systems	Structurally self-maintaining	Flames, biological cells	Theory of metabolism (information theory)
5. Lower organisms	Organised whole with functional parts, 'blue-printed' growth, reproduction.	Plants	Botany
6. Animals	A brain to guide total behaviour, ability to learn.	Birds and beasts	Zoology
7. Man	Self-consciousness, knowledge of knowledge, symbolic language	Human beings	Biology, psychology
8. Socio-cultural systems	Roles, communication, transmission of values	Families, the Boy Scouts, drinking clubs, nations	History, sociology, anthropology, behavioural science
9. Transcendental systems	'Inescapable unknowables'	The idea of God	Unknown

Notes: (1) Emergent properties are assumed to arise at each defined level.
(2) From level 1 to level 9: complexity increases; it is more difficult for an outside observer to predict behaviour; there is increasing dependence on unprogrammed decisions.
(3) Lower level systems are found in higher level systems - e.g. man exhibits all the distinguishing properties of levels 1-6, and emergent properties at the new level.

The second pair of core concerns for systems thinking is *communication* and *control*. Checkland states that the collection, transfer and processing of information and subsequent control action resulting from it are germane to complex systems. Thus we can immediately postulate that every system above the "clock-work" level of the systems hierarchy must contain an information system.

Figure 4, extracted from Flood and Jackson (1991), illustrates these concepts and the idea of a systems boundary. The boundary establishes the limit of the system of interest for the systems practitioner and the explicit inclusion of inputs and outputs indicates that the system is "open" in that the system interacts with its environment and these interactions need to be understood.

Systems thinking has been successfully applied to a wide range of problems and a significant number of methodologies have been developed to support this burgeoning activity. The first step in identifying appropriate methodologies is to determine the generic type of the area of concern (A). Figure 5, also extracted from Checkland (1981) is helpful here.

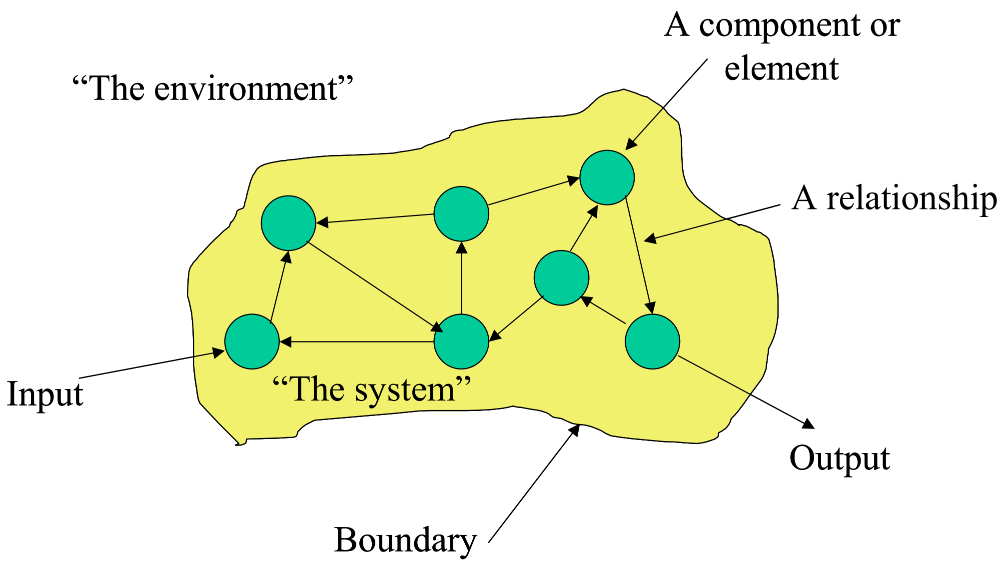

Figure 4. The general concept of a system (Flood and Jackson, 1991)

The first area of concern (A) is a designed physical system (that also contains human components). The second area of concern is a human activity system (engineering organisation). This observation is valuable as it indicates that the two areas of concern are of fundamentally different types and hence will probably have to be approached with different methodologies. The identification of suitable methodologies for each of the areas of concern is the topic of the following section.

