Integrating Systems Science, Systems Thinking, and Systems Engineering: understanding the differences and exploiting the synergies

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Abstract: There is a need to properly define the "intellectual foundations of systems engineering"; and we need to look beyond systems engineering to do this. This paper presents a new framework for understanding and integrating the distinct and complementary contributions of systems science, systems thinking, and systems engineering to create an "integrated systems approach". The key step is to properly separate out and understand the relationship between the triad of: systems science as an objective "science of systems"; systems thinking as concerned with "understanding systems in a human context"; and systems engineering as "creating, adjusting and configuring systems for a purpose". None of these is a subset of another; all have to be considered as distinct though interdependent subjects. A key conclusion of the paper is that the "correct" choice of system boundary for a particular purpose depends on the property of interest. The insights necessary to inform this choice belong in the domain of "systems thinking", which thus provides a key input to "systems engineering". In many systems businesses, the role of "systems architect" or "systems engineer" integrates the skills of systems science, systems thinking and systems engineering - which are therefore all essential competencies for the role.

Background

An integrated systems approach for solving complex problems needs to combine elements of systems science, systems thinking and systems engineering. But as these different communities come together, they find that assumptions underpinning their worldviews are not shared. This paper was originally drafted in an attempt to understand and unify some of the belief systems revealed by early discussions in the INCOSE Systems Science Working Group in January 2011 and by work in the BKCASE project on describing "the integrated systems approach". This led me to look in more detail at some of the underpinning publications and philosophy.

One "hot topic" is whether systems exist in nature or are purely a construct of human thought. I follow Bertalanffy's taxonomy (Bertalanffy, 1968) in believing that both "real" and "conceptual" systems are a necessary and valid part of an integrated systems approach. This involves accepting two belief systems often viewed as contradictory, the "positivist and constructivist ontologies" (Cupchik, 2001).

Another dichotomy has to be reconciled to allow an effective systems approach is the hard versus soft systems divide – because "hard systems exist inside soft systems" (Bristol). The common statement "all systems have purpose" is also limiting and has to be questioned. And the use of the word "ontology" itself seems to be significantly different in computer science and social science contexts, both of which are relevant to complex systems engineering. And the reductionist and holistic approaches lead to two different types of question about systems:

What is different about different kinds of system? This question leads to "reductionist" enquiry, resulting in a wide diversity of concepts, taxonomies, and dimensions of variation, with correspondingly wide diversity of practice, experience and opinions. It encourages differentiation and silo thinking: for example, the physical, biological and social sciences are essentially separate.

What is similar about different kinds of system? This question encourages a holistic perspective, seeking similarities not differences. It allows re-use of patterns, insights and models in different domains, and to integrate across domains.

The term "systems praxis" is sometimes used to describe something very similar to what I am calling a "total systems approach". Systems Praxis has been described (Ring, 2011) as "the practice of recognising and creating systems". A joint INCOSE/IFSR project has started to explore "A language for systems praxis". This paper serves as one of the contributions to this "conversation".

Core assumptions

This paper starts with the premise that there is a "**systems science**", including a "theory of systems", that defines systems and system properties. These properties of a system - which can be either natural or man-made, and which can exhibit a greater or lesser degree of adaptive behaviour – are independent of how and why it was created. Systems can exist independent of human intentionality, and we see similar or identical system properties and patterns recurring across natural and man-made systems and across different domains of application. (Bertalanffy, 1968)

Systems engineering relates to the purposeful creation or adaptation, adjustment, and operation, of systems. From this perspective, the core function of **systems engineering** is "making choices about how to create and adjust a new system or modify an existing one the better to achieve a purpose", taking full account of the through-life context of operations and wider environment (for example PESTEL - Political, Economic, Social, Technological and Legal).

