Systems Engineering Principles

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Every discipline has a set of underlying principles which fundamentally characterize it. Discipline knowledge and practice are either explicitly or implicitly derived from its principles. For example, one of the principles of physics is that the speed of light is constant. This specific principle has been validated countless times in practice and is broadly accepted as how the universe works. One common economic principle is that "Every choice has an opportunity cost". (University of Minnesota n.d.) Another is the principle of supply, which states that "The quantity of a good supplied rises as the market price rises and falls as the price falls". (Ehrbar 2007) Generally, disciplines do not have one authoritative complete set of principles. Different authors emphasize different aspects of a discipline in the principles they identify and explain. As fields mature, new principles emerge, and old principles may change. For example, Einstein's Theory of Relativity revealed that the principles underlying Newtonian physics were not absolutely true. Yet, they are still immensely valuable most of the time.

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Introduction

Systems engineering is a young discipline. The emergence of a set of systems engineering principles occurred over the past 30 years within the discipline. The development of these principles derives from many sources including heuristics Systems Engineering Heuristics (i.e., experience based), sociology, physical sciences, and mathematics. The INCOSE Systems Engineering Principles Action Team (SEPAT) reviewed various sources of systems principles and systems engineering principles identified in literature over this period. This article surveys this work and identifies a set of systems engineering principles based on this review.

Systems engineering principles are a form of guidance proposition which provide guidance in application of the systems engineering processes and a basis for the advancement of systems engineering. Systems engineering has many kinds of guidance propositions that can be classified by their sources, e.g. heuristics (derived from practical experience), conventions (derived from social agreements), values (derived from cultural perspectives), and models (based on theoretical mechanisms). Although these all support purposeful judgement or action in a context, they can vary greatly in scope, authority, and conferred capability. They can all be refined, and as they mature, they gain in their scope, authority, and capability, while the set becomes more compact. A key moment in their evolution occurs with gaining insight into why they work, at which point they become principles. Principles can have their origins associated in referring to them as "heuristic principles", "social principles", "cultural principles", and "scientific principles", although in practice it is usually sufficient to just refer to principles. Systems engineering principles are derived from principles of these various origins providing a diverse set of transcendent principles based on both practice and theory (Rousseau, Pennotti, & Brook 2022).

System principles differ from *systems engineering* principles differ in important ways (Watson 2018a). System principles address the behavior and properties of all kinds of systems, looking at the scientific basis for a system and characterizing this basis in a system context via specialized instances of a general set of system principles. SE principles are a specialized and contextualized instantiation of systems principles that address the approach to the realization, use, and retirement of systems. SE principles build on systems principles that are general for all kinds of systems (Rousseau, 2018a) and for all kinds of human activity systems (Senge 1990, Calvo-Amodio & Rousseau 2019). Hence, system principles guide the definition and application of SE processes – a strong systems engineer must be the master of both system principles and SE principles.

A number of people have proposed SE underlying principles, in part by building on system principles. Perhaps because of its youth, a consensus among the community is still developing on which SE principles are most central. Yet, it is valuable to examine a number of proposed SE principles as they offer insight into what some of the best minds in the field think are fundamental to the discipline. In reviewing various published SE principles, a set of criteria emerged for valid SE principles. A principle:

- transcends a particular lifecycle model or phase
- transcends system types
- transcends a system context
- informs a world view on SE
- is not a “how to” statement
- is supported by literature or widely accepted by the community; i.e. has proven successful in practice across multiple organizations and multiple system types
- is focused, concise, and clearly worded

Thus, system type, the context in which the system is developed and operated, or a life cycle phase do not narrowly define systems engineering principles. Systems engineering principles transcend these system characteristics and inform a worldview of the discipline. Principles are not “how to” statements, which are embodied in the processes, but provide guidance in making decisions in applying the systems engineering processes. Principles should have a strong reference basis supported by literature, or widely accepted in practice (i.e. heuristic basis) (keeping in mind that this success must transcend the system characteristics mentioned above), or both. Principles are focused, concise, and clear in well-constructed principles statements.