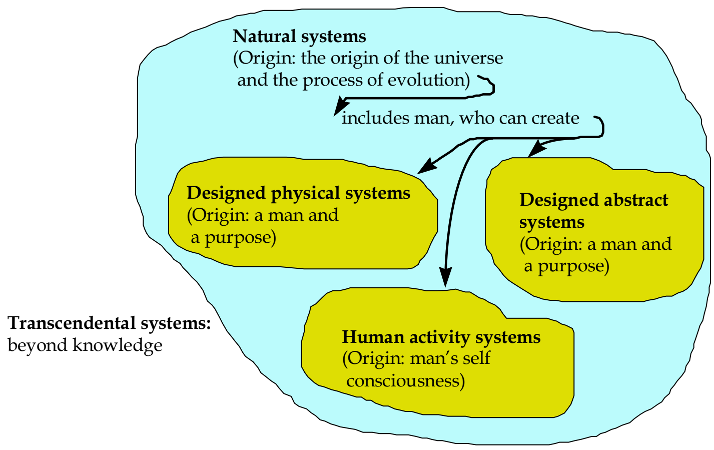

Figure 5. Five classes of system that make up Checkland's systems map of the universe, (Checkland, 1981).

Methodologies for Engineering Complex Systems

We now turn our attention to the subject of identifying the methodologies that are appropriate to the two areas of concern (A).

Total Systems Intervention

Jackson (2000) identifies over twenty methodologies that could have applicability for dealing with complex systems. Our task in this paper is to identify which of these, or combinations of these, might be useful to our areas of concern. We find that Total Systems Intervention (TSI), Flood and Jackson (1991), is helpful in this respect. The seven principles of TSI are as follows:

- Organisations are too complicated to understand using one model.
- Organisations, their strategies, and the difficulties they face should be investigated using a range of system metaphors.
- System metaphors can be linked with systems methodology to guide intervention.
- Different system metaphors and methodologies can be used in a complementary way to address different aspects of organisations and the difficulties they confront.
- It is possible to appreciate the strengths and weaknesses of different systems methodologies and to relate each to organisational concerns.
- TSI sets out a systemic cycle of enquiry.
- Facilitators, clients, and others need to be engaged at all stages of the TSI process.

Total Systems Intervention (TSI) is a product of management science, specifically problem solving. The process employs a range of system metaphors to encourage creative thinking about organisations and the difficult issues that managers have to confront. The metaphors are linked through a framework entitled *a system of systems methodologies* to various systems approaches; so that once the metaphors are agreed a small number of appropriate methodologies can be identified for tackling the problem in hand. The appeal of TSI is that it is open ended in that it can encompass additional metaphors and methodologies and in that it forces the practitioner to characterise the problem domain thoroughly from as many perspectives as are appropriate and hence is essentially a pluralist metamethodological approach.

Flood and Jackson map the various systems methodologies into a two-dimensional space:

- The vertical dimension is concerned with the complexity of the system being investigated.
- The horizontal dimension is concerned with relationships between participants.

In the vertical dimension, system complexity is considered to be a continuum with the terms simple and complex bounding the ends of the scale and having the characteristics given in Table 2.

The two areas of concern fit the "complex system" definition well.

The horizontal dimension concerns the relationship between participants and Flood and Jackson divide it into three categories. Unitary relationships exist when all the participants share a common goal and work synergistically in a team. Pluralist relationships exist when there are diverging group interests but it is possible to achieve some accommodation of the different points of view. These relationships have inherent but manageable conflict that is resolved by the application of authority. In contrast, coercive relationships display oppositional and contradictory interests that lead to inevitable and often irreconcilable conflict. Power in such relationships is unequally distributed: domination and subjugation are evident.

Table 2. Definitions of system complexity.

