Perspective 1 of the SoSE methodology: framing the system under study

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Abstract: The first perspective in the system of systems engineering (SoSE) methodology is to ensure that the engineering analysis is supported by an explicit understanding and framing of the problem under study. By explicitly framing the problem and its associated context, the SoSE methodology minimises the chance of a Type III error (i.e., correctly rejects the null hypothesis for the wrong reason) committed at study's outset. This paper addresses the methodology's Perspective 1, framing the system under study, and the nine component execution elements serving to operationalise it. The paper will illustrate those elements as tools with which SoS problems may be framed in terms of their most prominent contextual and environmental influences.

Keywords: system theory; systems thinking; system of systems; SoS; system of systems engineering; SoSE.

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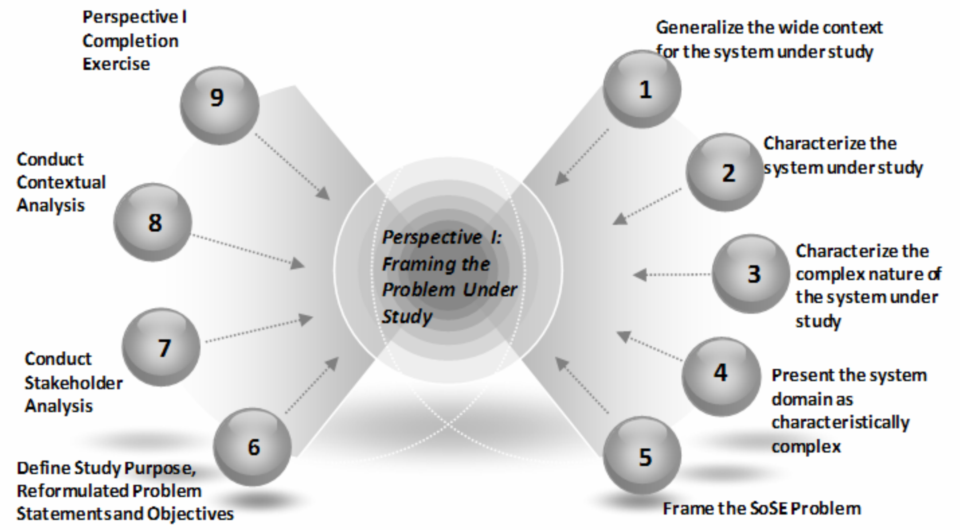
1 Introduction

The system of systems engineering methodology (SoSE methodology), presented by Adams and Keating in this issue, is used to frame the conduct of an engineering analysis of a system of systems (SoS) problem. The SoSE methodology is a rigorous engineering analysis that invests heavily in the understanding and framing of the problem under study. Rigorous engineering analyses of such problems and their associated contexts and environmental settings can minimise chances of *Type III errors* (Mitroff and Featheringham, 1974) related to problem formulations that supposedly represent problems of interest. *Type III* error is committed when "... correctly rejecting the null hypothesis for the wrong reason" [Mosteller, (1948), p.61], and it is therefore also described as "the error associated with solving the wrong problem precisely" [Mitroff, (1998), p.15]. Analyses plainly suffer from *Type III errors*.

The SoSE methodology's Perspective 1 establishes logic for the analysis of SoS, and Figure 1 shows that logic to include nine of the methodology's total of 23 execution elements. Like all 23, the Perspective 1 elements invoke the application of rigorous engineering methods to expose problems under study and produce actionable results; therefore, each element is associated with: a need for certain inputs; methods or techniques able to promote the understanding or transformation of problems of interest; and outputs of element application. The balance of this paper will demonstrate how Perspective 1 proceedings can productively illuminate contextual and environmental influences that most influence SoS problems of interest.

Figure 1 Elements of Perspective 1



2 Element 1: generalise the wide context for the system under study

The first step of a SoSE analysis requires identification of contextual and environmental factors of greatest influence upon the system under study. Table 1 simply describes such a process in terms of a goals-inputs-outputs construct to be observed with each of Perspective 1's nine execution elements.

Table 1 Element 1 attributes and description

Element attributes	*Attribute description*
Goal	Create an initial wide-view contextual diagram that captures the key elements of the problem system under study.
Input	Problem description.
Output	High-level, wide-view context diagram.

The construction of the high-level, wide-view context diagram is conducted to capture the set of circumstances, factors, conditions, values, or patterns (see Table 2) that constrain and enable the SoSE process, the system solution design, system solution deployment, and interpretation of outputs and outcomes. The wide area context diagram must account for relevant perspectives associated with the problem system under study.

The wide-view diagram noted in Table 1 would capture the Table 2 set of high-level circumstances, factors, conditions, values, or patterns that most constrain and enable the SoSE process, the system solution design, system solution deployment, and interpretation of outputs and outcomes.

Table 2 Contextual elements

Contextual elements	*Description*
Circumstances	Particulars of the situation that define the state of affairs. Example: the decision process is bound by a specific procedure.
Factors	Specific characteristics or variables that affect the situation. Example: number of stakeholders involved with the system.
Conditions	The prevailing state of the situation that influences outcomes. Example: current system performs in a high risk environment.
Values	General beliefs for which the system' stakeholders have an emotional investment. Example: individual subsystems should be autonomous.
Patterns	A perceived structure, operation, or behaviour that is recurring. Example: recurring system modifications performed without concern for consequences.

It would invoke the systems *principle of complementarity* (addressed in the article by Adams in this issue) that suggests we consider problem contexts of no single reality just as we do problem systems, *per se*, because:

> "Different perspectives or models of a system will reveal truths regarding the system that are neither entirely independent nor entirely compatible."

If we think of a perspective as the state of one's ideas or the known facts, then we can represent the world-view of the observer as a function of the number (n) of perspectives (P) is being used to represent the problem under study.

$$\text{Contextual Understanding} = \sum_{i=1}^{n} P_i$$

Perfect understanding requires complete knowledge of an infinite number of perspectives, a fact that engineers struggle to control when bounding complex systems of systems problems.

$$\text{Perfect Understanding} = \sum_{i=1}^{\infty} P_i$$

As we can never completely understand or manage everything related to systems' contexts or environments, we must ignore those domains' inconsequential components in favour of building models accounting for some manageable number of elements of each identified with both of what are termed hard and soft models linked to systems of interest, their settings, and the team of analysts seeking to understand both.