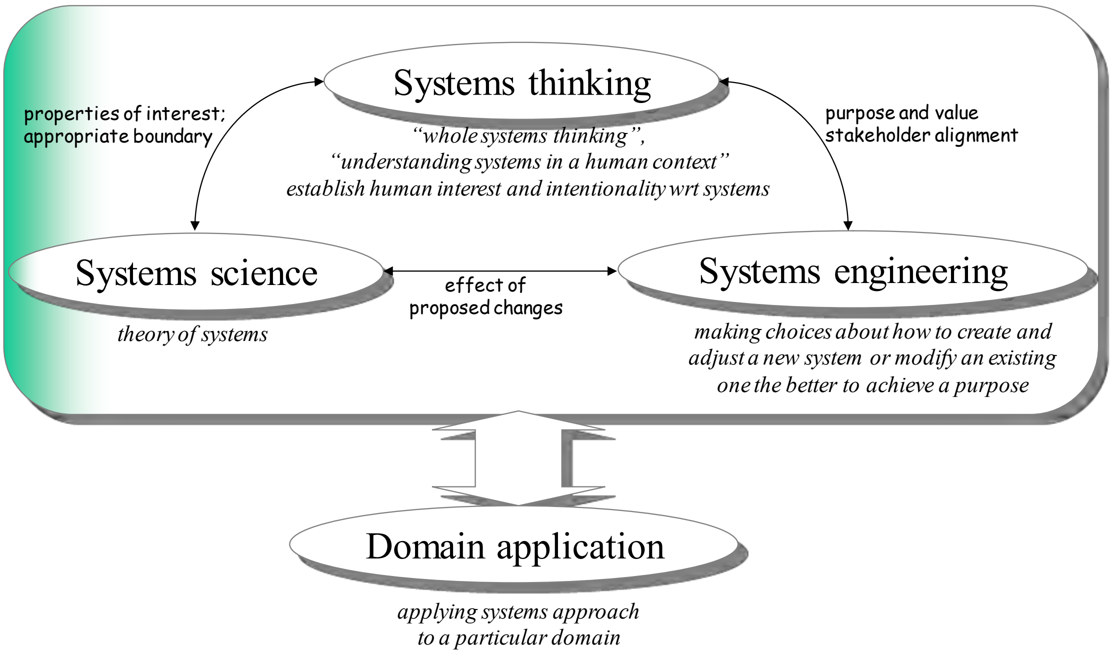

Figure 1: Systems science, systems thinking and systems engineering all contribute to an "integrated systems approach"

So if systems science is concerned with systems including those that exist independent of human intentionality, and systems engineering makes choices about creating or modifying systems "for a purpose", where do we establish purpose? If we consider **systems thinking** to be about "understanding systems in a human context", we can then view it as the activity that looks at systems through a lens of human intentionality, and establishes the "purpose" and "value" that drive systems engineering.

This triad approach, treating systems science, systems thinking and systems engineering as equal partners in an integrated systems approach, allows us to propose resolutions to paradoxes that have troubled practitioners for some time.

Background from a systems engineering perspective:

There has long been a divide between systems practitioners concerned with "hard" systems – often involving software and complex technologies – and "soft systems", concerned with social systems and human understanding of systems and human response to complex situations. Both sets of practice seek an underpinning theory or science of systems. However the relationship of systems science to systems thinking and systems engineering is uncertain, or at least not widely agreed.

Current systems engineering practice owes much to a process-oriented approach that developed out of US DoD and NASA practices in the 1960s and onwards.

Peter Checkland developed "soft systems methodology" as a way of introducing systems thinking and systemic understanding into complex organisational problem situations.

Derek Hitchins in a number of publications between 1990 and 2007 (e.g. Hitchins 2007) has presented a set of definitions that allow us to characterise "systems" and systemic behaviour. There is increasing interest in "complex adaptive systems".

Recently the University of (Bristol) in the UK has sought to unify the "systems engineering" and "systems thinking" communities using the principle "hard systems exist within soft systems". This view, while useful for integrating the domains of "systems engineers" and "systems thinkers", does not account the fact that many systems – all natural ones and some man-made ones as well – exist and evolve independent of human intentionality.

Jack Ring's "System value cycle" describes an integrated system approach that addresses a "community situation" focusing in turn on "value", "purpose" and "system". (Ring, 1998)

Bud Lawson's "system coupling model" shows systems as being configured from available assets in response to a "problem situation". (Lawson, 2010)

There is a renewed interest within INCOSE – often regarded as a purely "hard systems" and process-oriented community– in systems science as a theoretical underpinning for systems engineering and in the use of ontologies and model based systems engineering methods to improve the rigour and predictability of systems engineering endeavour. (SSWG, IFSR)

Recently there have been important advances in Systems Biology, and (Dawkins, 1976, revised and reprinted 2006) provides a fascinating and very systemic insight into a possible model of the evolution of modern life forms from the "primeval soup".

Essential elements of the Science or Theory of Systems

What is science anyway?

According to Wikipedia, "*Science is a systematic enterprise that builds and organizes knowledge in the form of testable explanations and predictions about the universe. An older and closely related meaning [of science] still in use today is that found for example in Aristotle, whereby "science" refers to the body of reliable knowledge itself, of the type that can be logically and rationally explained*".

The authors add "working scientists usually take for granted a set of basic assumptions that are needed to justify the scientific method: (1) that there is an objective reality shared by all rational observers; (2) that this objective reality is governed by natural laws; (3) that these laws can be discovered by means of systematic observation and experimentation."

