Concepts of Systems Thinking

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This article forms part of the Systems Thinking knowledge area (KA). It describes systems concepts, knowledge that can be used to understand problems and solutions to support systems thinking.

The concepts below have been synthesized from a number of sources, which are themselves summaries of concepts from other authors. Ackoff (1971) proposed a system of system concepts as part of general system theory (GST); Skyttner (2001) describes the main GST concepts from a number of systems science authors; Flood and Carlson (1993) give a description of concepts as an overview of systems thinking; Hitchins (2007) relates the concepts to systems engineering practice; and Lawson (2010) describes a system of system concepts where systems are categorized according to fundamental concepts, types, topologies, focus, complexity, and roles.

Contents

Wholeness and Interaction

A system is defined by a set of elements which exhibit sufficient cohesion, or "togetherness", to form a bounded whole (Hitchins 2007; Boardman and Sauser 2008).

According to Hitchins, interaction between elements is the "key" system concept (Hitchins 2009, 60). The focus on interactions and holism is a push-back against the perceived reductionist focus on parts and provides recognition that in complex systems, the interactions among parts is at least as important as the parts themselves.

An open system is defined by the interactions between system elements within a system boundary and by the interaction between system elements and other systems within an environment (see What is a System?). The remaining concepts below apply to open systems.

Regularity

Regularity is a uniformity or similarity that exists in multiple entities or at multiple times (Bertalanffy 1968). Regularities make science possible and engineering efficient and effective. Without regularities, we would be forced to consider every natural and artificial system problem and solution as unique. We would have no scientific laws, no categories or taxonomies, and each engineering effort would start from a clean slate.

Similarities and differences exist in any set or population. Every system problem or solution can be regarded as unique, but no problem/solution is in fact entirely unique. The nomothetic approach assumes regularities among entities and investigates what the regularities are. The idiographic approach assumes each entity is unique and investigates the unique qualities of entities, (Bertalanffy 1975).

A very large amount of regularity exists in both natural systems and engineered systems. Patterns of systems thinking capture and exploit that regularity.

State and Behavior

Any quality or property of a system element is called an attribute. The state of a system is a set of system attributes at a given time. A **system event** describes any change to theenvironment of a system, and hence its state:

- **Static** - A single state exists with no events.
- **Dynamic** - Multiple possible stable states exist.
- **Homeostatic** - System is static but its elements are dynamic. The system maintains its state by internal adjustments.

A stable state is one in which a system will remain until another event occurs.

State can be monitored using state variables, values of attributes which indicate the system state. The set of possible values of state variables over time is called the "'state space'". State variables are generally continuous, but can be modeled using a finite state model (or, "state machine").

Ackoff (Ackoff 1971) considers "change" to be how a system is affected by events, and system behavior as the effect a system has upon its environment. A system can

- **react** to a request by turning on a light,
- **respond** to darkness by deciding to turn on the light
- **act** to turn on the lights at a fixed time, randomly or with discernible reasoning.

A stable system is one which has one or more stable states within an environment for a range of possible events:

- **Deterministic** systems have a one-to-one mapping of state variables to state space, allowing future states to be predicted from past states.
- **Non-Deterministic** systems have a many-to-many mapping of state variables; future state cannot be reliably predicted.

The relationship between determinism and system complexity, including the idea of chaotic systems, is further discussed in the Complexity article.

Survival Behavior

Systems often behave in a manner that allows them to sustain themselves in one or more alternative

viable states. Many natural or social systems have this goal, either consciously or as a "self organizing" system, arising from the interaction between elements.

Entropy is the tendency of systems to move towards disorder or disorganization. In physics, entropy is used to describe how organized heat energy is "lost" into the random background energy of the surrounding environment (the 2nd Law of Thermodynamics). A similar effect can be seen in engineered systems. What happens to a building or garden left unused for any time? Entropy can be used as a metaphor for aging, skill fade, obsolescence, misuse, boredom, etc.

"Negentropy" describes the forces working in a system to hold off entropy. Homeostasis is the biological equivalent of this, describing behavior which maintains a "steady state" or "dynamic equilibrium". Examples in nature include human cells, which maintain the same function while replacing their physical content at regular intervals. Again, this can be used as a metaphor for the fight against entropy, e.g. training, discipline, maintenance, etc.

Hitchins (Hitchins 2007) describes the relationship between the viability of a system and the number of connections between its elements. Hitchins's concept of connected variety states that stability of a system increases with its connectivity (both internally and with its environment). (See variety.)

Goal Seeking Behavior

Some systems have reasons for existence beyond simple survival. Goal seeking is one of the defining characteristics of engineered systems:

- A **goal** is a specific outcome which a system can achieve in a specified time
- An **objective** is a longer term outcome which can be achieved through a series of goals.
- An **ideal** is an objective which cannot be achieved with any certainty, but for which progress towards the objective has value.