Holistic understanding of context requires engineers to address both *hard* and *soft* elements of the systems problem. Jackson (2000) characterises *hard systems* approaches as having the following four characteristics:

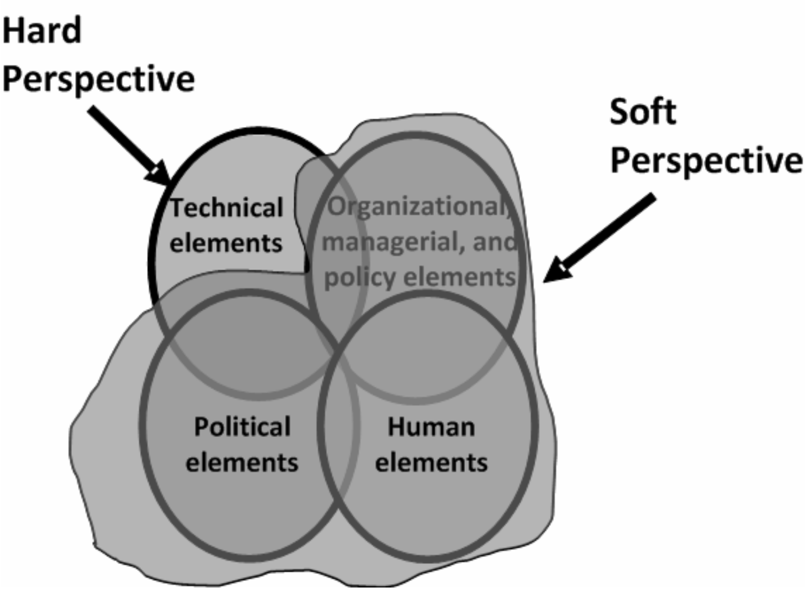
1. there is a desired state of the system, S_1, which is known
2. there is a present state of the system, S_0
3. there are alternative ways of getting from S_0 to S_1
4. it is the role of the systems person to find the best means of getting from S_0 to S_1 (p.135)

and *soft system* approaches as having the following characteristics:

1. systems possess a much more precarious existence, as the creative constructions of human beings ...
2. it is necessary, therefore, to proceed by trying to understand subjectively the points of view and the intentions of the human beings concerned ...
3. models are used to explicate particular worldviews rather than to capture some truth about the nature of the system ...
4. methodology should be geared to getting as close as possible to what is going on, preferably by getting inside people's heads to find out and influence what they are thinking (p.211).

The contrast between these two approaches affords engineers significantly different but mutually supportive views of problems they wish to solve. Soft system-oriented models render views typically able to well characterise organisational, managerial, policy, political, and human factor aspects of problem SoSs, while hard system orientations offer understanding of SoS's technical elements. The *principle of holism* (addressed in the article by Adams in this issue) demands use of both approaches within a construct depicted with Figure 2.

Figure 2 Hard and soft perspectives in systems context



SoSE methodology accordingly promotes balance in identifying hard and soft contextual and environmental aspects that constrain and enable operations of problem systems of interest. Table 3 provides additional details of hard and soft approaches to SoS analysis.

Table 3 Attributes of hard systems and soft systems views

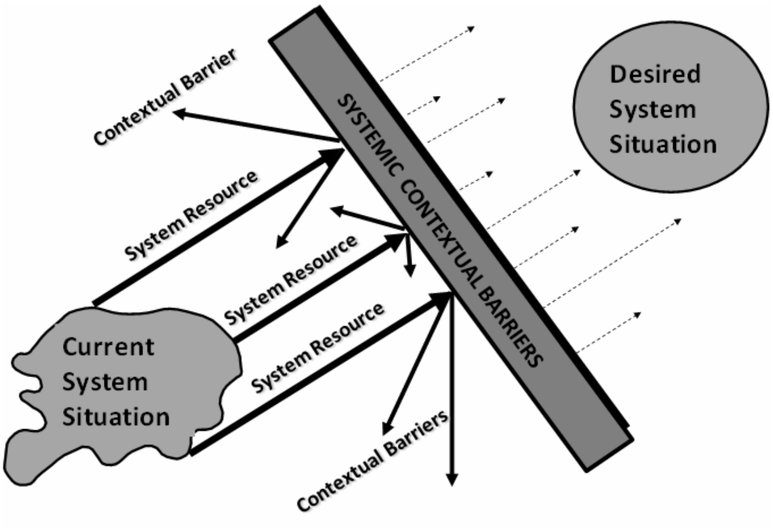
Attributes	*Hard systems view*	*Soft systems view*
World view	A real world exists external to the analyst.	Perspectives of reality are dynamic and shifting.
Data	Factual, truthful and unambiguous data can be gathered, observed, collected, and objectively analysed.	Data is subjective in collection and interpretation – analysis strives for transparency.
System	The system in focus is unaffected by either the analysis or the analyst.	The system in focus is affected by both the analysis as well as the analyst
Analysis results	The results of analysis are replicable.	Results of analysis are *credible* and capable of compelling *reconstruction*.
Value	The analysis can be conducted free of value judgements.	The analysis and interpretation of analysis is value-laden.
Boundaries	The system in focus can be bounded and the analysis can be controlled – this is both possible and desirable.	Bounding of the system in focus is problematic, control of the analysis is questionable – emergence is dominant.

Engineers must understand and ultimately represent context if they are to move a system or SoS of interest from some current state to a different, desired state. In order to understand the system resources required to move from current to desired states, engineers must identify and analyse systemic contextual barriers to such changes.

Figure 3 represents how current system resources might be applied in order to overcome barriers and achieve desired states.

Contextual assessments, too, support the identification and consideration of contextual information related to problem systems of interest, and Table 4 displays certain of the analytical domains and domain-related concerns to be addressed with such assessments. What can be termed contextual assessment matrices offer means by which systems engineers can perhaps most precisely explore opportunities to advance the SoS problem to the desired end-state.

Figure 3 Representation of contextual barriers



Such matrices can be difficult to develop because they must display many implicit elements of the SoS problem. In order to construct a meaningful representation, a contextual assessment matrix is constructed. The contextual assessment matrix is constructed to answer the questions posed in Table 4.

Table 4 Questions for contextual analysis and response

Contextual analysis area	*Question*
Identification	What are the relevant aspects of context that are of concern (influence the system solution, development process, or deployment)?
Assessment	What are the potential impacts of the contextual aspects identified?
Response	What strategies, initiatives, or activities will be pursued in response to the assessment?
Monitoring	How will changes in context be identified, processed, and scanned?

Construction of the contextual assessment matrix is an exercise in explicitly stating the elements of context that are often threatening and ugly and often only receive tacit treatment. This is hard work, requires active thinking, testing, and adjustment, and a proactive worldview designed to ultimately influence context. Finally, the contextual assessment matrix helps the analysis team understand how to invest system resources in overcoming or controlling the barriers present in the relevant context. Constructing and understanding the impacts of relative context greatly reduce the likelihood of committing a *Type III error* in the early stages of the SoSE analysis.

3 Element 2: characterise the system under study

This element focuses on describing the problem system or SoS of interest in terms of 13 characteristics associated with the SoSE methodology (Adams and Keating, 2009). The SoS problem description is analysed in order to construct the elements contained in Table 5.

Table 5 Element 2 attributes and descriptions

Element attributes	*Attribute description*
Goal	Understand the basic structure and characteristics of the SoS under study. These include the 1 system's definition 2 components 3 objectives 4 functions 5 environment 6 resources 7 governance structure
Input	1 Problem description or research question. 2 High-level wide context diagram.
Output	List of system characteristics.

3.1 System definition

Understanding the definition of the system under study requires an understanding of what a system is. An excellent definition of a system was proposed by Blanchard and Fabrycky (2006, p.2):

> "A system is a set of interrelated components working together toward some common objective or purpose."

Emphasis is placed on three words:

1 interrelated

2 components

3 common objective or purpose.

Once the system definition is agreed upon, further analysis is required to understand the all the characteristics of the system.

3.2 System components

A system can have any number of components. The components are the elements of the system that realise system objectives by accomplishing jobs, tasks or activities. Components are normally grouped as shown in Table 6.

Table 6 System component classification

Component classification	*Description*
Structural components	Static parts
Operating components	Processing parts
Flow components	Parts being altered

The interaction between system components can be linear or complex. Linear systems are easily identified because they have a clear segregation and separation of phases and any connections between sequences are few and normally sequential. In contrast, complex systems have little segregation and separation and phases are integrated and highly dependent upon one another. Table 7 reviews the characteristics of linear and complex systems.