Modern science is based on the Scientific Method, which can be summarised as: observe the real world, form a theory as to why things are as they are (or as they appear to be), form a hypothesis that allows us to test the theory by experiment, and depending on the evidence provided by the experiment, reject, adapt or provisionally accept the theory. When there is sufficient confidence in the theory it can be used to make predictions about the world. Testing these predictions builds further knowledge about the correctness and utility of the theory in different circumstances.

Scientific theories are always "provisional", because new experiments may reveal limits to accepted theories. The eminent British physicist Lord Kelvin, after whom the SI unit of temperature is named, had the misfortune to be quoted thus towards the end of the 19th century: "there is nothing new to be discovered in physics now; all that remains is more and more precise measurement"; and "X-rays will prove to be a hoax." On the positive side, he is credited with the following insight:

"*In physical science the first essential step in the direction of learning any subject is to find principles of numerical reckoning and practicable methods for measuring some quality connected with it. I often say that when you can measure what you are speaking about, and express it in numbers, you know something about it; but when you cannot measure it, when you cannot express it in numbers, your knowledge is of a meagre and unsatisfactory kind; it may be the beginning of knowledge, but you have scarcely in your thoughts advanced to the state of Science, whatever the matter may be*." (Kelvin)

So we have concepts of science as a process, as a philosophical approach to acquiring and validating knowledge, and as a body of knowledge per se.

"Purpose" and Scope of systems science in a systems approach

The purpose of systems science in the context of a systems approach can be stated as:

"to provide useful and relevant theories about systems to inform systems practice".

There is a plethora of fields included in the current scope of systems science – see for example the IFSR website (IFSR), (Hybertson), SEBOK V0.5 (BKCASE, 2011), (Warfield).

We have already noted the dichotomy between "soft" and "hard" approaches to systems engineering. There is a similar dichotomy in systems sciences between the view of systems (implicit or explicit) in the "hard sciences" which are inherently quantitative (where Kelvin's quote above provides an excellent litmus test of whether we can yet claim there is a "systems science") and the softer scientific domains where measurements are necessarily less direct and knowledge is more qualitative. In particular the extent to which we can claim that systems are "real" has been a matter of much discussion in the INCOSE Systems Science discussion forum (Ref). This dichotomy seems to be mirrored in the list of fields relevant to "systems science", and in the distinction between "positivist" and "constructivist" ontologies.

Reviewing these lists and discussions, and following a taxonomy set out by (Bertalanffy 1968, p xxi) it seems that they can be aggregated into four broad categories:

- Science of real systems governed by the laws of physics
- Science of real systems governed by the "laws" of biological
- Science of real systems governed by the "laws" of social behaviour
- Science of conceptual systems, governed by the laws of mathematics and logic

These can be referred to in short-hand as the science of "physical", "biological", "social" and "conceptual" systems.

Two matters of great interest to practitioners are the relationship between real systems and system models, and the occurrence of hybrid systems involving parts controlled by different "laws". An important sub-class of "conceptual systems" is what (Bertalanffy 1969, p xxi) refers to as "abstracted systems – conceptual systems corresponding to reality". So in this worldview, the mathematical and logical laws of real systems are captured in "abstracted systems". As an example of current practice, as jointly defined by NATO and the Open Group in the annex of TOGAF V8, "a physical system can be described by conceptual and logical models".