Literature currently contains several good articles on system principles. These principles provide a basis for the functioning of a system and seek to group scientific axioms, laws, and principles into a set of system principles. The main themes seen in the literature on system principles include system governance, system theory axioms, and system pathologies with a focus on complex systems and system of systems. Complex System Governance provides a set of nine Metasystem functions “To provide control, communication, coordination, and integration of a complex system”. These functions provide a basis from which to understand the functions of complex systems and how to manage their acquisition (i.e., governance). (Keating et al. 2017a) These Metasystem functions also extend to systems of systems engineering (Keating et al. 2017b).

Advances in system theory produced a set of unified propositions stated as seven axioms “From which all other propositions in systems theory may be induced”. These seven axioms map to 30 scientific laws and principles (Adams et al. 2014). These axioms focus on the scientific basis of systems. Further work on these axioms provides an integration construct and a slightly different mapping to the underlying scientific laws and principles (Whitney et al. 2015). This work provides a strong integration and advancement in system theory, focusing on the principles behind the scientific basis of a system.

System science approaches also incorporate system theory leading to 10 concepts of systems theory and systems thinking (Sillitto 2014). These 10 concepts focus on system principles providing a definition of system characteristics. A further development in system sciences produced a list of 12 systems sciences principles that also focus on the characteristics of systems (Mobus and Kalton 2015). Rousseau formally derived a statement and derivation of three principles of systems (Rousseau 2018a). In addition, an architecture of systemology and typology of system principles provides a good classification of scientific principles spanning from system philosophy through system practice (Rousseau 2018b). This work led to a framework for understanding system science principles (Rousseau 2018c).

Other early work included a set of seven system science principles exhibited by systems (Hitchins 1992). Organizational principles were also defined as a set of 11 principles dealing with how to work successfully within an organization (Senge 1990). Principles of Systems

Thinking describes a set of 20 system thinking principles captured and integrated from a variety of sources.

System pathologies is another interesting approach to understand “Circumstances that act to limit system performance or lessen system viability (continued existence) and as such they reduce the likelihood of a system meeting performance expectations”. These pathologies define diagnostics for understanding systems derived from a set of 45 system laws and principles. (Katina et al. 2016)

INCOSE compiled an early list of principles. This list consisted of 8 principles and 61 sub-principles (Defoe 1993). These principles were important considerations in practice for the success of system developments and ultimately became the bases for SE processes. These principles are reflective of how SE works in general. Following this work, several early versions of SE principles were compiled leading up to one of the first documented sets of SE processes. Project Performance International (Halligan 2019) has a set of SE principles that follow along the model set by Defoe providing considerations in the practice of SE, focusing on specific aspects within life cycle phases.

The Korean Council on Systems Engineering provided a survey article of 8 works on SE principles spanning the time from Defoe’s principles through 2004 (Han 2004), including an early version of the PPI principles. These 8 works showed evolution of systems engineering principles from practice focused to more transcendent focused principles. In 1997, the INCOSE Systems Engineering Principles Working Group (no longer active) generated a set of 8 principles building from the work of Defoe over the course of several years of discussions. These principles were a mixture of process basis, modeling guidelines, and an early world view of the SE focus. The Institute of Electrical Engineers (IEE 2000), now part of the Institution of Engineering and Technology (IET), produced a set of 12 principles that also provided some basis for the systems engineering processes which are no longer extant. Lawrence Berkley National Laboratory (LNBL 2001) produced a set of systems engineering principles that embody the concepts captured by the INCOSE SE processes. In England, the Defence Engineering Group (DEG 2002) produced an SE Handbook with a brief set of principles guiding their processes and capturing some aspects of systems principles. Iowa State University is reported to have produced an SE Student Handbook containing a short list of SE heuristic phrases stated as principles.

The KCOSE paper also referenced a lecture on SE principles from a course at the University of Southern California (USC) (Jackson, 2003). This lecture defined a principle as “A statement or generalization of a truth reflected in the systems engineering process”, showing the focus on processes in the early SE principle development.