Systems may be single goal seeking (perform set tasks), multi-goal seeking (perform related tasks), or reflective (set goals to tackle objectives or ideas). There are two types of goal seeking systems:

- purposive systems have multiple goals with some shared outcome. Such a system can be used to provide pre-determined outcomes within an agreed time period. This system may have some freedom to choose how to achieve the goal. If it has memory it may develop processes describing the behaviors needed for defined goals. Most machines or software systems are purposive.

- purposeful systems are free to determine the goals needed to achieve an outcome. Such a system can be tasked to pursue objectives or ideals over a longer time through a series of goals. Humans and sufficiently complex machines are purposeful.

Control Behavior

Cybernetics, the science of control, defines two basic control mechanisms:

- **Negative feedback**, maintaining system state against a set objectives or levels.

- **Positive feedback**, forced growth or contraction to new levels.

One of the main concerns of cybernetics is the balance between stability and speed of response. A black-box system (glossary) view looks at the whole system. Control can only be achieved by carefully balancing inputs with outputs, which reduces speed of response. A white-box system (glossary) view considers the system elements and their relationships; control mechanisms can be imbedded into this structure to provide more responsive control and associated risks to stability.

Another useful control concept is that of a "meta-system", which sits over the system and is

responsible for controlling its functions, either as a black-box or white-box. In this case, behavior arises from the combination of system and meta-system.

Control behavior is a trade between

- **Specialization**, the focus of system behavior to exploit particular features of its environment, and
- flexibility, the ability of a system to adapt quickly to environmental change.

While some system elements may be optimized for either specialization, a temperature sensitive switch, flexibility, or an autonomous human controller, complex systems must strike a balance between the two for best results. This is an example of the concept of dualism, discussed in more detail in Principles of Systems Thinking.

Variety describes the number of different ways elements can be controlled, and is dependent on the different ways in which they can then be combined. The Law of Requisite Variety states that a control system must have at least as much variety as the system it is controlling (Ashby 1956).

Function

Ackoff defines function as outcomes which contribute to goals or objectives. To have a function, a system must be able to provide the outcome in two or more different ways. (This is called **equifinality**).

This view of function and behavior is common in systems science. In this paradigm, all system elements have behavior of some kind; however, to be capable of functioning in certain ways requires a certain richness of behaviors.

In most hard systems approaches, a set of functions are described from the problem statement, and then associated with one or more alternative element structures (Flood and Carson 1993). This process may be repeated until a system component (implementable combinations of function and structure) has been defined (Martin 1997). Here, function is defined as either a task or activity that must be performed to achieve a desired outcome or as a transformation of inputs to outputs. This transformation may be:

- **Synchronous**, a regular interaction with a closely related system, or
- **Asynchronous**, an irregular response to a demand from another system that often triggers a set response.

The behavior of the resulting system is then assessed as a combination of function and effectiveness. In this case behavior is seen as an external property of the system as a whole and is often described as analogous to human or organic behavior (Hitchins 2009).

Hierarchy, Emergence and Complexity

System behavior is related to combinations of element behaviors. Most systems exhibit **increasing variety**; i.e., they have behavior resulting from the combination of element behaviors. The term "synergy", or weak emergence, is used to describe the idea that the whole is greater than the sum of the parts. This is generally true; however, it is also possible to get **reducing variety**, in which the whole function is less than the sum of the parts, (Hitchins 2007).

Complexity frequently takes the form of hierarchies (glossary). Hierarchic systems have some common properties independent of their specific content, and they will evolve far more quickly than non-hierarchic systems of comparable size (Simon 1996). A natural system hierarchy is a consequence of wholeness, with strongly cohesive elements grouping together forming structures which reduce complexity and increase robustness (Simons 1962).

Encapsulation is the enclosing of one thing within another. It may also be described as the degree to which it is enclosed. System encapsulation encloses system elements and their interactions from the external environment, and usually involves a system boundary that hides the internal from the external; for example, the internal organs of the human body can be optimized to work effectively within tightly defined conditions because they are protected from extremes of environmental change.

Socio-technical systems form what are known as control hierarchies, with systems at a higher level having some ownership of control over those at lower levels. Hitchins (2009) describes how systems form "preferred patterns" which can be used to the enhanced stability of interacting systems hierarchies.

Looking across a hierarchy of systems generally reveals increasing complexity at the higher level, relating to both the structure of the system and how it is used. The term emergence describes behaviors emerging across a complex system hierarchy.

Effectiveness, Adaptation and Learning

Systems effectiveness is a measure of the system's ability to perform the functions necessary to achieve goals or objectives. Ackoff (Ackoff 1971) defines this as the product of the number of combinations of behavior to reach a function and the efficiency of each combination.

Hitchins (2007) describes effectiveness as a combination of **performance** (how well a function is done in ideal conditions), **availability** (how often the function is there when needed), and **survivability** (how likely is it that the system will be able to use the function fully).

System elements and their environment change in a positive, neutral or negative way in individual situations. An adaptive system is one that is able to change itself or its environment if its effectiveness is insufficient to achieve its current or future objectives. Ackoff (Ackoff 1971) defines four types of adaptation, changing the environment or the system in response to internal or external factors.

A system may also **learn**, improving its effectiveness over time, without any change in state or goal.

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