Attribute	Simple Systems	Complex Systems
Number of system elements	Small	Large
Interactions between elements	Few	Many
Attributes of elements	Predetermined	Not predetermined
Interaction between elements	Highly organised	Loosely organised
Behaviour	Governed by well-defined laws	Probabilistic
Evolution	Does not evolve	Evolves over time
Nature of sub-systems	Do not pursue their own goals	Are purposeful and generate their own goals
Interaction with environment	None	Interacts strongly

Table 3 extracted from Flood and Jackson (1991), shows a grouping of systems methodologies based on the assumptions they make about problem contexts. Simple unitary systems are said to map onto a machine metaphor or closed system view. In management and organisation theory the machine view is typified by early theories of bureaucracy and scientific management that appeared in the late 19th century. A machine is recognised as a technical apparatus that has several parts, each with a definite function. The machine operates in a routine and repetitive fashion to perform a predetermined set of activities seeking rational and efficient means of reaching preset goals and objectives. It is a useful view providing the tasks to be performed are straightforward and well understood, the human parts fit into the design and are prepared to follow machine-like commands, and the environment is stable.

Table 3. A grouping of systems methodologies based upon problem contexts (Flood and Jackson, 1991).

	Unitary	Pluralist	Coercive
Simple	Operations research Systems analysis Systems engineering Systems dynamics	Social systems design Strategic assumption surfacing and testing	Critical systems heuristics
Complex	Viable system diagnosis General system theory Socio-technical systems thinking Contingency theory	Interactive planning Soft systems methodology	?

More complex unitary systems can be viewed through the organismic metaphor. Management theorists, who recognised that individuals operate most effectively when their social and psychological needs were catered for, derived this metaphor from organismic biology that is concerned with whole organisms in their environment. In this view, organisations can be considered analogous to organisms where their primary aim is survival rather than goal seeking. The system is seen as a complex network of elements and relationships that intersect forming highly organised feedback loops. Complex unity systems exist in an open environment from which they draw inputs and dispense outputs. They are also homeostatic in that there is selfregulation and repair. The organismic metaphor is useful when there is an open relationship between an organisation and its changing environment and where there are needs to be satisfied to promote survival. The system is responsive to change and can cope with a complex environment and is useful for considering more complex organisations such as industrial free-market enterprises. The most significant limitation of this model is that it sees change as being generated externally and something to which the system must adapt: it does not provide for proactive development.

The neurocybernetic perspective, in contrast to the above, emphasises active learning and control rather than passive adaptability and focuses on information processing and viability. As the name implies this metaphor looks at the brain as a well-tried and tested control system. It builds upon the standard cybernetic model that has a transformation process, an information system, a control unit, and an activating unit, by adding the important attribute of learning. Thus the model can accept dynamic aims and objectives and is capable of self-questioning rather than merely self-regulating. The neurocybernetic view is useful in practice for systems that exhibit self-enquiry, self-criticism, and dynamic goal seeking based on learning. It is useful in environments that exhibit a high degree of uncertainty where creativity is encouraged. It could well provide a useful model for adaptive information systems. The neurocybernetic view does, however, neglect to recognise that organisations are socially constructed phenomena and that the purposes of the parts of a system can be different from that of the whole.

The pluralist system methodologies are valuable when the cultural metaphor is applicable. In a broad sense, culture refers to various nebulous shared characteristics at all levels of organisation: societal, corporate group, etc. Typical features include shared language, religion, history, values and beliefs, and a shared sense of belonging. The cultural metaphor is useful when it shows that rational aspects of organisational life are only rational in terms of the installed culture. It highlights that the cohesion generated by shared social and organisational practices can both inhibit and encourage organisational development and as such is something to be managed and something that will take time to change. The cultural metaphor, like all the others is only appropriate for certain circumstances. It fails to address the structure of complex organisations and its adoption can lead to feelings of manipulation and resentment stemming from attempting explicit ideological control of the people within an organisation.

