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A cognitive framework for engineering systems thinking

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Abstract

Engineering educators, researchers, and practitioners have recognized that a capacity for systems thinking is necessary for successful design of large scale, complex engineered systems. While early efforts have been made to classify behaviors, tendencies, and competencies of systems thinkers, there exist little rigorous understanding of the cognitive processes and skills in systems thinking. This paper establishes a connection between the concept of engineering systems thinking and well-studied processes from cognitive psychology. The eventual goal is development of a deeper understanding and a formal methodology for systems thinking.

Keywords: Systems engineering; systems thinking

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1. Introduction

Systems Thinking (ST) has been identified as having the potential to mitigate a number of problems brought on by the ever-increasing complexity of large-scale engineered systems[1]. However, without a cogent definition of ST in the literature and a purposeful practical ST use, wide adoption within engineering practice remains limited. Furthermore, strong emphasis on deep subject matter expertise and institutional neglect of so-called 'soft skills' in technical professions indicate that the holistic approach of systems thinking has limited appeal. The ST concept, its image, and its implementation require further elucidation and maturity so that its value can be realized and more inclusive systems engineering paradigms can be developed.

Reimagining systems thinking as a rigorous process is a daunting proposition. ST as a concept can be deconstructed

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into a set of cognitive competencies and habits within a larger framework: Systems thinking—like all thinking—is at its core an exercise in cognition, and relies upon high-order cognitive skills and a knowledge of why, when, and how to utilize them. Understood in this way, we can draw upon well-established fields such as neuroscience and cognitive science in building a strong case for systems thinking in engineering. Methods and guidelines for its practical implementation from the field of cognitive education are likely to be also useful in dissemination of this new knowledge.

The purpose of the present paper is thus twofold: First, the engineering systems thinking literature will be examined and shortcomings of existing definitions and methodologies will be discussed. Second, a clear mapping between engineering approaches to understanding systems thinking and cognitive science approaches will be laid out, aiming at the creation of a descriptive and pragmatic framework for understanding and applying systems thinking in engineering.

2. Background

Recent technological, scientific, and societal advances have created opportunities and challenges beyond what might have been predicted a decade ago. The future of science and engineering is similarly promising and daunting: Our world view may change quickly and it is impossible to know which technical trends will evolve predictably and which will become revolutionary. One may also assume that some findings or trends may necessitate a complete reconceptualization of engineering practice. For example, our physics understanding of the universe has evolved dramatically in the past fifty years with significant implications for scientific research and capabilities[2].

Engineering practitioners and educators have recognized the need for divergent approaches to engineering in order to accommodate these changes. As we develop increasingly complex systems that address broader requirements, the individual engineer's skill set and training must span a greater breadth than is currently covered by traditional curricula. The National Academy of Engineering recommended a cognitive approach to training in the systems perspective in 2004, but few educational institutions have integrated this paradigm into engineering curricula as yet, and even fewer industrial and government entities have explored methodologies for applying systems thinking in practice[2,3]. A review of the engineering literature reveals interesting gaps in the study of systems thinking that may illuminate why this is the case. First, the topic of systems thinking in engineering has remained largely understudied. While there are researchers and engineering educators interested in engineering systems thinking, this rather limited group is alone responsible for the majority of publications on systems thinking in engineering journals[4-8]. Consequently, much of the existing literature is self-citing, resulting in a rather narrow scope of insight and expertise.

Second, the bulk of the work on systems thinking (and engineering systems thinking in particular) has evolved from the study of natural sciences and biological systems[9]. While the study of natural processes is certainly useful for revealing patterns in general system functionality, such an approach only tackles the problem of systems thinking from one angle. The 'thinking' component is what sets ST apart as a concept distinct from systems science: It is one thing to study and make observations about a system, but another to "do systems thinking." Thus, the second significant problem with the current approach to understanding engineering systems thinking is that, despite the fact that we are quite obviously referring to a "way of thinking" when we describe engineering ST, there is paucity in the articulation of a rigorous cognitive framework for understanding engineering systems thinking. This paper offers a first attempt at such a framework.

3. Studying systems thinking in engineering: Contributions and missing voices

Research in engineering systems thinking is sparse. This is inherently problematic, as the experiences, perspectives, and expertise represented in the literature are limited and the extant work may appear more definitive than what it can be. Notable contributions to this literature come from Moti Frank, a trained engineer and engineering educator, and Donna Rhodes and her co-workers at the Massachusetts Institute of Technology's Systems Engineering Advancement Initiative. We discuss this work below.