Some early forms of SE principles were also contained in textbooks on complex system development. (Adamsen II 2000) This set of principles assume a hierarchical system representation (complex systems have since shown to be more networks than hierarchies) and include statements on SE processes. Finally, system architecting books also included some early SE heuristics (Maier and Rechtin 2002). These heuristics read as sayings about some aspect of systems engineering practice.

The KCOSE Technical Board reviewed these 8 sources and voted that 8 of the principles from these sources as a set of SE principles, leading to an early form of transcendent principles consistent with the criteria defined above. These sources all show the early evolution stages of the SE principles as people looked at both formal and informal (i.e., course notes and student handbooks) sources to try to understand SE principles. The definition of the SE processes in works such as the INCOSE Systems Engineering Handbook fulfilled some of the objectives of these early works on SE principles and consolidated a lot of the work in this area. Recently, the need for more transcendent SE principles has been recognized, as a guide for applying the processes, which is the focus of current work by the SEPAT.

Over the last several years, a fresh look at the set of SE principles has emerged from the SEPAT. (Watson, et al. 2019) (INCOSE 2022) Its effort is based on SE postulates, principles, and hypotheses from the NASA Systems Engineering Research Consortium. This consortium followed the approach of Ludwig Boltzmann in defining his postulates on gas distribution laws. Boltzmann’s work is an early example of how to characterize the interactions of complex systems. A postulate is something assumed without proof to be true, real, or necessary. (Webster 1988) This led to the articulation of a set of postulates and hypotheses underlying SE which were expanded into a proposed set of SE principles. The underlying SE postulates and hypotheses matured over the course of 4 years (Watson et al. 2014; Watson et al. 2015; Watson & Farrington 2016). As the postulates matured so did the SE principles, providing more specifics in the application of

SE, and the proof of a hypothesis becoming a principle (Watson et al. 2018; Watson 2018b). The final version of the principles is contained in a NASA Technical Publication on theory of systems engineering (Watson, et. al. 2020a) and a NASA Technical Publication on application of systems engineering approaches in practice. (Watson, et. al. 2020b)

The SEPAT developed 15 principles and 3 hypotheses, some expanded by subprinciples, described in INCOSE (2022). These were peer reviewed by several professional societies and represent the firsts steps towards consensus on systems engineering principles. These principles are:

1. SE in application is specific to stakeholder needs, solution space, resulting system solution(s), and context throughout the system life cycle.
2. SE has a holistic system view that includes the system elements and the interactions amongst themselves, the enabling systems, and the system environment.
3. SE influences and is influenced by internal and external resources, and political, economic, social, technological, environmental, and legal factors.
4. Both policy and law must be properly understood to not overly constrain or under-constrain the system implementation.
5. The real system is the perfect representation of the system. (models are only representations of real systems)
6. A focus of SE is a progressively deeper understanding of the interactions, sensitivities, and behaviors of the system, stakeholder needs, and its operational environment.
7. Systems Engineering addresses changing stakeholder needs a over the system life cycle.
8. SE addresses stakeholder needs, taking into consideration budget, schedule, and technical needs, along with other expectations and constraints.
9. SE decisions are made under uncertainty accounting for risk.
10. Decision quality depends on knowledge of the system, enabling system(s), and interoperating system(s) present in the decision-making process.
11. SE spans the entire system life cycle.
12. Complex systems are engineered by complex

organizations.

13. SE integrates engineering and scientific disciplines in an effective manner.
14. SE is responsible for managing the discipline interactions within the organization.
15. SE is based on a middle range set of theories.

The SEPAT's recent articulation of SE principles elaborates on points made earlier by Defoe and emphasizes additional aspects of current SE practices, but there is nothing inconsistent between the two sets.

Principles of SE such as those proposed by Defoe and more recently articulated by the SEPAT are domain independent; i.e. they apply independent of the type of system being built, whether it is for transportation, healthcare, communication, finance, or any other business or technical domain. As they are applied, these principles can take more specialized forms, and/or can be complemented by other context-specific principles. Indeed, general SE principles such as these have been successfully applied in virtually every domain.

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Additional References

None.