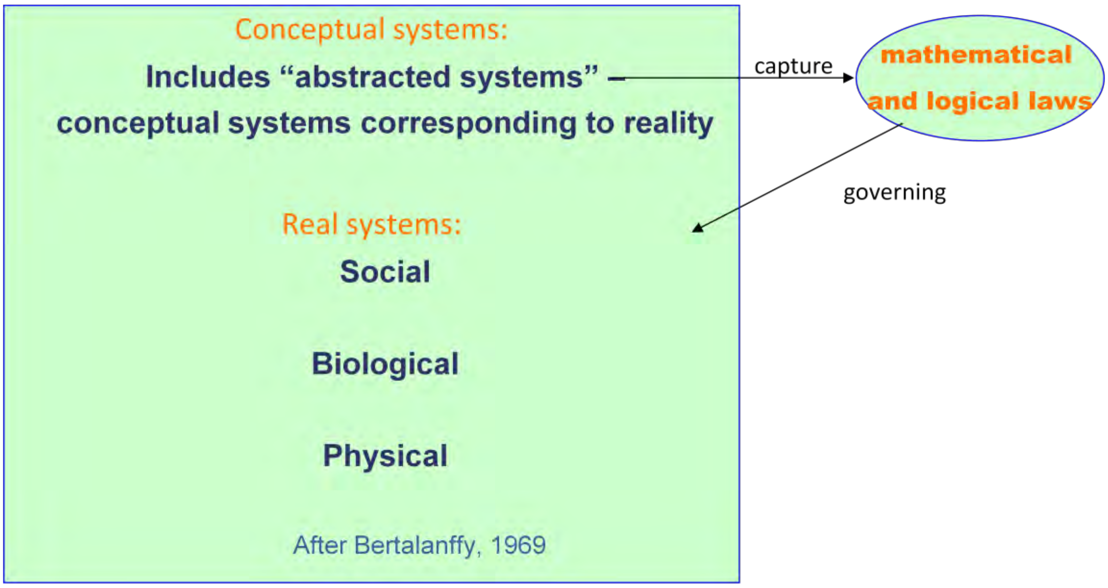

Figure 2: Bertalanffy's systems taxonomy. Generic "system laws" are required to unify thinking about hybrid systems spanning multiple domains

The most complex "real systems" may include physical, biological and social elements. For example (Lovelock's) "Gaia hypothesis" shows how we can understand the whole planet earth as a system, and is concerned with interactions between the biosphere, the climate and the earth's energy balance. Other hybrid systems containing all three of the above types include man-made socio technical systems. And a bee is both a whole biological system in its own right, and part of a social system. Clearly, such a "system" cannot be understood using methods restricted to any of the individual "real system" domains, so it is of great interest to find or develop universal "laws" applicable to all kinds of systems. Generic system models allow us to unify our thinking at the "whole system" level across domains, and system dynamic modelling and computational methods from complexity science are a valuable part of the practitioner's toolkit.

Generic system theories and models

Drawing on Bertalanffy's General Systems Theory, Derek (Hitchins, 2007) has consistently used and described a "generic system reference model" which, briefly stated, assumes that a system: has form (structure), function (process), and behaviour; exists in three conceptual environments - operational environment, threat environment and resource environment; and has three core functions - perform mission, maintain viability, and manage resources. Other authorities use an orthogonal set of generic functions, expressed in a variety of ways but generally corresponding to the "OODA loop" – Observe, Orientate, Decide, Act.

Most definitions state that systems are made up of inter-connected parts and exhibit emergent properties – properties of the whole not uniquely attributable to any of the parts. Because of the nature of emergence, the system may have performance characteristics as well as function and behaviour that are qualitatively different from, though dependent on, those of its parts. Performance can be related to function ("how well"?) and to behaviour ("how quickly, how reliably"?). Structure ties this all together by defining the paths through which the parts of the system can interact with each other and the external environment.

(Hubka and Eder) in the 1980s published a treatise on "the theory of technical systems" that formalises a number of concepts familiar in both systems engineering and product design. These include two distinct functional architectures – "service functions" as seen by the system's users, and "technical functions" as seen by the designers – and two levels of physical architecture – "organic architecture", the conceptual physical organisation of the major elements, and the "product structure", the complete listing of parts and their interfaces. This is broadly in line with subsequent Architecture Framework definitions.

David Blockley with a background in civil engineering suggests that "a system is a process" and that systems can be considered wholly in terms of their process characteristics. (Ring, 2011) argues similarly, that "systemness" is exhibited through behaviour not structure. Dov Dori suggests that system properties are determined by structure and behaviour and the two must be considered in tandem. He suggests that these determine function and process, which in turn contribute to purpose. This approach underpins the "OPM" (Object process methodology), which underpins the OPCAT systems engineering tool (Dori, 2011).

Delving back into the older literature we find that most of the modern thinking on systems science and systems engineering can be traced back to three sources: Hall, 1962, often referred to (e.g. by Hitchins) as the definitive account of systems engineering; Bertalanffy, 1969, whose book on General systems Theory is the basis for much of the following discussion, and (Ashby, 1956). It may be time to recognise these seminal works as the core intellectual foundation of our discipline rather than continually reinventing what turn out to be essentially the same ideas. Bertalanffy in particular emphasises the concept of “isomorphy of laws in different fields” – the idea that if we use appropriate levels of abstraction, we find fundamental “laws” and “patterns” occurring repeatedly in different fields. This leads to the hypothesis that if we can recognise such repeating laws and patterns, we can transfer experience, knowledge and predictions. (Sillitto, 2010) suggests that this is a very important principle in the design or management of Ultra-Large Scale Systems, and illustrates examples of complex behaviour from well-characterised fields of physics, which seem to read across into socio-technical systems. The essence of these various perspectives is summarized in two sets of statements in the following tables: one set in the style of “a system is (or does)”, the other in the style of “a system may”.