Frank's studies in systems thinking in engineering first appeared in 2000[7] followed by a substantial body of research over the past 15 years[1, 7-8, 10-16], focusing on engineering systems thinking as it exists in both education and practice. This work is important in its early advocacy of updating the engineering curricula to incorporate systems thinking skills as part of standard engineering training. Frank, in his 2011 work[15], demonstrates a correlation between what he calls the "capacity for engineering systems thinking (CEST)" and project success—again, a first step in conveying the potential for the improvement of engineering practice that could result from a rigorous study of systems thinking. However, this work is yet to be substantially tested and validated, and the traits that Frank identifies as the "capacity" for or "cognitive characteristics of" engineering systems thinking are rather loosely defined. For example, in describing the cognitive characteristics of systems thinkers in his 2012 paper[1], each one of the ten characteristics Frank identifies begins with "understanding." What constitutes this understanding and how systems thinkers come to understand things in this way remain open questions.

Frank describes systems thinking (or engineering systems thinking) in terms of *behaviors* that result from systems thinking or *demonstrations* of the act of systems thinking, rather than the underlying psychological processes required for *doing* systems thinking. Frank refers to systems thinking as "a high-order thinking skill[1]" when it is likely a collection of individual skills that only used together can produce the desired outcome or systems-level understanding (this distinction to be discussed in depth in a later section). Frank's work is beneficial in recognizing the behaviors or tendencies of systems thinking that can be useful in practice, but there is still much work to define ways to develop the skills required to become a systems thinker.

Frank also refers to the capacity for engineering systems thinking as a distinct personality trait [10]. Psychology, however, defines personality traits and thinking abilities as distinctly different aspects. By describing the capacity for systems thinking as an innate ability or personality characteristic, the potential for methodically teaching systems thinking is lost, reducing a rather sophisticated concept to a simple interaction of personality and experience. The psychological distinction is important if the study and advancement of systems thinking is to progress in beneficial ways.

The work by Rhodes and co-workers Lamb, Nightingale, and Davidz is important to opening up the discussion about systems thinking in engineering, but may be subject to a similar critique. In their 2008 paper, Davidz and Nightingale suggest that enabling systems thinking is a critical step in advancing the development of senior systems engineers; they recognize at the same time that fundamental questions still remain about how systems thinking develops in engineers[4]. The authors attempted to answer these questions through field studies and interviews with 205 engineers across 10 host companies in the US aerospace sector[5]. Engineers of various levels of expertise and experience and with varying levels of proficiency in systems thinking were asked how they define systems thinking, and were also given a definition of systems thinking and were then asked to comment on what aspects of the definition they agreed and disagreed with. This approach resulted in divergent definitions of systems thinking, which did not help in developing a single, unified framework from which to advance its study. The authors organized these disparate results into five broad foundational elements that explain what perspectives and behaviors constitute systems thinking, but do not address the underlying commonalities or constructs. Only one element, deemed the "modal" element, describes *how* an individual performs systems thinking, but the authors described this "how" in the context of tools, methods, models, and simulations and do not address the actual cognitive processes required to do systems thinking. Despite this shortcoming, the work identifies some important enablers to the development of systems thinking, such as experiential learning, education, interpersonal interactions, and training in a supportive environment.

Other research by Rhodes, Lamb, and Nightingale[6] was an effort at studying systems thinking empirically. As in the work by Davidz and Nightingale[4], the authors seek to uncover the enablers, barriers, and precursors to engineering systems thinking. The authors recognize that both an in-depth understanding of engineering practice coupled with an orientation in social science is necessary to properly capture the essence of engineering systems thinking.

In an effort to move away from the limitations of the earlier work[4-6], Rhodes et al. offered a different explanation for engineering systems thinking by suggesting that it is perhaps not something that can be evaluated at the individual level at all. Rather, this paper and others by the same group[17-18] suggest that systems thinking may be better understood as "*an emergent behavior of teams resulting from the interactions of the team members… utilizing a variety of thinking styles, design processes, tools, and languages to consider system attributes, interrelationships, context, and dynamics towards executing systems design.*"

While social context is certainly a relevant and important factor in systems thinking, one can argue against describing systems thinking as an emergent behavior of teams. The study in [4] relied on testimony from "proven stellar systems thinkers;" if systems thinking were simply an emergent property of teams, these individuals could not exist independent of the teams in which they work. Clearly, certain individuals have a more refined systems thinking skill set than others, and it is imperative to understand why and how it is that this occurs. A cognitive psychological approach at the individual level of analysis is a good first step in this direction. Offering additional support for this strategy, Davidz and Nightingale recognized the importance of addressing systems thinking at the level of the individual[4]: they argue that understanding how systems thinking develops in an individual is important for subsequently understanding how systems thinking develops in a team. If systems thinking is to be described in terms of emergence, it is more appropriate to summarize systems thinking as an emergent feature of a highly refined set of individual cognitive processes rather than an emergent feature of teams.