Table 7 Linear and complex systems characteristics

Complex systems	*Linear systems*
Tight spacing of equipment	Equipment spread out
Proximate production steps	Segregated production steps
Many common-mode connections of components not in the production sequence	Common-mode connections limited to power supply and the environment
Limited isolation of failed components	Easy isolation of failed components
Personnel specialisation limits awareness of interdependencies	Less personnel specialisation
Limited substitution of supplies and materials	Extensive substitution of supplies and materials
Unfamiliar or unintended feedback loops	Few unfamiliar or unintended feedback loops
Many control parameters with potential interactions	Control parameters are few, direct, and segregated
Indirect or inferential information sources	Direct, online information sources
Limited understanding of some processes (typically transformation processes)	Extensive understanding of all processes (typically fabrication or assembly processes)

Source: Perrow (1999, p.88)

Systems display two basic types of interactions; linear interactions and complex interactions.

> “Linear interactions overwhelmingly predominate in all systems. But even the most linear of systems will have at least one source of complex interactions, the environment, since it impinges upon many parts or units in the system. Complex interactions suggest that there are branching paths, feedback loops, [that] jump from one linear sequence to another because of proximity or certain other features ...” [Perrow, (1999), p.75]

Table 8 reviews the characteristics associated with linear and complex interactions.

Table 8 Component interaction classification

Interaction	*Description*
Linear interaction	• Interactions of one component with one or more components that precede or follow it immediately in the sequence of production. • Expected and familiar in the production or maintenance sequence and if unplanned, they are quite visible. • Occur within well-defined and segregated segments of the production or maintenance sequence.
Complex interaction	• One component can interact with one or more other components outside of the normal production sequence. • Occur in unfamiliar sequences, or unplanned and unexpected sequences, and are either not visible or not immediately comprehensible. • Occur in systems with a fair degree of complex interactions, however, well-defined and segregated segments do not necessarily exist.

The final characteristic of component interactions is coupling. Coupling refers to the ability of components in a system to interact. Tight coupling occurs when there is no slack or buffer between components and loose coupling occurs when a buffer exists between components. Table 9 reviews the characteristics of tight and loose coupling.

Table 9 Coupling characteristics

	Tight coupling	*Loose coupling*
Processing delay	• Not possible	• Possible
Sequencing	• Invariants	• Can be changed
Methods to achieve goals	• Only one method	• Alternative methods available
Resources	• Little slack possible	• Slack possible
Buffers	• Designed-in, deliberate	• Fortuitously available
Recovery aids	• They take the form of engineered safety devices (ESD) and engineered safety features (ESF)	• Normally limited to human intervention or legally mandated features (contained in legal codes)

Source: Adapted from Perrow (1999)

Component interaction and coupling are variables that are independent of one another and as such, can greatly affect system reliability and safety. These are important characteristics in system analysis.

3.3 System objectives

The conduct of engineering analysis for a SoS includes an examination of the SoS objectives. This is not a simple task and requires us to understand how we define a SoS.

3.3.1 Definition of a SoS

Maier (1999, p.267) notes that, "While the term system-of-systems has no widely accepted definition, the notion is widespread and generally recognized." A SoS is a new type of system. It is the super-system, the meta-system, the SoS which is made up of components which are large-scale complex systems themselves. We propose the following definition for a SoS:

> "A meta-system comprised of multiple autonomous embedded complex systems that can be diverse in technology, context, operations, geography, and conceptual frame."

If we are to understand SoS we must be able to differentiate them from the more common monolithic complex systems. Five distinguishing characteristics have been proposed by Maier (1999, p. 271) and Sage and Cuppan (2001, p.326) that include:

1. *Operational independence of the individual systems:* A SoS is composed of systems that are independent and useful in their own right. If a SoS is disassembled into the component systems, these component systems are capable of independently performing useful operations independently of one another.
2. *Managerial independence of the systems:* The component systems not only can operate independently, they generally do operate independently to achieve an intended purpose. The component systems are generally individually acquired and integrated, and they maintain a continuing operational existence that is independent of the SoS.
3. *Geographic distribution:* Geographic dispersion of component systems is often large. Often, these systems can readily exchange only information and knowledge with one-another and not substantial quantities of physical mass or energy.
4. *Emergent behaviour:* The SoS performs functions and carries out purposes that do not reside in any component system. These behaviours are emergent properties of the entire SoS and not the behaviour of any component system. The principal purposes supporting engineering of these systems are fulfilled by these emergent behaviours.
5. *Evolutionary development:* A SoS is never fully formed or complete. Development of these systems is evolutionary over time and with structure, function and purpose added, removed, and modified as experience with the system grows and evolves over time.

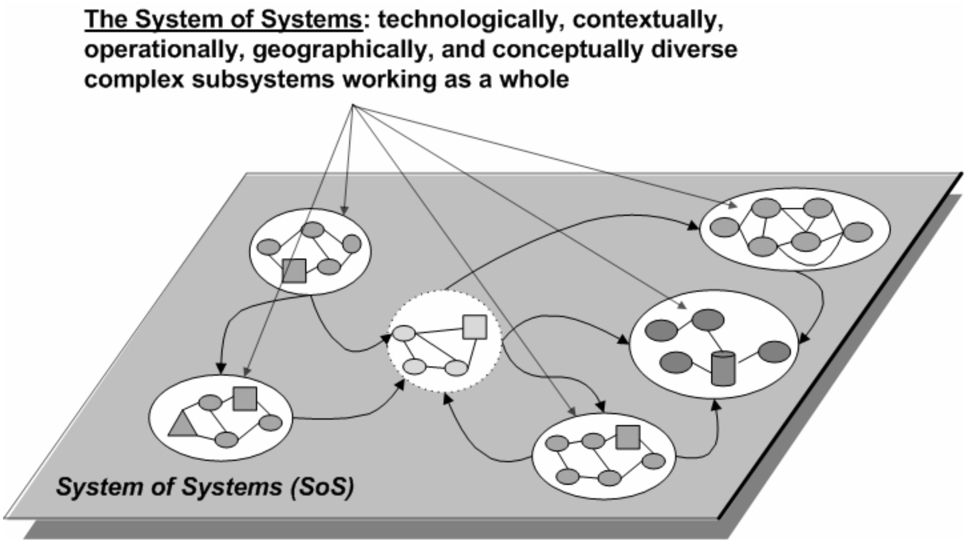
These five distinguishing characteristics begin to place some degree of formality on the notion of SoS, but something is missing. In order to go beyond the traditional perspective of a fully integrated SoS which perfectly shares data in what we call hard interoperability, we must invoke a more systemic view. The ideal state for a SoS requires what we will *call systemic interoperability*. Systemic interoperability is a holistic view of interoperability and requires compatibility in worldview and conceptual, contextual, and cultural interoperability, allowing the SoS to act consistently with regard to purpose, function, and form. A revision to the five characteristics proposed by Maier (1999) and Sage and Cuppan (2001) is important in achieving a more thorough understanding of the nature of a SoS and is presented in Table 10.