1. A system exists within a wider “context” or environment. • The environment includes (Hitchins) an “operational environment”, a “threat environment” and a “resource environment” • The environment may also contain collaborating and competing systems.
2. A system is made up of parts that interact with each other and the wider environment. • The parts may be any or all of hardware, software, information, services, people, organisations, processes, services, - - • Interactions may include exchange of information, energy and resources.
3. A system has system-level properties (“emergent properties”) that are properties of the whole system not attributable to individual parts. • Emergent properties depend on the structure (parts and relationships between them) of the whole system, and on its interactions with the environment • This structure determines the interactions between functions, behaviour and performance of the parts, and interaction of the system with the environment - in ways both intended an unintended.

4. A system has
• Structure
  o a boundary, (which may be static or dynamic, and physical or conceptual)
  o a set of parts,
  o the set of relationships and potential interactions between the parts of the system and across the boundary
• Function
  o which can be characterised following Hitchins as “operate - maintain viability - manage resources”, or as “observe – orient – decide – act”.
• Behaviour - including state change, and exchange of information, energy, resource (need to relate this to Dov Dori’s definition of process)
• A lifecycle
• Performance characteristics associated with function and behaviour in given environmental conditions and system state

5. A system both changes, and adapts to, its environment when it is deployed (i.e. inserted into its environment).
6. Systems contain multiple feedback loops with variable time-constants so that cause and effect relationships may not be immediately obvious or easy to determine.

Table 1: “A system does”

1. A system may exist independent of human intentionality.
2. A system may be part of one **or several** wider "containing systems".
3. A system may be self-sustaining, self-organising, dynamically evolving, (such systems include "complex adaptive systems")
4. A system may offer "affordances" – features that provide the potential for interaction by "affording the ability to do something" (Norman, 1990) • Affordances will lead to interactions whether planned or not, e.g. the affordance of a runway to let planes land and take off also leads to a possibly unintended affordance to drive vehicles across it (which may get in the way of planes, leading to undesirable emergent whole-system behaviour)
5. A system may be • clearly bounded and distinct from its environment (the solar system, Earth, planes, trains, automobiles, ships, people) • closely coupled with or embedded in its environment (a bridge, a town, a runway, the human cardiovascular system, the internet) • of fluid and dynamic make-up (a club, team, social group, ecosystem, flock of geese, and again the internet)
6. A system may be technical (requiring one or multiple disciplines to design), social, ecological, environmental, or a compound of any or all of these.

Table 2: "A system may"

Don't all systems have purpose?

I have seen numerous circular arguments where people tie themselves in knots trying to reconcile a belief that "systems must have purpose, by definition" with evidence that "real systems" occur in nature with no (or no human) purpose. Many of these discussions become unhelpfully metaphysical. It doesn't seem to make sense artificially to impute purpose to natural systems, nor to deny their existence, nor to say "if they have no purpose they cannot be systems". Some suggest that the POSIWID principle (purpose of a system is what it does) reconciles the paradox. This is a useful "systems thinking" concept to govern interventions in working systems, but hardly meets the test for scientific knowledge.

This matters because we are more likely to be successful when designing complex adaptive systems if we understand the characteristics of successful ones, many of which are natural or accidental.

The best way I can make sense of this is as follows:

- Engineered systems are engineered for a purpose.
- Some human-made systems are "accidental systems", in the sense that the parts of the system that people have created for a purpose (the "engineered system") have unforeseen interactions, internally or with their wider environment, that lead to unintended consequences. The "wider system" that produces these unintended consequences is then an "accidental system",

created by humans by accident when deploying or modifying a (usually smaller) system for another purpose.

- Natural systems exist (and persist and evolve in some dynamically stable fashion) because they provide some stability or viability benefit to the constituent parts of the system. Good examples of this include the many symbiotic relationships in biological systems. **It would seem that such systems are better understood in terms of "mutual benefit" rather than "purpose".**

This implies that it is NOT the case that all systems (not even all man-made systems) have a purpose. So purpose is not an essential or defining characteristic of systems – though systemic behaviour is (Ring, 2011). Purpose is, however, an essential and defining characteristic of human-engineered systems, and should guide all human interventions in systems.

The boundary paradox: a key insight

We have said that a system has a boundary that encloses the parts of the system. Once we have set the system boundary, all the above properties and characteristics are "objective", independent of human values or intentionality. But how do we reconcile this claimed objectivity with the apparent need for a human choice – presumably a subjective choice? - of the system boundary? There are two answers to this.