This prior research provides valuable contributions and strong evidence for the importance of studying systems thinking in engineering, but contributions from extant knowledge in psychology and cognitive science are not included. The next section offers an initial approach towards such inclusion.

4. A new cognitive paradigm for understanding engineering systems thinking

Frank's work offers a solid foundation for developing a cognitive approach to engineering systems thinking. A next step should be transforming these behavioral descriptions into established concepts in cognitive psychology. This section attempts to establish a mapping between the behaviors and competencies Frank describes to topics of psychological inquiry, to ground Frank's observations and systems thinking on social science research.

In his 2012 paper[1], Frank identifies sixteen cognitive competencies of successful systems engineers, extrapolated from a meta-analysis of several systems thinking studies and systems engineering competency models. The cognitive competencies Frank identifies are reproduced below:

> *Understand the whole system and see the big picture; understand interconnections; understand system synergy; understand the system from multiple perspectives; think creatively; understand systems without getting stuck on details; understand the implications of proposed change; understand a new system/concept immediately upon presentation; understand analogies and parallelism between systems; understand limits to growth; ask good (the right) questions; (are) innovators, originators, promoters, initiators, curious; are able to define boundaries; are able to take into consideration non-engineering factors; are able to "see" the future; are able to optimize*

The paper then goes on to describe what each of these competency titles represents, i.e., what the systems engineer does to embody or outwardly exhibit the competency. While these characteristics and behaviors are certainly examples of systems thinking at work, the paper does not discuss the internal thought processes required to produce them. For example, in describing the ways in which systems engineers "understand the implications of proposed change," Frank writes: "*Successful systems engineers understand the system as a whole, are able to analyze the impact of proposed changes, and are capable of anticipating and dealing with all implications of changes in the system."*

The specific cognitive processes or skills required to achieve this competency are left out in the above statement; specifically, hypothetical thinking is required to "understand the implications of proposed change." Hypothetical thinking is defined as the ability to reason about alternatives to the way the world (or system, in this case) is believed to be[19]. While this may seem like a subtle distinction, the translation of these observed competencies into well-studied internal cognitive processes is the first step in developing these processing abilities in systems engineers. In a sense, a shift from using engineering terminology to describe cognitive phenomena to using cognitive terms to describe cognitive phenomena is necessary in order to open the toolbox of cognitive psychology to engineers. This ultimately enables engineering management to create or refine the desired cognitive skillset using well-established methods from cognitive psychology, and to achieve the goal of improving systems thinking and interdisciplinary collaboration. Again, as systems thinking is an exercise in cognition, it makes sense to utilize methods and approaches from cognitive psychology in fostering these skills in engineers.

Some of the cognitive competencies Frank identified map directly to concepts from cognitive psychology, while others require refinement. The complete list of competencies as described by Frank and their correlates in cognitive psychology are shown in Table 1. Some competencies have direct mappings, although the majority do not. We note that these mappings are not perfect and at this stage serve only as examples of how we might move from engineering descriptions of cognitive competencies to cognitive descriptions. Higher-level factor analysis is required to determine which cognitive processes specifically combine to create the phenomenon we describe as engineering systems thinking.

Table 1: Mapping between cognitive competencies of systems engineers and cognitive processes required for generating these behaviors.

Frank's cognitive competencies [1]	**Cognitive psychology related concepts [20-25]**
Understand the whole system and see the big picture	Sensemaking; information integration; mental model formation; generalization
Understand interconnections	Induction; classification; similarity; information integration
Understand system synergy	Deductive inference
Understand the system from multiple perspectives	Perspective taking (direct mapping)
Think creatively	Creativity (direct mapping)
Understand systems without getting stuck on details	Abstraction; subsumption
Understand the implications of proposed change	Hypothetical thinking
Understand a new system/concept immediately upon presentation	Categorization; conceptual learning; inductive learning/inference
Understand analogies and parallelism between systems	Analogical thinking (direct mapping)
Understand limits to growth	Information integration
Ask good (the right) questions	Critical thinking
(Are) innovators, originators, promoters, initiators, curious	Inquisitive thinking
Are able to define boundaries	Functional decomposition
Are able to take into consideration non-engineering factors	Conceptual combination
Are able to "see" the future	Prospection
Are able to optimize	Logical decision-making

While the behaviors identified by Frank do not map directly to cognitive processes, the processes identified in Table 1 are implicated in and required for the actions Frank describes.