Table 10 SoS characteristics

Characteristic	*Description*
Technologically diverse	• SoS subsystems may contain a vast diversity of component types. • Component types include a wide variety of technologies; from the proven to the emerging.
Contextual diversity	• SoS subsystems have been designed to operate independently. A natural tension between connectedness in the SoS and autonomy at the subsystem is inherent. • The context within which each of the SoS subsystems operates may include additional levels of connectedness beyond the SoS of interest. • The purpose, goals, and objectives of the SoS subsystems may be at odds or in conflict with the larger SoS to which they belong.
Operational diversity	• SoS subsystems have been independently designed, acquired, tested and are independently operated, managed, and funded.
Geographic diversity	• SoS subsystems may be located across the planet and in space. This separation effectively limits their exchange between one another to include only information and knowledge.
Conceptual frame diversity	• SoS subsystems each has their own conceptual frame within which they were designed, acquired, and are operated.

Figure 4 is a depiction of a SoS with multiple, complex subsystems.

Figure 4 Representation of a SoS



3.3.2 Definition of purpose for a SoS

Churchman and Ackoff (1950) noted a number of similarities in purpose-built objects (i.e., man-made systems). Three of these similarities are important to our study of SoS.

1. *Presence of choice:* "The basis of the concept of purpose is the awareness of *voluntary activity*" [Rosenblueth et al., (1943), p.19]. Choice is essential to identify purpose.
2. *Inclusion of time*: "Purposive behavior can only be studied relative to a period of time" [Churchman and Ackoff, (1950), p.35].
3. *Production requirement:* "The purposive object or behavior is at least a potential producer of some end-result (end, objective, goal)" [Churchman and Ackoff, (1950), p.35].

In summary, purposive behaviour, to which all man-made systems prescribe, requires the system to have choices, and to produce some end result over a period of time. In order to provide a complete view of the objectives of a SoS, an understanding of the SoS purpose is necessary. Comprehension of purpose provides the foundation for framing the objectives that result from the purpose.

3.4 System functions

"Structure is a very general concept that includes geometric, kinematic, mechanical, physical, and morphological concepts. Therefore, we treat these aspects of structure first, then derive the meaning of structure from them" [Ackoff and Emery, (2006), p.16]. Knowledge of these facets of structure is helpful in understanding the functions within a system. The structure of the system serves to connect the systems components and hold them together as a distinct unity.

Understanding the functions in a SoS is a more formidable task based on the size and complexity of the SoS and myriad of functions being accomplished within the subsystems and across the larger SoS.

3.5 System environment

The environment for a SoS can be described as "a set of elements and their relevant properties, which elements are not part of the system, but a change in any of which can cause or produce a change in the state of the system" [Ackoff and Emery, (2006), p.19].

In a SoS the environment consists of a wide variety of variables that can affect its state (i.e., the systems properties present at that point in time). An understanding of these variables is an important aspect of the SoSE analysis.

3.6 System resources

Each system has a number of resources dedicated to maintaining the systems stability and long-term viability. Because resources can directly affect system viability they must be well understood and subject to both monitoring and control. Because systems operate in the real world, where they are subjected to stress and disturbance, a level of redundancy must be managed in order to maintain stability in the system. Resources are frequently categorised as shown in Table 11.

Table 11 System resources

Resource category	*Explanation*
Money	Funds required for system design, operations, maintenance, and disposal.
Manpower	Human beings required to design, build, operate, and dispose of the system.
Material	Physical entities that constitute the system are inputs to the system, or outputs from the system.
Minutes (time)	Time from inception to disposal.
Methods	Techniques used to design, build, operate, maintain, and dispose of the system.
Information	Data required to design, operate, maintain, and dispose of the system.

3.7 Governance structure

Management of a system is a fairly well-defined field of endeavour. However, the practices established for management of subsystems are not easily extrapolated to a larger SoS. In fact, we believe that this inability to articulate methods and practices for *governing* a SoS is an *Achilles heel* for operational SoS.

A deeper look at the literature reveals that experts, theorists and practitioners alike all defer to *governance* of systems as an important concept when dealing with large complex systems in a variety of venues. There are studies addressing system *governance* in multiple fields, including the internet (Mathiason, 2009), economics (Ostrom, 2010), knowledge (Stehr, 2004), enterprise information systems (Marks, 2008), networks (Provan and Kenis, 2008), and critical infrastructures (Gheorghe et al., 2007). In some general sense, all these initiatives seem to universally accept the inherent goodness in the notion of a method by which large, complex systems may be satisfactorily *governed*. In many instances, there are several successful instantiations where indeed positive outcomes are realised because of the application of a method or technique for *governing* a large, complex system. The extent of each claim, regardless of the context, however, does not assure that there is a shared conceptualisation of system *governance* and an ability to *generalise* the concepts for broader application.

The National Centers for System of Systems Engineering, in Norfolk, Virginia has initiated a programme research stream to address the absence of a generalisable systems governance methodology (Keating et al., 2010).

4 Element 3: characterise the complex nature of the system under study

The goal of this element is to present the system under study as a complex systems problem by contrasting it against the characteristics of complex systems problems.

For the problem domain, the problem solver must consider 13 domain characteristics that are found in most complex systems problems. Recognising and formally addressing each of the 13 characteristics, as they present themselves in the problem under study, is an important element in understanding the complexity present and the need for a robust SoSE solution.

The sections that follow will present the 13 domain characteristics that are found in most complex systems problems.

4.1 Hyper-turbulent conditions

A complex system is said to exhibit hyper-turbulent conditions when the environment of the problem is highly dynamic, uncertain, and rapidly changing. This flux places traditional forms of thinking and problem solution framing in question. Stable methods for clearly bounding and solving problems are ineffective, relegated to the past. A new era of problems management emerges – requiring the trade of precision and metered approaches for agility and resiliency.

4.2 Ill-defined problems

A complex systems problem is ill-defined when circumstances and conditions surrounding the problem are potentially in dispute, not readily accessible, or lack sufficient consensus for initial problem formulation and bounding. There may be multiple and possibly divergent perspectives or worldviews, rapidly shifting and emergent conditions that render stable solution methods innocuous, and difficulty in framing the problem domain such that the *path forward* can be engaged with sufficient alignment of perspectives to remain viable. Rittel and Webber (1973, p.161) termed this a *wicked problem*, where:

> "The information needed to understand the problem depends upon one's idea for solving it. That is to say: in order to describe a wicked-problem in sufficient detail, one has to develop an exhaustive inventory of all conceivable solutions ahead of time. The reason is that every question asking for additional information depends upon the understanding of the problem – and its resolution – at that time. Problem understanding and problem resolution are concomitant to each other. Therefore, in order to anticipate all questions (in order to anticipate all information required for resolution ahead of time), knowledge of all conceivable solutions is required."

The immediate result of a *wicked problem* is a questionable ability of traditional approaches to be successful.

Similarly, Russell Ackoff [1919–2009] coined the concept of a mess and messes in 1979 when he stated:

> "Because messes are systems of problems, the sum of the optimal solutions to each component problem taken separately is not an optimal solution to the mess. The behavior of the mess depends more on how the solutions to its parts interact than on how they interact independently of each other." (p.100)

More recently, Sousa-Poza et al. (2009, p.8) reinforce this condition and state:

> "The range of alternatives for bounding and approaching SoSE problems is limitless. There is no correct 'recipe' or 'heuristic' that can provide a repeatable successful approach to doing SoSE. On the contrary, shifts in problem boundary conditions, contexts and interpretations dictate that each SoSE problem is unique and will have a range of possibilities for addressing the problem."