Some systems have a very clear physical boundary and are loosely coupled from the rest of the universe: for example the solar system, the earth, an aeroplane, an animal.

In such cases it is usually convenient to define the boundary of the "system of interest" as the physical boundary of the "system".

Sometimes we are interested in a particular "property of interest" – the earth's energy balance, the profitability of a business, the viability of a community, the operational effectiveness of a military system.

Once we have established the "property of interest", the "system of interest" and corresponding system boundary can be determined by finding the set of parts and relationships that are necessary and sufficient to account for the property or properties of interest*. (This I believed to be a key and novel insight - but Ashby said something similar in 1956! See also (Meadows, 2010), (BKCASE, 2012))*

Often the system of interest, and corresponding boundary, will be different depending on the property of interest: for example whether the question is "what are we contracted to deliver", "what is needed to provide a reliable service", or "what is needed to achieve our purpose or goal"? This is the difference between a "product systems engineering" (BKCASE 2011), a "service systems engineering" (BKCASE 2012) and a "capability systems engineering" (Henshaw et al, 2011) viewpoint. Another key question is "what factors in the environment will adversely affect the successful operation of our system".

There are usually at least two boundaries we need to consider (Sillitto 2005): the "responsibility boundary" that encloses the new or modified system (or part of a system) that we are responsible for and have control over; and the "analysis boundary" which includes everything else we need to consider to understand what the system of interest will actually do when deployed into the real environment.

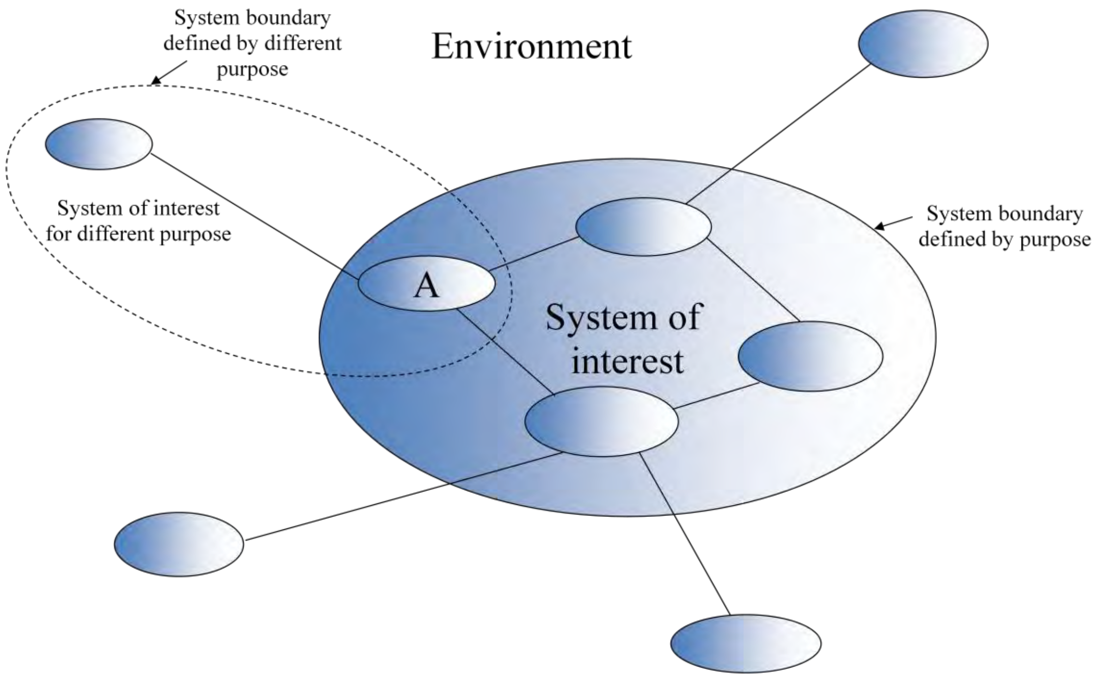

Figure 3: Once we have established the "property of interest", the "system of interest" and corresponding system boundary can be determined by finding the set of parts and relationships that are necessary and sufficient to account for the property or properties of interest.

Once the purpose and value are decided – or perhaps it is better to use the word "chosen", because this is a human choice - the appropriate system boundary can be determined. If the wrong boundary is chosen for a systems engineering effort, the wrong design choices will be made, purpose will not be achieved and value will not be delivered. So the skill and process for relating and aligning purpose, value and system boundary is key to the success of a systems approach. This brings us to systems thinking.