Coercive situations can be viewed through the psychic prison metaphor. In the original formulation of TSI only a few methodologies were described to assist in even simple coercive situations and nothing was offered for complex coercive ones.

Armed with the foregoing it is now possible to try and use the TSI to help identify appropriate methodologies for the areas of concern.

Methodologies for Engineering Complex Designed Systems

The logic of TSI is to identify appropriate methodologies through metaphors or through relating the problem to the problem context map shown in Table 3. Consider the first area of concern: creating a substantial socio-technical system.

The engineering of a substantial socio-technical system is clearly a complex problem. Consider the design of a new passenger transport aircraft. The design phases require large numbers of people[4], the activity spans decades from concept exploration to retirement and many interacting systems (eg airlines) are involved in operating the aircraft. Also, the aircraft and their support systems evolve over their operational life. Information systems are even more complex and certainly comprise subsystems that pursue their own goals!

As a first-order approximation, it is fair to say that the parties share common interests, they wish to create a successful system as defined by a set of contemporary criteria that would cover such things as performance, schedule, cost and hence profit, to environmental and workplace issues. The parties also would have compatible values and beliefs, often based on engineering, at least in the design phase. Thus it would be reasonable to invoke the team metaphor and the neurocybernetic metaphor to reflect the learning and adaptation that is now a feature of mature engineering enterprises (EIA-731, 2001).

None of the methodologies in the complex-unitary domain of Table 3 cover the range of issues needed to harness the human and other resources to succeed in this area of concern. What is needed is a scalable engineering methodology that can handle the technical aspects from a holistic perspective but one that also includes interpretive and critical components.

We proffer that the only appoach that has sufficient scope and methodological richness to tackle such problem domains is systems engineering, the breadth of which is apparent from Figure 2. Thus we consider systems engineering to be worthy of investigation and in the section below investigate the degree to which it can deal with complex-unitary problems.

Contemporary Systems Engineering

We start by considering the discipline of engineering. The US Accreditation Board for Engineering and Technology defines engineering as:

> "… the profession in which a knowledge of the mathematical and natural sciences gained by study, experience, and practice is applied with judgement to develop ways to utilise economically, the materials and forces of nature for the benefit of mankind."

Cook (2003) states that when undertaking complex, large-scale engineering activities, the engineering of the system must be placed ahead of the concern for components thereof and emphasis needs to be placed on the following:

- Improving methods for defining the product and system requirements.
- Addressing the total system with all of its elements from a life-cycle perspective.
- Considering the overall system hierarchy and interactions between the various levels.
- Organising and integrating the necessary engineering and related disciplines into the main systems engineering effort in a timely, coherent manner.
- Establishing a disciplined approach with appropriate review, evaluation, and feedback provisions to ensure efficient progress from the initial identification of need through to phaseout and disposal.

One of our favourite definitions of systems engineering summarises this:

---

[4] For example, Boeing (2003) cites that 6,500 people were employed in the design of the Boeing 777 within the company and another 13,500 in subcontractors scattered across the world. In total, there were 238 design teams that worked concurrently on the design.

> "Systems engineering is a branch of engineering that concentrates on the design and applications of the whole as distinct from the parts … looking at a problem in its entirety, taking into account all the facets and all the variables and relating the social to the technological aspects." (Simon Ramo, 1973, quoted in Rechtin 1991)

Aslaksen (1996; p44 onward) states that systems engineering is a requirements-driven *design* methodology with the inherent capability to handle complexity and uncertainty. He goes on to add that systems engineering introduces a functional domain (to add to the physical domain that engineers are accustomed to operating in), a focus on user needs, and the optimisation of the value of the solutions based on user needs from a life-cycle balanced, whole-of-system perspective. These features give us clues to the types of frameworks of ideas that might be appropriate.

Although systems engineering seeks to establish clear goals, Aslaksen among others is emphatic that it does not ignore human or societal concerns as is often thought to be the case.