4.3 Contextual dominance

The technical or *hard* aspects of the problem are overshadowed by the contextual or soft aspects. The *soft* aspects are contextual and include those circumstances, factors, conditions, and patterns that influence the framing of the problem, solution development form, solution deployment, and interpretation of deployment results. The range of contextual elements cross a number of dimensions which include:

- technical and technology
- organisational and managerial
- human and social
- policy and political.

Context can play a more significant role than the technical aspects of system solution adequacy.

4.4 Uncertain approach

The path of progression on how best to proceed with the SoSE effort is indeterminate. Standard processes applied to the ill-defined problem inherent in this domain may have failed, be failing, or likely to fail to resolve the issues in the problem domain. Agreement on the nature of the problem (framing), and even if there is a problem, the approach, and expectations for successful resolution are potential sources of divergence.

4.5 Ambiguous expectations and objectives

The ability to establish explicit measures of success, system objectives, or requirements for the SoSE effort is questionable. This may be a result of inadequate understanding, hidden motives, or lack of technical competence to proceed with the effort. This is not likely to be remedied by *doing a better job*. The problem domain may be so confounding that clarity is not possible and attempts at *nailing down the problem* may be artificial at best. Instead, the problem landscape may simply be too complex and emergent to falsely assume that sufficient knowledge can be generated at the present point in time to adequately address the solution space.

4.6 Excessive complexity

Complexity is a situation that is highly dynamic, uncertain, emergent, and containing a high number of richly interconnected elements or factors. The bounds of the system of interest may be such that the complexities are beyond capabilities of traditional approaches to adequately address. To proceed using traditional approaches would require significant reduction, assumptions, and potential oversimplification of the problem domain – a recipe for failure to meet expectations for resolution of complex SoSE problems.

4.7 Pluralistic perspectives

The range of variability of individual perspectives, objectives, and perceived interests may be so divergent that sufficient alignment necessary to move forward may be unattainable. Many traditional approaches assume a *unitary* perspective where there is assumed agreement on the problem domain that alignment is also assumed. Complex SoSE problem domains may have deep rooted or philosophical divergence. Divergence may involve such issues as allocation of scarce resources, power distribution, control, personal preferences or interests, and other areas that may exist at a tacit level. Assuming alignment in complex SoSE problem domains may be problematic.

4.8 Extended stakeholders

Stakeholders are generally taken as customers, clients, suppliers, employees, team members, etc. In complex SoSE problem domains, there are two issues with this limited view of stakeholders. First, traditional lists of stakeholders are likely to be incomplete because stakeholders must be considered to be those individuals or entities that have an interest or a *perceived interest* in the problem resolution. This forces the casting of the stakeholder net much wider. Second, the range of stakeholders may likely emerge as the problem domain is further explored.

4.9 Emergence

The structure, patterns, and behaviours in the problem domain will only come to be known in the future – as time passes and our knowledge of the domain increases. This is not an indication of inappropriate methods of analysis or lack of expertise. On the contrary, in accordance with the principle of darkness (addressed in the article by Adams in this journal) with complex problem domains our knowledge will always be incomplete and fallible.

4.10 Ambiguous boundaries

The inclusion and exclusion boundary criteria are arbitrary and necessarily qualitative in nature. This implies they are ambiguous by nature. The nature of boundaries, and the organising boundary paradigms, can take many forms (e.g., geography, time, conceptual, functional, and physical). These forms may be explicit, but are as likely to exist at a tacit level. None of these organising paradigms are correct or incorrect, but they are certainly problematic, particularly if they are divergent. The complex SoSE problem domain boundaries are not static – they may, and probably should, change over time with increased understanding of the domain.

4.11 Unstable planning foundations

With fluctuations in the environment and uncertainty of resources, requirements and problem situations in SoSE problems are subject to sudden, and potentially radical, shifts. For instance, there may be continual shifts in scarce resources, policy, directives, initiatives, and scenarios that make addressing the situation difficult. This may make traditional forms of planning and execution inadequate for these problem domains. Rather than development of planned *optimal* solutions, the likelihood leans more toward *satisficing* (addressed in the article by Adams in this journal) solutions, capable of rapid reconfiguration based on unforeseen shifts.

4.12 Information saturation

Many complex SoSE problems are subject to a proliferation of data and information. Development of effective approaches to scan, filter, reduce, and process data/information into actionable forms are not yet sufficient. Problem solvers must wade through a morass of data and information seeking to identify the *bits* that are essential to drive decision and action. Understanding *saliency* (addressed in the article by Adams in this journal) is a major consideration.

4.13 Identity coherence

Identity is the set of fundamental values, patterns, and attributes that provides a consistent reference point and baseline logic for making grounded decisions, taking consistent actions, and providing self-reinforcing interpretation of abstract events. Modern technical enterprises are confronted with an accelerating pace, blurring of ethical value systems, and complexity. Incoherent or ambiguous identity deepens the inability to achieve consistency in the face of the *new realities* facing organisations working on complex SoSE problems.

Recognising and formal addressing each of these characteristics as they present themselves in the SoSE problem under study is an important element in understanding the complexity present and the need for a robust SoSE solution. This is an essential input for the next elements which will formally characterise the system domain.

5 Element 4: present the system domain as characteristically complex

The goal of this element is to present the system under study as a complex SoSE problem by contrasting it against eight generic complex systems characteristics that apply to SoS. The generic complex SoSE characteristics are as follows.

5.1 Large number of systems elements

The size of a system is best represented by the number of possible states, which is a function of the number of variables present. Ashby (1957, p.61) states:

> "... a system's 'largeness' must refer to the number of 'distinctions' made: either to the number of states available or, if its states are defined by a vector, to the number of components in the vector (i.e. to the number of its variables or of its degrees of freedom). The two measures are correlated, for if other things are equal, the additions of extra variables will make possible extra states."

The systems' elements or objects are:

> "... simply the parts or components of a system, and these parts are unlimited in variety." [Hall and Fagen, (1956), p.18]

Each of the system' parts have attributes, which are properties. The properties of the parts of the system have a direct affect on the number of *distinctions* or *states* that the system may exhibit.

5.2 Interaction between systems elements

The interactions between system parts is referred to as *relationships*. It is the specific relationship between the parts that governs the properties of the system. In many cases, the system is more than a sum of the properties of its elements, and has new or *emergent* properties (note that emergence is more fully addressed in the article by Adams in this journal).

> "... emergence simply means that the parts of a complex system have mutual relations that do not exist for the parts in isolation." [Simon, (1996), p.170]

Simon (1996, pp.183–184) makes a further distinction:

> "... by a complex system I mean one made up of a large number of parts that have many interactions."

5.3 Pre-determined attributes

The vast majority of attributes in a SoS are predetermined. This is because a SoS is constructed of independent, purposefully designed, acquired, and managed subsystems with unique goals and objectives. The subsystems have discrete parts with unique attributes or properties. The number of unique attributes present in the subsystems has a direct affect on the number of distinct states that the subsystems and larger SoS may exhibit.

5.4 System evolution over time

Systems may or may not change over time. A *static system* is one in which no change occurs. The static system is a single state system in which no system properties change over time (i.e., no events occur). A *dynamic system* is one which has multiple states in which one or more system properties change over time (i.e., an *event* occurs). Finally, there is the *homeostatic system*. "A *homeostatic system* is a static system whose elements and environment are dynamic. Thus, a homeostatic system is one that retains its state in a changing environment by internal adjustments" [Ackoff, (1971), p.664].