Systems thinking

Various references (Senge, Meadows, Seddon, Checkland, - -) describe systems thinking and "soft systems" approaches independent of systems engineering. The INCOSE SE Competency Framework (INCOSE 2010) recognises the need for systems thinking within systems engineering by including a set of "systems thinking" competencies.

Current definitions of Systems Thinking seem unsatisfactory and non-rigorous compared with the potential rigour of a properly grounded systems science. They have several key elements, including:

- "whole systems (or "holistic") thinking", seeing the overall systems aspects of a problem situation
- "loopy thinking", seeing and understanding patterns of system behaviour, feedback loops and system dynamic behaviour (Godfrey et al), usefully expressed in terms of "systems archetypes" (Senge, Meadows)
- understanding stakeholder interests and concerns and methods for aligning purpose – e.g. the CATWOE approach in Soft Systems Methodology (Checkland)

A comprehensive review of the similarities and differences between different expositions of systems thinking is given by (Buckle Henning & Chen, 2011)

Clarity of definition is often aided by focusing on outputs. It seems that the key outputs required of systems thinking as part of an integrated systems approach include:

- correct choice of problem
- correct identification of stakeholders and their concerns
- correct choice of system properties of interest
- correct choice of system boundary, or criteria for making that choice
- alignment of stakeholder purpose, values and incentives
- correct identification of those parts of a wicked problem situation that must be "managed" and those that can be "solved" (see Sillitto 2010)
- correct programme construct for a complex system development or intervention
- clear definition of purpose and value for each set of systems engineering activities.

The key role of systems thinking in an integrated systems approach is **to establish the purpose and value of the system of interest.**

"Systems engineering"

*"**Systems Engineering** is an interdisciplinary approach and means to enable the realization of successful systems. It focuses on defining customer needs and required functionality early in the development cycle, documenting requirements, then proceeding with design synthesis and system validation while considering the complete problem: Operations Performance Test Manufacturing Cost & Schedule Training & Support Disposal. Systems Engineering integrates all the disciplines and specialty groups into a team effort forming a structured development process that proceeds from concept to production to operation. Systems Engineering considers both the business and the technical needs of all customers with the goal of providing a quality product that meets the user needs."* (INCOSE website definition)

So - "Systems Engineering" is concerned with at least the following **choices**:

- The function, behaviour and performance we believe are required to achieve purpose, satisfy stakeholders, and avoid unintended negative consequences (the latter often receiving insufficient attention);
- The structure, behaviour and performance attributes of the system of interest and of its components (which may include people, processes, services etc as well as physical and software components);
- Making, or providing evidence to support, value-driven trade-offs between different approaches and solution options
- Those variables in the external environment of the system that will be explicitly measured by the system;
- We can also make design choices that will influence how susceptible the system of interest is to environmental variables we have chosen not to explicitly measure;
- How we will prove that the system meets stakeholders' needs and expectations and is fit for purpose

These are all design choices that should result in a system that is in some sense optimally or adequately fit for purpose, and will be improved by a good understanding of those aspects of systems science relevant to the class of system being "engineered". They are quite apart from the "process" aspects that dominate current systems engineering standards.

Activities falling within the generally accepted scope of Systems Engineering (see e.g. INCOSE) include:

- Get the system working as a system and delivering the intended benefits
- Define the parts and their interfaces and associated processes and behaviour of
    - The operational system
    - Enabling systems including:
        - The development organisation
        - The test system
        - The manufacturing system and supply chain
        - The setting to work system
        - The support system
        - The decommissioning system
- Document these items and related processes, practices and assumptions so the system can be replicated and managed through life

The deeper aspects of system design include proving that the design will work at as early a stage in the project as possible, to avoid heavy investment in a flawed design or in a solution to the wrong problem.

Effective Systems Thinking will ensure the right systems boundary and success criteria are considered for the numerous analyses and trade-offs involved in the design process. It is also required to make an appropriate choice of system lifecycle for the development and deployment; and to construct an appropriate measurement framework to give feedback to the systems engineers during development.

So Systems Thinking is a key skill within the SE process as well as in the precursor activities.

Systems Approach

The "systems approach" integrates elements of all three (Systems Science, Systems Thinking and Systems Engineering) in order to create "the practice of recognising and creating systems", or more generally, to recognise and scope system problems and define appropriate response.

Good examples of overall conceptual process models for a system approach include Jack Ring's "system value cycle" and Bud Lawson's "system coupling model".