In comparison to the methodologies one finds described in the management science literature, systems engineering is best thought of as a multimethodology because of its breadth (ISO/IEC 15288, 2002; Leibrandt, 2001, Whalen et al, 2000) and because many paradigms are employed in the various facets of the field. Indeed, it would be unusual for a systems engineer to have practiced in all of them, even over the course of an entire career.

Methodologies for Dealing with Engineering Organisations

Engineering organisations are concerned with acquiring or supplying goods and/or services and display all the management issues that organisations with this focus can be expected to exhibit. Hence, this area of concern relates directly to management science and a wide range of methodologies is applicable. TSI would be an appropriate metamethodology to direct their use and achieve the pluralistic richness necessary for the size of the enterprises needed to engineer complex systems.

At this point, it is worth mentioning that many of the methodologies found in the literature have insufficient scope to deal with Layers 4 and 5 that comprise consortia of enterprises employing thousands of people. Many of the methodologies are only useful for specific activities and are poorly suited to dealing with projects or policy issues whose life can be measured in decades.

The Framework of Ideas Revisited

The initial discussion on the framework of ideas limited itself to systems thinking because this was seen as a strong unifying underpinning concept that applied to both areas of concern. This section extends the framework of ideas by discussing first the philosophy of systems thinking and secondly social theory.

The reason to discuss the philosophy of systems practice is that there has been a considerable amount written about the history and philosophy of science and the inappropriateness of scientific approaches to many classes of problems. In these discussions, engineering is considered to be synonymous with science. Checkland (1981), however, clearly elucidates the difference between the aims and methods of professional scientists and engineers. Checkland states that science implies that the highest value attaches to the advancement of knowledge whereas engineering prizes most highly the efficient accomplishment of some defined purpose. Hence the principal question that scientists ask is "have we learned anything" whereas the engineers and technologists ask "does it work". In the subsection below we argue that systems thinking and systems engineering share a similar philosophical basis.

Pragmatism

Pepper (1942) argued that there are four fundamentally different World Hypotheses, being Formism, in which a complete worldview is built out of categories of essences identified, Mechanism which regards things from the viewpoint of a primary metaphor of a machine, Pragmatism, with the root metaphor of an historical event in its context, and Organicism, built on the metaphor of an organism (Barton, 1999: p8-9).

The physical sciences tend to assume the Formism approach in which entities are investigated as having properties associated with their fundamental form, and analysis is based on ideal cases. The biological and social sciences tend to take an Organicist approach, and are the foundation of this fundamental metaphor. Organicism regards its objects of investigation as complex wholes, but limits its view to the object under investigation. Traditional engineering tends to take the Mechanism view, and seeks to establish mechanical outcomes in a world that is assumed to operate primarily as a mechanism with clear cause and effect relationships. Pragmatism or as Pepper referred to it, Contextualism, is an approach taken by the sciences that emphasizes the system characteristics of things because Contextualism enjoins the method of considering both the system of interest and its context (environment) in a significant interaction. Thus, the context of an entity is regarded, in the system sciences, as significant to the kind of understanding of the thing that can be developed.

Pragmatism is a kind of philosophy developed by Charles Peirce, 1839-1914 (Barton, 1999: p1). Pragmatism provides a major critique of Cartesian rationalism and British Empiricism (Barton, 1999: p2), and so represents a significantly different approach to philosophy than other approaches available at the time. Peirce sought to "incorporate the logic of experimental science into philosophy", but not to simply take the positivist tradition of science into philosophy because Peirce's conception of science drew on a stronger social basis (Barton, 1999: p3). Therefore, issues associated with the knowledge of science, and the context of that knowledge, were introduced into Peirce's pragmatism. The major strands in Peirce's pragmatism are a pragmatic criterion on meaning, a theory of signs, an all-encompassing structure of categories, and a theory of continuity (Barton, 1999: p4).

Peirce elaborated three modes of inference, deduction, induction, and abduction, and argued that abduction is the only form of inference capable of extending knowledge (Barton, 1999, p5) and providing insight in the complex situations presented by systems, rather than the relatively simple abstractions of reality investigated in scientific experiments.