5.5 Subsystems pursue own goals

Section 3.3 provided a systemic definition for a *SoS* that extended the traditional perspective of a fully integrated SoS. Five distinguishing characteristics were presented in Table 10 in order to achieve a more thorough understanding of the nature of a SoS. A key characteristic of a modern SoS is that its subsystems have been designed to operate independently. Independent operation means that each subsystem has a purposive object or behaviour and is a producer of some end-result, objective, or goal (Churchman and Ackoff, 1950). A natural tension between the connectedness required for operation within the SoS and autonomy required to meet the goals and objectives of its own operations will exist.

The *principle of suboptimisation* (Hitch, 1953) states that if each subsystem, regarded separately, is made to operate with maximum efficiency, the system as a whole will not operate with utmost efficiency (Hitch, 1953). When dealing with a SoS, this principle must be accounted for. Optimising each subsystem in the larger SoS independently will not in general lead to a system optimum, or more strongly, improvement of a particular subsystem may actually worsen the overall SoS in what is called suboptimisation. (Note that *suboptimisation* is more fully addressed in the article by Adams in this journal.)

5.6 Predominately open to environment

We have defined the environment as "a set of elements and their relevant properties, which elements are not part of the system, but a change in any of which can cause or produce a change in the state of the system" [Ackoff and Emery, (2006), p.19]. SoS are predominantly open to their environments. This is an important point because it permits the conceptualisation of the SoS problem in a hierarchical manner.

> "The elements that form the environment of a system and the environment itself may be conceptualized as systems when they become the focus of attention. Every system can be conceptualized as part of another larger system." [Ackoff, (1971), p.663]

5.7 Interaction organisation

Because most SoS are part of another larger systems, and themselves contain subsystems, the concept of systems hierarchy is an important concept (note that *hierarchy* is more fully addressed in the article by Adams in this journal). The hierarchic structure in a SoS can be defined by the following:

> "By a 'hierarchic system', or hierarchy, I mean a system that is composed of interrelated subsystems, each of the latter being in turn hierarchic in structure until we reach some lowest level of elementary subsystem." [Simon, (1996), p.184]

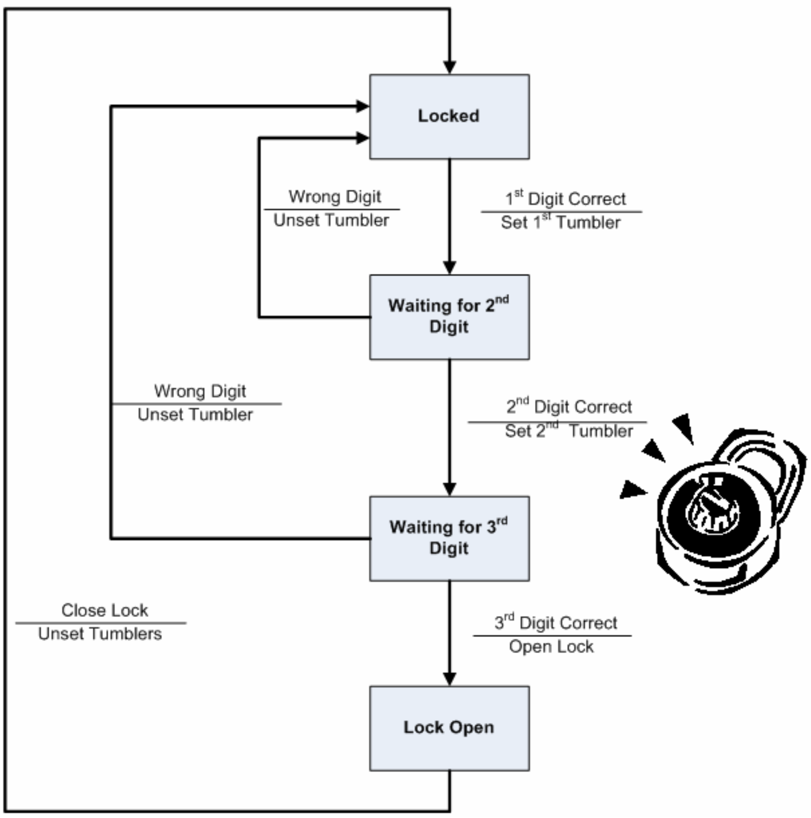
The hierarchical nature of SoS has far reaching effects which include the high-frequency dynamics involving the internal structure of the components and the low-frequency dynamics involving the interaction among components (Simon, 1996).

5.8 System affected by behavioural influences

A SoS is routinely affected by behavioural influences from the systems environment. Because SoS are predominantly open to the environment, environmental disturbances impact the states of the SoS. The state of the SoS is said to change when one or more system properties change over time, in what we term an event.

The time-dependent behaviour of a system may be modelled in a state transition diagram (STD). The STD accounts for the impact of external events that cause a change in the systems internal properties or state. Figure 5 is an STD for a standard combination lock (Hatley and Pirbhai, 1988). The rectangular boxes represent unique system states. The arrows that connect the boxes show the state change and contain both the *condition* required to cause the change of state, and the *actions* that the system takes when the condition changes.

Figure 5 STD for a rotary combination lock (see online version for colours)



6 Element 5: frame the SoSE problem

The goal of this element is to depict the problem situation by expressing the structure, elements of process and the situation climate in a single diagram. When framing a complex system problem, the problem solver must consider the following:

1 All complex systems are arbitrary and only come about through their representations.

2 A complex systems problem solution cannot develop independent of the complex system that produced the solution.

3 Complex systems are neither bad nor good – in accordance with the *law of consequent production* (addressed in the article by Adams in this journal) they can only produce what they produce. Although the behaviour or performance might not be desirable, the producing system will continue to produce the behaviour and performance unless the system is changed.

4 Complex systems problems cannot be understood independent of the context within which they exist.

5 A single model of a complex systems problem is not capable of totally capturing the system. The *law of complementarity* (addressed in the article by Adams in this journal) states that multiple models (framings) are necessary.

6 The essence of an effective complex systems solution is simplicity, which comes about through iterative understanding and analysis.

7 When using multiple possible approaches – compatibility is the key feature.

8 System solution failure is a desirable and inevitable condition – the earlier, faster, more frequent, and deeper the failure modes, the better and more sustainable the solution.

The preferred methodology for framing an unstructured complex systems problem is Checkland's *rich picture*, an element of his soft systems methodology (Checkland, 1993; Checkland and Scholes, 1999). Checkland's *rich pictures* allow the analyst to develop a fully articulated contextual map of a complex systems problem. Jackson (2000, p.253) comments on rich pictures stating:

> "A good way of doing the expression stage was to take the notion of rich pictures literally, and to draw pictorial, cartoon-like representations of the problem situation which highlight significant and contentious aspects in a manner likely to lead the original thinker ... rich pictures aid creativity, allowing the easy sharing of ideas ..."

The construction of rich pictures reveals questions and observations about the problem situation. The value of rich pictures becomes particularly clear when they are shared with others, identifying different perspectives, assumptions, and boundaries in the problem domain. The simplified method for representation present in the rich picture permit the analyst and stakeholders to see connections, barriers, bottlenecks, resource constraints, possibilities and contradictions that more structured methods often overlook. Rich pictures serve as a vehicle to improve systemic thinking.

