Complexity

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This article is part of the Systems Science knowledge area (KA). It gives the background of and an indication of current thinking on complexity and how it influences systems engineering (SE) practice.

Complexity is one of the most important and difficult to define system concepts. Is a system's complexity in the eye of the beholder, or is there inherent complexity in how systems are organized? Is there a single definitive definition of complexity and, if so, how can it be assessed and measured? This topic will discuss how these ideas relate to the general definitions of a system given in What is a System?, and in particular to the different engineered system contexts. This article is closely related to the emergence topic that follows it.

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Defining System Complexity

Complexity has been considered by a number of authors from various perspectives; some of the discussions of complexity relevant to systems are described in the final section of this article. Sheard and Mostashari (Sheard and Mostashari 2011) synthesize many of these ideas to categorize complexity as follows:

1. **Structural Complexity** looks at the system elements and relationships. In particular, structural complexity looks at how many different ways system elements can be combined. Thus, it is related to the potential for the system to adapt to external needs.
2. **Dynamic Complexity** considers the complexity which can be observed when systems are used to perform particular tasks in an environment. There is a time element to dynamic complexity. The ways in which systems interact in the short term is directly related to system behavior; the longer-term effects of using systems in an environment is related to system evolution.
3. **Socio-Political Complexity** considers the effect of individuals or groups of people on complexity. People-related complexity has two aspects. One is related to the perception of a situation as complex or not complex, due to multiple stakeholder viewpoints within a system context and social or cultural biases which add to the wider influences on a system context. The other involves either the “irrational” behavior of an individual or the swarm behavior of many people behaving individually in ways that make sense; however, the emergent behavior is unpredicted and perhaps counterproductive. This latter type is based on the interactions of the people according to their various interrelationships and is often graphed using systems dynamics formalisms.

Thus, complexity is a measure of how difficult it is to understand how a system will behave or to predict the consequences of changing it. It occurs when there is no simple relationship between what an individual element does and what the system as a whole will do, and when the system includes some element of adaptation or problem solving to achieve its goals in different situations. It can be affected by objective attributes of a system such as by the number, types of and diversity of system elements and relationships, or by the subjective perceptions of system observers due to their experience, knowledge, training, or other sociopolitical considerations.

This view of complex systems provides insight into the kind of system for which systems thinking and a systems approach is essential.

Complexity and Engineered Systems

The different perspectives on complexity are not independent when considered across a systems context. The structural complexity of a system-of-interest (SoI) may be related to dynamic complexity when the SoI also functions as part of a wider system in different problem scenarios. People are involved in most system contexts, as part of the problem situation, as system elements and part of the operating environment. The human activity systems which we create to identify, design, build and support an engineered system and the wider social and business systems in which they sit are also likely to be complex and affect the complexity of the systems they produce and use.

Sheard and Mostashari (2011) show the ways different views of complexity map onto product system, service system and enterprise system contexts, as well as to associated development and sustainment systems and project organizations. Ordered systems occur as system components and are the subject of traditional engineering. It is important to understand the behaviors of such systems when using them in a complex system. One might also need to consider both truly random or chaotic natural or social systems as part of the context of an engineered system. The main focus for systems approaches is **organized complexity** (see below). This kind of complexity cannot be dealt with by traditional analysis techniques, nor can it be totally removed by the way we design or use solutions. A systems approach must be able to recognize and deal with such complexity across the life of the systems with which it interacts.

Sillitto (2014) considers the link between the types of system complexity and system architecture. The ability to understand, manage and respond to both objective and subjective complexity in the problem situation, the systems we develop or the systems we use to develop and sustain them is a key component of the Systems Approach Applied to Engineered Systems and hence to the practice of systems engineering.

Origins and Characteristics of Complexity

This section describes some of the prevailing ideas on complexity. Various authors have used different language to express these ideas. While a number of common threads can be seen, some of the ideas take different viewpoints and may be contradictory in nature.

One of the most widely used definitions of complexity is the degree of difficulty in predicting the properties of a system if the properties of the system's parts are given (generally attributed to Weaver). This, in turn, is related to the number of elements and connections between them. Weaver (Weaver 1948) relates complexity to types of elements and how they interact. He describes simplicity as problems with a finite number of variables and interaction, and identifies two kinds of complexity:

1. **Disorganized Complexity** is found in a system with many loosely coupled, disorganized and equal elements, which possesses certain average properties such as temperature or pressure. Such a system can be described by “19th Century” statistical analysis techniques.
2. **Organized Complexity** can be found in a system with many strongly coupled, organized and different elements which possess certain emergent properties and phenomena such as those exhibited by economic, political or social systems. Such a system cannot be described well by traditional analysis techniques.

Weaver's ideas about this new kind of complex problem are some of the foundational ideas of systems thinking. (See also Systems Thinking.)