5. Implications for cognitive research directions

Understanding engineering systems thinking as an emergent property of some of these highly refined cognitive skills enables engineers and researchers to begin to develop a prescriptive approach for teaching and implementing systems thinking methodologies in engineering. This section provides a mapping between some of the cognitive competencies of successful systems engineers as described by Frank and the work of Reuven Feuerstein, a clinical, developmental, and cognitive psychologist who has developed an educational method designed to create or correct many of the same cognitive functions that Frank describes.

Feuerstein is recognized in particular for his development of the theory of structural cognitive modifiability and his foundational teaching method, the Mediated Learning Experience (MLE)[26]. The theory of structural cognitive modifiability builds on three basic tenets: The brain is plastic and structurally modifiable throughout life; cultural transmission provides an important method for the creation of cognitive structures; and a human mediator may intervene in the mental processes of a learner, creating missing structures or correcting dysfunctional structures in the brain. The essential feature of this approach is that these changes are not simply psychological, but rather of a structural nature that alter the course and direction of cognitive development[27]. The changes that occur "are not a fragmented, episodic consequence of exposure to experiences, but rather a type of change that affects the basic structure of behavior[27, 28]."

These are important claims. Feuerstein is suggesting that, through use of a well-trained mediator, subconscious information processing skills can be brought to conscious awareness and be created, corrected, and improved, ultimately resulting in physiological changes in the brain in addition to psychological ones. Recent research in neuroscience seems to offer substantive support for Feuerstein's work[29-31].

A thorough discussion of the intricacies of MLE is beyond the scope of this paper. A more pertinent point is the commonalities between the goals of MLE and the desired traits of engineering systems thinking as described by Frank and Rhodes and co-workers. Figure 1 identifies the cognitive processes targeted by MLE; processes in the elaboration phase and output phase are quite similar to the cognitive competencies of individuals with the capacity for engineering systems thinking. To provide an example, "seeing relationships" is a universal theme in the systems thinking literature[4-8, 10, 17-18], and Feuerstein's method is directed at improving such processes. Hypothetical thinking, inferential thinking, and flexibility are also attributes of systems thinkers, and egocentric communication or behavior are barriers to systems thinking; Feuerstein's approach offers a methodology for addressing them.

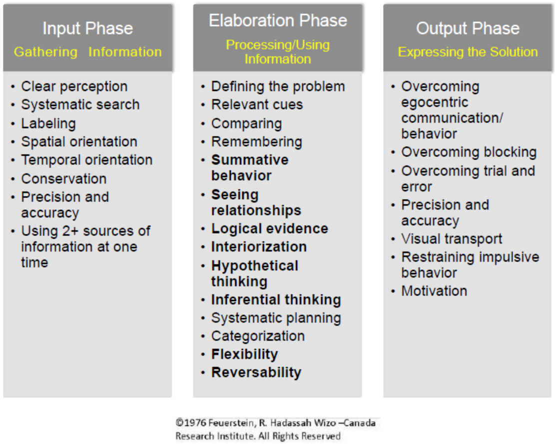

Figure 1: Cognitive processes targeted by Feuerstein's MLE

A deeper exploration of Feuerstein's work is required before claiming that the MLE is an effective way to develop systems thinking skills in engineers; these early mappings seem to provide a promising direction for future studies.

6. Conclusion

Engineering systems thinking is an important concept in advancing systems engineering practice. As the systems become larger, more complex, and more distributed, better ways of conceptualizing and thinking about these systems are required to ensure their success and efficiency. A first step in developing systems thinking is to understand more deeply what it entails and to draw upon well-established work in psychology, cognitive science, and neuroscience. A working understanding of both engineering practice and social science theory is necessary in this endeavor.

This work represents an early effort to interpret engineering challenges through the lens of social science. Engineering researchers have already begun to identify this need. Further work from a more diverse community is required for accelerated progress to be realized.

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