7 Element 6: define problem statement and objectives

The goal of this element is to clearly explain the nature of the SoSE effort (explore, investigate, describe, address), the purpose of the effort (in order to ...), the high-level approach (method, technique) and, the objectives that will create the desired outputs and outcomes.

7.1 Nature of the SoSE effort

The goal of this element is to clearly explain the nature of the effort (explore, investigate, describe, address) the purpose of the effort (in order to ...) the high-level approach (method, technique) and the objectives that will support the desired outputs and outcomes.

The nature of the SoSE effort is the principle guiding element to be answered during the SoSE analysis. It takes the form of a question which supports the analysis objective, purpose and the problem. The question is generated from the analysis objective and "... is a statement of the question being examined in its most general form" [Creswell, (2003), p.105].

7.2 Objectives tree

The principal element that converts the goals for the SoSE effort into actionable tasks is the objectives tree. The tree is established to identify objectives that analysis needs to achieve in order to satisfactorily answer the higher-level analysis question. Each objective in the tree provides a specific areas to be explored in support of the primary analysis question. As such, the objectives guide the exploration of the SoSE problem. As part of the objective development, weightings are established for each distinct objective. This serves to establish a relative ranking of importance for each of the objectives.

8 Element 7: conduct stakeholder analysis

The goal of this element is to explicitly account for and address the multiple interests (rational and irrational, inside and outside) which can impact achievement of the SoSE analysis objectives. Stakeholder analysis is important in order to address individuals or entities potentially affected; understand influences, interests, and priorities in play during the SoSE analysis effort; fill knowledge gaps in understanding; appreciate relationships in play among different stakeholders (coalitions); shape the SoSE analysis options and approach; and enlist support – deflect derailment. One must also consider managing stakeholders because most likely one may leave some stakeholders out (hopefully they are not critical); get some of the stakeholder perspectives wrong; fail to recognise some stakeholder shifts in perspective; not adequately engage some stakeholders; have to rely on assumptions and intuition too heavily, and find out they were wrong; and inadequately verify/validate some conclusions. There are three steps in stakeholder analysis.

8.1 Identification and classification of stakeholders

Identification and classification answers the questions – who are they and how do we classify them? Table 12 describes the three primary stakeholder types.

Table 12 Stakeholder types

Stakeholder type	*Explanation*
Primary	Have direct authority, accountability, influence, or responsibilities for decisions, actions and execution of the system-of-interest.
Secondary	Have indirect involvement in the decisions, actions, and execution of the system-of-interest but have interests in the initiative as a perceived benefit or detriment to their interests. They can impact achievement of the objectives.
Tertiary	Have an indirect interest in the system-of-interest and are not directly impacted by the initiative. They could interject to threaten achievement of the objectives.

Another aspect to consider in the classification of stakeholders is influence and importance. Stakeholders who have influence have the power to control relevant decisions as well as have influence to the extent to persuade or coerce others into making decisions and taking certain actions. Sources of stakeholder power include legitimate, expert, reward, referent, and coercion. Importance describes those stakeholders whose problems, needs and interests are a priority for the effort. Deeper classifications of stakeholders include dormant, discretionary, demanding, dominant, dangerous, dependent, definitive, and non-stakeholders. Understanding and classifying stakeholders is essential to increase the probability of success for a SoSE effort.

8.2 Stakeholder interests and impact

Stakeholder interests answers the questions – what are their interests and what impact can they have? Knowing the particulars surrounding why a stakeholder is interested in the SoSE analysis can provide valuable insight about the SoS, its environment, and impact on others.

Knowledge about the potential impact of either positive or negative stakeholder support can help develop strategies for advancing or mitigating stakeholder impact during development of the stakeholder response plan.

8.3 Stakeholder response

Stakeholder response answers the question – how can we best deal with them? In developing a strategy for stakeholder response, one must develop a plan that formally deals with the concerns of each of the stakeholders. The strategy must mitigate negative issues and support positive ones. Four primary strategies for dealing with stakeholders include:

1 involve – leverage key relationships/network – possibly engage in active champion role
2 collaborate – enter strategic alliances or partnerships – can educate
3 defend – move towards reducing dependency
4 monitor – gather information and observe.

The primary outputs of the three steps in stakeholder analysis are

1 the external and internal stakeholder analysis matrices depicted in Table 13
2 the stakeholder influence and support grid in Figure 6.

Table 13 Stakeholder analysis matrix

Stakeholder identification	*Stakeholder 1*	*Stakeholder 2*	*Stakeholder n*
Type			
Influence (source of power)			
Interests			
Classification importance v. influence			
Coalitions (linkages)			
Confidence in analysis and support data			
Worldview			
Response strategy			

Figure 6 Stakeholder influence and support grid

	Stakeholder Involvement			
Stakeholder Influence	**Monitor**	**Defend**	**Collaborate**	**Committed**
Significant				
Mixed				
Limited				
None or Unknown				

9 Element 8: conduct contextual analysis

The goal of this element is to account for the set of circumstances, factors, conditions, values and/or patterns that are influential in constraining and enabling the SoSE analysis process, the system solution design, system solution deployment, and interpretation of outputs/outcomes for of the analysis.

Context is infinite. Context can never be fully understood, known, or managed. As a result, we must purposefully limit the context being evaluated in the study. The reduction of contextual complexity to a manageable set results in what is called the *relevant context*.

Context is often either tacit/explicit or formal/informal; but it must be accounted for when addressing complex systems problems. Every complex SoSE effort must consider three interacting elements

1 the hard or technical perspective

2 the soft or contextual perspective

3 the contextual analysis and response.

The simultaneous consideration of these elements ensures that the system study includes a holistic perspective.

9.1 Hard or technical perspective

The central theme for the hard system perspective is that *a real world exists external to the analyst*. In this perspective, factual, truthful and unambiguous data can be gathered, observed, collated, and objectively analysed. The system in focus is unaffected by either the analysis or the analyst. The results of analysis are highly replicable and the analysis can be conducted free of subjective value judgements. The hard system perspective requires the system in focus to be bounded where the analysis can be controlled – this is both possible and desirable.

The *hard system perspective* includes words and activities like objectivity, clear system definition, unitary, explicit, quantitative assessment, analysis of alternatives, and optimal.

9.2 Soft or contextual perspective

The central theme for the soft system perspective is that *the system in focus is affected by both the analysis as well as the analyst*. Reality is dynamic and constantly shifting. In the soft system perspective, data is subjective in collection and interpretation. Analysis strives for transparency and the results of analysis are evaluated in terms of credibility. Analysis is focused on building a compelling reconstruction of the problem. The analysis and interpretation of analysis is value-laden. Bounding of the system in focus is problematic, control of the analysis is questionable, and emergence is dominant.

The *soft system perspective* includes words and activities like interpretative, uncertainty in system, pluralistic and tacit, qualitative assessment, multiple models, and satisficing.

9.3 Contextual analysis and response

Contextual analysis and response requires the consideration of four elements.

1. Identification – What are the relevant aspects of context that are of concern that may influence the system solution, development process, or deployment?
2. Assessment – What are the potential impacts of the contextual aspects identified?
3. Response – What strategies, initiatives, or activities will be pursued in response to the assessment?
4. Monitoring – How will changes in context be identified, processed, and scanned?