Much of the problem in achieving an effective systems approach is social rather than technical – how do we get stakeholders to recognise the complexity of a situation and buy into a systems approach? The methods set out in (Warfield) are concerned with helping stakeholders to recognise and develop a shared understanding of complex situation; these are similar to the problem-domain visualisation techniques described by (Wilkinson).

A systems approach in a particular domain will apply these general principles within the context of existing knowledge about the particular domain. This may include an understanding of domain problems, constraints, risks and opportunities; and in particular the best order to tackle issues as we approach a problem in the domain. The advantage of a domain-specific approach is better efficiency based on risk-aware replication of known practices and proven design rules. Potential disadvantages are blindness to cross-domain opportunities and issues, and a risk of the "wrong-problem syndrome", solving the problems that interest domain experts rather than what is needed to resolve the problem situation. ("If my only tool is a hammer, every problem begins to resemble a nail!")

Specific domains in which systems approaches are used and adapted include

- Technology products – requiring single or multiple engineering disciplines
- Information-rich systems – command and control, air traffic management etc
- Platforms – aircraft, civil airliners, cars, trains, etc -
- Organisational systems, which may be focused on delivering service or capability
- Civil engineering/infrastructure systems

We may look at systems through the lenses of "product", "service", "capability" or "self-organising self-sustaining complex adaptive system" approaches. (BKCASE 2012) has chosen the primary categorisations of "product", "service" and "enterprise".

System scale or "extent" is also an important domain variable. Particular classes of system of wide interest include

- increasing scales of technology-centric systems:
  - "Technical systems" (Hubka & Eder) – in its simplest form, a complex product or technical artefact
  - "Whole systems" including a technical system integrated with the people, organisation, resources, process, control etc required for it to perform a useful function according to a "concept of operations" or Conops
  - "Systems of systems" characterised by operational and managerial independence of the parts of the system, which are viable and useful systems in their own right (Maier);
- increasing scales of people-centric systems: social groups and project teams; programme and business systems; industry systems; societal systems
- and very large scale systems: "Ultra-large scale systems" (Northrop et al), scaled-up systems of systems where systems issues are dominated by complexity, emergence and socio-technical factors; planet-scale ecosystems and the environment (Lovelock).

The specific skill-sets for each domain and scale may be quite different. However there are certain underlying unifying principles based on systems science and systems thinking that will improve the effectiveness of the systems approach in any domain.

Summary and conclusions

An integrated systems approach requires effective integration of systems science, systems thinking and systems engineering, and the effective application of the whole within real domains of application. The scope and boundary of and interactions between all three of these (systems science, thinking and engineering) are still fluid.

This paper:

- Identified the key purposes of each within an integrated systems approach;

- Recalled and summarised from the literature a set of core statements about systems that provide the basis of an underpinning “theory of systems”;
- Asserted that these definitions mean that systems can exist independent of human intentionality, and that purpose is not a defining characteristic of systems
- Identified a key principle which is that the correct boundary for a system of interest depends on the properties of interest – this choice of properties of interest is therefore related to human intentionality and so falls within the domain of systems thinking;
- Identified systems thinking as the domain in which purpose and value are established and stakeholder interests identified and aligned.

Systems Engineering depends on systems thinking to identify purpose and value, and appropriate programme portfolio and stakeholder alignment; and on systems science for a fundamental understanding of the nature and characteristics of systems. So Systems Thinking is used to establish strategies for Systems Engineering. If Systems Science can be correctly codified it allows us to develop useful domain independent system concepts, abstractions, principles and models that will aid the practice of systems engineering. Domain specialisation adds specific knowledge of key constraints, functions and performance parameters in the domain.

Systems engineers need to understand elements of Systems Science and Systems Thinking to be able to operate as effective systems engineers. These subjects are themselves diverse, with many largely separate communities of practice, and consequently are not clearly defined or bounded. The approach set out in this paper will help the SE community “ask the right question” of Systems Science and Systems Thinking.

Biography

Hillary Sillitto is Thales UK’s Systems Engineering Director. He started engineering in the 1970s, working on the design of novel optical systems for a wide range of system applications. He then worked successfully on increasingly diverse and complex systems, mostly for defence and aerospace applications, holding increasingly responsible positions in industry and government, running the UK MOD Integration Authority as an industrial secondee from 2005-8. He has been awarded 8 patents, and has published several papers at INCOSE international symposia (three of them winning Best Paper awards). He is a Visiting Professor at the University of Bristol, and a member of the BKCASE SEBOK author team. He was INCOSE UK Chapter president in 2004-6, was elected an INCOSE Fellow in 2009 and certified as an ESEP in February 2010. He is a Chartered Engineer and a Fellow of the Institute of Physics.

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