Later authors, such as Flood and Carson (1993) and Lawson (2010), expand organized complexity to systems which have been organized into a structure intended to be understood and thus amenable to engineering and life cycle management (Braha et al. 2006). They also suggest that disorganized complexity could result from a heterogeneous complex system evolving without explicit architectural control during its life (complexity creep). This is a different use of the terms “organized” and “disorganized” to that used by Weaver. Care should be taken in mixing these ideas

Complexity should not be confused with "complicated". Many authors make a distinction between ordered and disordered collections of elements.

Ordered systems have fixed relationships between elements and are not adaptable. Page (2009) cites a watch as an example of something which can be considered an ordered system. Such a system is complicated, with many elements working together. Its components are based on similar technologies, with clear mapping between form and function. If the operating environment changes beyond prescribed limits, or one key component is removed, the watch will cease to perform its function.

In common usage, chaos is a state of disorder or unpredictability characterized by elements which are not interconnected and behave randomly with no adaptation or control. Chaos Theory (Kellert 1993) is applied to certain dynamic systems (e.g., the weather) which, although they have structure and relationships, exhibit unpredictable behavior. These systems may include aspects of randomness but can be described using deterministic models from which their behavior can be described given a set of initial conditions. However, their structure is such that (un-measurably) small perturbations in inputs or environmental conditions may result in unpredictable changes in behavior. Such systems are referred to as deterministically chaotic or, simply, chaotic systems. Simulations of chaotic systems can be created and, with increases in computing power, reasonable predictions of behavior are possible at least some of the time.

On a spectrum of order to complete disorder, complexity is somewhere in the middle, with more flexibility and change than complete order and more stability than complete disorder (Sheard and Mostashari 2009).

Complex systems may evolve “to the edge of chaos,” resulting in systems which can appear deterministic but which exhibit counter intuitive behavior compared to that of more ordered systems. The statistics of chance events in a complex system are often characterized by a power-law distribution, the “signature of complexity” (Sheard 2005). The power-law distribution is found in a very wide variety of natural and man-made phenomena, and it means that the probability of a low probability—large impact event is much higher than a Gaussian distribution would suggest. Such a system may react in a non-linear way to exhibit abrupt phase changes. These phase changes can be either reversible or irreversible. This has a major impact on engineered systems in terms of the occurrence, impact and public acceptance of risk and failure.

Objective complexity is an attribute of complex systems and is a measure of where a system sits on this spectrum. It is defined as the extent to which future states of the system cannot be predicted with certainty and precision, regardless of our knowledge of current state and history. Subjective complexity is a measure of how easy it is for an observer to understand a system or predict what it will do next. As such, it is a function of the perspective and comprehension of each individual. It is important to be prepared to mitigate subjective complexity with consistent, clear communication and strong stakeholder engagement (Sillitto 2009).

The literature has evolved to a fairly consistent definition of the characteristics of system elements and relationships for objective systems complexity. The following summary is given by Page (2009):

1. **Independence**: Autonomous system elements which are able to make their own decisions, influenced by information from other elements and the adaptability algorithms the autonomous elements carry with themselves (Sheard and Mostashari 2009).
2. **Interconnectedness**: System elements connect via a physical connection, shared data or simply a visual awareness of where the other elements are and what they are doing, as in the case of the flock of geese or the squadron of aircraft.
3. **Diversity**: System elements which are either technologically or functionally different in some way. For example, elements may be carrying different adaptability algorithms.
4. **Adaptability**: Self-organizing system elements which can do what they want to do to support themselves or the entire system in response to their environment (Sheard and Mostashari 2009). Adaptability is often achieved by human elements but can be achieved with software. Pollock and Hodgson (2004) describe how this can be done in a variety of complex system types, including power grids and enterprise systems.

Due to the variability of human behavior as part of a system and the perceptions of people outside the system, the inclusion of people in a system is often a factor in their complexity. People may be viewed as observing systems or as system elements which contribute to the other types of complexity (Axelrod and Cohen 1999). The rational or irrational behavior of individuals in particular situations is a vital factor in respect to complexity (Kline 1995). Some of this complexity can be reduced through education, training and familiarity with a system. Some is irreducible and must be managed as part of a problem or solution. Checkland (1999) argues that a group of stakeholders will have its own world views which lead them to form different, but equally valid, understandings of a system context. These differences cannot be explained away or analyzed out, and must be understood and considered in the formulation of problems and the creation of potential solutions.

Warfield (2006) developed a powerful methodology for addressing complex issues, particularly in the socio-economic field, based on a relevant group of people developing an understanding of the issue in the form of a set of interacting problems - what he called the “problematique”. The complexity is then characterized via several measures, such as the number of significant problems, their interactions and the degree of consensus about the nature of the problems. What becomes clear is that how, why, where and by whom a system is used may all contribute to its perceived complexity.

Sheard and Mostashari (2011) sort the attributes of complexity into causes and effects. Attributes that cause complexity include being non-linear; emergent; chaotic; adaptive; tightly coupled; self-organized; decentralized; open; political (as opposed to scientific); and multi-scale; as well as having many pieces. The effects of those attributes which make a system be perceived as complex include being uncertain; difficult to understand; unpredictable; uncontrollable; unstable; unrepairable; unmaintainable and costly; having unclear cause and effect; and taking too long to build.

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