Two formal analysis techniques are used when considering contextual analysis;

1. the force field diagram
2. the contextual analysis matrix.

9.3.1 Force field diagram

The force field diagram is derived from the work of social psychologist Kurt Lewin [1890–1947]. According to Lewin's theories (1938, 1939, 1943)[1], human behaviour is caused by forces – beliefs, expectations, cultural norms, and the like – within the life space of an individual or society. The forces are either driving movement toward a goal (driving forces) or blocking movement toward a goal (restraining forces). The force field technique is designed to portray these driving forces and restraining forces that affect a central question or problem as a vector. The vector has both magnitude and direction. The direction of the vector identifies the force as either driving or restraining, and the magnitude of the vector represents the relative strength of the force. Table 14 is a force field diagram.

Table 14 Force field diagram

Driving force (positive)	*Driving force vector*	*Restraining force vector*	*Restraining force (negative)*
Driving force 1	━━━━▶	◀━━━━	Restraining force 1
Driving force 2	━━━━▶	◀━	Restraining force 2
Driving force 3	━━━▶	◀━━━	Restraining force 3
Driving force 4	━▶	◀━	Restraining force 4

Notes: ━━━━▶ strong force
━━━▶ medium force
━▶ weak force

9.3.2 Contextual analysis matrix

The contextual analysis matrix is used to identify specific aspects of the problem context that must be considered in the analysis. Context is taken as the circumstances, factors, conditions, and patterns that influence the design, analysis, maintenance, or transformation of complex system problem domains (Keating et al., 2003). For example, context might include a cultural impediment to implementing an engineering design solution. Failure to account for contextual considerations may result in a failure to effectively implement a sound technical solution because it is not compatible with the context within which it must be deployed.

In many cases, context represents the *soft* aspects of a complex system problem analysis. As such, it is not generally considered as an integral part of traditional systems engineering. However, for SoSE, context can be much more influential in developing a holistic system solution. These solutions must be appreciative of the enabling and constraining influence that contextual factors might have on technical solution analysis, design, plan for deployment, and effectiveness. In essence, technical solutions to SoSE problems are always incomplete if they do not take into consideration the influences stemming from the context. Appropriate consideration of context opens the inquiry to include organisational, managerial, human, social, political, and policy considerations that must be part of the analysis.

Table 15 is a contextual analysis matrix that can be used to assist in the necessary thinking to account for contextual considerations.

Table 15 Contextual analysis matrix

Criteria	*Explanation*
Contextual factor, circumstances, conditions, patterns, values	Identifies the specific contextual area of consideration for the analysis team. The area is identified in sufficient detail to permit more rigorous analysis and consideration of impact on the effort.
Potential impacts that enable (E) or disable (D) system design	Each contextual area is assessed as either a potential Enabler (enhances the capability for successful design) or Disabler (impediment to successful design).
Potential Impacts that enable (E) or disable (D) system deployment	Each contextual area is assessed with respect to potential impacts (enabling or disabling) on the ability to deploy solutions or actions to address issues stemming from the analysis.
Criticality (1 to 5)	The degree to which the contextual area is deemed to be of an urgent nature to the effort.
Priority (1 to 5)	The numerical ranking of the degree of importance for the identified area.
Verification of element (supporting data source) and support data	The data sources that provide supporting detail for the area identified.
Response strategy: implications, activities, initiatives	The approaches that the team will pursue to appropriately deal with the identified area to either enhance or minimise the impact on the effort.

Failure to include context can derail the most prolific technical solution and relegate it to nothing more than a good engineering effort that will remain un-deployable, or ineffectively deployable, at best. The contextual analysis matrix depicted in Table 15 was developed by the National Centers for System of Systems Engineering (NCSoSE) as a guide to more effectively consider and account for the influence that context might have on the effort.

The thrust of the contextual analysis matrix is to identify and assess the potential impact, and to identify an appropriate response by the team. The matrix serves a vital and often short changed role in managing context in a complex systems problem in SoSE analysis.

10 Element 9: perspective completion exercise

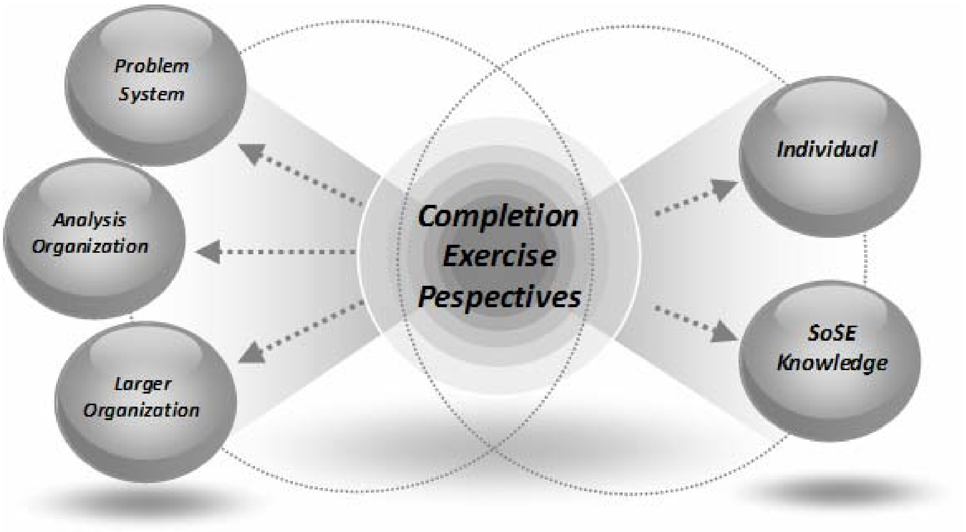
The objective of the completion exercise is to understand the implications of the outputs created in Perspective 1 of the SoSE methodology (Adams and Keating, 2009) and the implications that they have in the areas depicted in Figure 7.

1. implications for the problem system undergoing SoSE analysis
2. implications for the organisation conducting the SoSE analysis
3. implications for the larger organisational enterprise conducting the SoSE analysis

4 implications for the wider SoSE discipline

5 implications for the individuals conducting the SoSE analysis.

Figure 7 Influence of SoSE analysis



11 Conclusions

The paper has shown the first perspective, Framing the system under study, in the SoSE methodology (Adams amd Keating, 2009). The purpose of the perspective has been to rigorously frame the SoS problem, the contextual setting and the environment within which the problem system exists. The perspective is supported by nine execution elements which operationalise the steps in the SoSE methodology.

The nine execution elements in the perspective contain the details necessary to expose the SoSE problem and its related context. The perspective relies on the core of the methodology, which resides in the underlying foundation system principles. This establishes the systemic worldview that permits execution and interpretation of everything else that follows in the SoSE analysis. It is also important to note that the elements in the perspective are not intended to be approached as a linear stepwise set of elements to be accomplished independent or mutually exclusive of one another. On the contrary, there should be continual reframing and revisiting of the nine elements and their outputs as the SoSE analysis progresses.

It would be naïve to think that this perspective will have effective results if it is applied by those without sufficient grounding in the system fundamentals and/or approached as a prescriptive sequential set of steps that, if performed in a rote fashion, will generate successful SoSE outcomes. Only through appreciation of these limitations and considerations will the perspective be capable of deployment as it has been intended.

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Notes

1 A more contemporary treatment of Field Theory is presented in Martin (2003) and Ivancevic and Aidman (2007).