Barton asserts that Pragmatism may provide a suitable intellectual foundation for systems thinking. The corollary is that we suggest that it also could play the same role for systems engineering because Pragmatism parallels the systems engineering rationale of producing something given partial knowledge and finite resources. In this respect, systems engineering stands in relation to the systems sciences in the same way as the traditional engineering disciplines stand in relation to their related sciences[5].

---

[5] Our suggestion is not without a philosophical complication. This arises since systems engineering must work with both the Contextualist worldview and the Mechanistic worldview. This is problematic because it creates a demand to integrate two kinds of philosophy, which themselves are analytic in the case of one, and synthetic in the case of the other (Barton, 1999: p9). The result is that although Peirce's pragmatism appears useful for

Social theory

Jackson (2000) bases his newer taxonomy of systems methodologies on social theory. (It is noteworthy that this is the same taxonomy used by Neuman (2000) to discuss the meaning of methodology.) Table 4, extracted from Jackson (2000) makes it clear that the four research approaches listed have very different underlying frameworks of ideas. Indeed, the power of multi-methodological approaches such as TSI is the additional insight that combining the findings from various viewpoints provides.

Given the foregoing discussion about the differences in philosophical bases between science and engineering it is not clear that Table 4 provides a suitable column that describes engineering research or practice (where the basic goal is to get something to work as opposed to the four concepts shown).

Engineers tend not to concern themselves with the exposition of their values and beliefs in the same way that social scientist do and hence there is a paucity of literature in engineering philosophy and as such we recognise that this is an area that will require significant research in the future.

Methodologies Revisited

A contemporary theme in management science research is pluralism and multi-methodology. From the foregoing, it is clear that the scope of the areas of concern does, and will continue to, require pluralist approaches to deal with the myriad of problem situations that arise in engineering complex systems and in guiding the management of the organisations that undertake this work. The question now becomes “how can these methodologies be combined?” Jackson (2000; Chapter 11) states that the restraint imposed in the TSI framework of methodological purity achieved by conducting the selected methodologies in isolation until their findings are synthesised, is overly restrictive. Thus he argues that it is appropriate for systems practitioners to merge methodologies, apply only parts of methodologies, or indeed merge paradigms if it would be useful. This revised version conception of TSI provides a methodological basis for the second area of concern, engineering organisations.

It has been traditional to see systems engineering described as a functionalist methodology. Given the scope of the field, we believe it would be more appropriate to consider it as a metamethodology with a technical foundation in positivist science and a management scope encompassing functionalist, interpretive, and emancipatory approaches. In this context, contemporary systems engineering could be considered to be a metamethodology that possess a functionalist, imperialist methodological core, probably project management, which incorporates a wide range of concepts and methodologies to achieve the desired system outcomes. Thus we see systems engineering as an appropriate metamethodological framework for the first area of concern.

---

construction of a fundamental framework (F) for Systems Engineering it is not, alone, sufficient. It will be necessary to perform a considerable amount of work to construct a philosophical foundation for Systems Engineering that seamlessly integrates Pragmatism and Mechanism into some new synthesis that is itself coherent.

Table 4: Features of four research approaches from Jackson (2000: p42).

Features	Functionalist	Interpretive	Emancipatory	Postmodern
Basic goal	Demonstrate law-like relations among objects	Display unified culture	Unmask domination	Reclaim conflict
Method	Nomothetic science	Hermeneutics, ethnography	Cultural and ideological critique	Deconstruction genealogy
Hope	Efficiency, effectiveness, survival and adaptation	Recovery of integrative values	Reformation of social order	Claim a space for lost voices
Organization metaphor	Machine, organism, brain, flux and transformation	Culture, political system	Psychic prison, instruments of domination	Carnival
Problems addressed	Inefficiency, disorder	Meaninglessness, illegitimacy	Domination, consent	Marginalization, conflict suppression
Narrative style	Scientific/ technical, strategic	Romantic, embracing	Therapeutic, directive	Ironic, ambivalent
Time identity	Modern	Premodern	Late modern	Postmodern
Organizational benefits	Control, expertise	Commitment, quality of work life	Participation, expanded knowledge	Diversity, creativity
Mood	Optimistic	Friendly	Suspicious	Playful
Social fear	Disorder	Depersonalization	Authority	Totalization, normalization

Conclusion

In this paper we have attempted to identify the principal elements of a framework for the engineering of complex systems. We have tried to do this by identifying appropriate areas of concern, methodologies, and frameworks of ideas. The two very broad areas of concern span many disciplines and require pluralistic approaches that not only invoke multiple methodologies but ones that rest on quite distinctly different frameworks of ideas.

References

Barton, J. 1999, Pragmatism, systems thinking and systems dynamics, *17th International Conference of the Systems Dynamics Society & 5th Australian and New Zealand Conference*, Wellington, New Zealand, July, 19pp.

Boeing (2003), Boeing 777 Background, [Online accessed 26 August 2003] http://www.boeing.com/commercial/777family/

Boulding, K.E. (1956) ‘General systems theory - the skeleton of science’, *Management Science*, vol. 2, no. 3.

Capra F., *The Web of Life: A New Synthesis of Mind and Matter*, HarperCollins, ISBN 0 00 654751, 1996.

Checkland, P. (1981), *Systems Thinking, Systems Practice*, John Wiley and Sons, Chichester, ISBN 0 471 27911 0.

Checkland, P., and Holwell S., (1998) *Information, Systems and Information Systems*, Wiley, Chichester, ISBN 0-471-95820-4.

Cook, S.C., (2003) *Systems Engineering for Complex Problem Solving*, Course Lecture Notes, University of South Australia.

EIA/IS 731(2001) *Systems Engineering Capability Model*, Electronic Industries Association, Interim Standard.

Fabryky, W. (2003), *International SE Programs*, presented to the INCOSE Education and Research Working Group Meeting, Washington, USA, 29 June 2003.

Flood, R.L. and Jackson, M.C. (1991), *Creative problem solving*, John Wiley and Sons, Chichester, ISBN 0-471-93052-0.

Hitchins, D.K., (2003) World Class Systems Engineering – the five layer model, http://www.hitchins.co.uk, last accessed 19 August 2003.

Kasser, J.E. and Massie A., “A Framework for a Systems Engineering Body of Knowledge”, *Proceedings of the 11th Annual International Symposium of the International Council on Systems Engineering (INCOSE)*, Melbourne, Australia, 1-5 July 2001, Paper No. 8.5.3.

Kline S.J., *Conceptual Foundations for Multidisciplinary Thinking,* Stanford university Press, California, ISBN 0-8407-2409-1, 1995.

ISO/IEC 15288 (2002), *System engineering – System life cycle processes*, ISO/IEC 2002.

Jackson M. C., *Systems Approaches to Management*, Kluwer Academic/Plenum Publishers, ISBN 0-306-46506-X, 2000.
Leibrandt, R. What is the INCOSE guide to the systems engineering body of knowledge (SEBOK)?, *Proceedings of the 11th Annual International Symposium of the International Council on Systems Engineering (INCOSE)*, Melbourne, Australia, 1-5 July 2001, Paper No. 8.5.1.

Merriam-Webster (2003), Merriam-Webster Collegiate Dictionary and Thesaurus, in *Encyclopaedia Britannica 200, Deluxe Edition*, ISBN 0-85229-926-5.

Neuman W. L. (2000) *Social Research Methods: Qualitative and Quantitative Approaches*, Needham Heights, Massachusetts, Alyn and Bacon.

Pepper, S. (1942), *World Hypotheses*, Berkeley, University of California Press.

Whalen, J., Wray, R., and McKinney, D. (Eds), *Systems Engineering Handbook*, Version 2.0, July 2000, INCOSE.