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DESIGN THINKING VS. SYSTEMS THINKING FOR ENGINEERING DESIGN: WHAT'S THE DIFFERENCE?

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Abstract

Design thinking (DT) and engineering systems thinking (EST) are two complementary approaches to understanding cognition, organization, and other non-technical factors that influence the design and performance of engineering systems. Until relatively recently, these two concepts have been explored in isolation from one another; design thinking methods have been applied to industrial design and product development, while engineering systems thinking is used in professional systems engineering practice and large-scale, complex systems design. This work seeks to explore the relationship between these two concepts, comparing their historical development, values, applications, and methods. The primary contribution of the work is a set of four concept models that depict plausible relationships between design thinking and systems thinking for engineering design.

Keywords: Design cognition, Design theory, Design methodology, Systems Engineering (SE), Multi- / Cross- / Trans-disciplinary processes

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1 INTRODUCTION

Conceptual design of products and systems is a difficult process, during which cognitive, social, and technical challenges abound. To address these, formal design engineering methodologies offer theory, process models, and best practices, as well as insights about psychological processes and social behaviours that comprise "designerly ways of knowing (Cross, 1982)." Two such approaches, design thinking and systems thinking, have emerged in parallel as methods for tackling these "wicked" design problems in diverse settings (Rittel and Webber, 1973; Checkland, 1981; Clarke, 2000). Design thinking and systems thinking frameworks are useful for anticipating and addressing emergent features of products, systems, and organizations (Plattner et al., 2014; McGowan, 2014; Viswanathan and Linsey, 2014; Davidz and Nightingale, 2008), and have additional applications in engineering design (Forrester, 1961; Frank, 2000; Dinar et al., 2015; Watson et al., 2014; McGowan et al., 2017), management and organization (Senge, 1990; Checkland, 1981, 1999), pedagogy (Dym et al., 2005; Lammi and Becker, 2013), and other contexts.

While domain independence is considered an advantage of the design thinking and systems thinking frameworks, divergent definitions and approaches have created an ambiguous literature. At its worst, this situation has led to the dismissal of these concepts as "buzzwords," devaluing the empirical evidence that supports them (Patel and Mehta, 2016; Dinar et al., 2015; Shah et al. 2012; Jaradat, 2015).

Additional work is necessary to address this criticism, and to integrate and strengthen the existing body of knowledge. Until recently, design thinking and systems thinking have been explored mostly in isolation from one another. Systems thinking is sometimes described as a component of design thinking (Long, 2012), sometimes as separate but related to design thinking (Patel and Mehta, 2016), and is sometimes not described alongside design thinking at all. Likewise, references to design thinking research are not often found in systems engineering research on systems thinking or systems design.

Understanding how system designers think is key to advancing systems engineering methods, tools, and outcomes (Griffin, 2010; Watson et al., 2014). Design engineering researchers in academia have successfully adapted formal cognitive science approaches to study designer thinking (Dinar et al., 2015). Systems engineering researchers in industry and government have broadly identified skills, attitudes, and behaviours necessary for complex systems design (Frank, 2006; Williams and Derro, 2008; Davidz et al., 2005; Rhodes et al., 2008), but existing cognitive approaches are limited (Greene and Papalambros, 2016). Studying the relationship between designer thinking and systems thinking paradigms could be useful for addressing this gap, and for identifying other areas in which one methodology might be improved by the knowledge of the other.

This work makes a first attempt at comparing research perspectives on engineering design thinking (DT) and engineering systems thinking (EST). Its purpose is neither to provide a complete analysis of the literature nor to propose a new definition of either concept. Rather, it is intended to serve as a primer on the history, values, applications, and methods of each approach and to relate them to one another. Comparing the historical context and values underlying each approach is useful for explaining why design thinking and engineering systems thinking evolved independently into what they are today. Exploring contemporary applications and methods is useful for identifying opportunities to share knowledge and tools between communities in future research efforts.

The rest of the work is structured as follows to achieve these objectives. Sections 2 and 3 provide a brief introduction to relevant literature from the design engineering and systems engineering communities. The literature review is organized by high-level themes *history, values, applications, and methods* that recur throughout. Section 4 suggests several different ways to compare design thinking and systems thinking using these themes, represented by "concept models" that visually position DT and EST themes relative to one another. The themes and concept models proposed are coarse, and the authors do not suggest any single "correct" model for the relationship between DT and EST. Rather, these models represent several plausible theories about the relationship between design thinking and systems thinking methodologies, and are meant to encourage additional discourse and collaboration between the design and systems engineering communities.

2 DESIGN THINKING AND THE SCIENCE OF DESIGN

2.1 A brief history of design thinking research

Rapid technological development throughout the twentieth century generated a need for formal academic study of "the science of design (Simon, 1969)." Two important periods in the modern history of design science are identified by Cross (1982). The first, the "design products movement" of the 1920s, sought to "produce works of art and design based on objectivity and rationality;" that is, on the values of science. The second, the "design methods movement" of the 1960s, sought to establish design *processes*—in addition to the *products* of design—based on similar scientific principles. Despite some backlash against design methodology in the 1970s, the tradition continued to flourish in engineering and industrial design, and several prominent academic journals for design research, theory, and methodology emerged during the 1980s and 1990s.

Design methodology is defined by Cross (1982) as "the study of the principles, practices, and procedures of design" and "includes the study of how designers work and think." Over the past several decades, engineering researchers have successfully leveraged cognitive and social science approaches to study how designers think through engineering design problems, exploring a breadth of topics including creativity, ideation in early conceptual design, the role of analogies in creative problem solving, differences between novices and experts, and strategies for overcoming fixation and mental blocking. Verbal protocol analysis, cognitive ethnography, controlled laboratory experiments, and other formal methods from cognitive science have been rigorously applied to the study of designer thinking in engineering (Dinar et al., 2015; Shah et al., 2012).

Results of these studies and others suggest that design thinking approaches use solution-based methods to explore human-centred values throughout the engineering design process. This finding is reflected in many applications of design thinking: prototyping, a solution-based method, is often cited as a useful way to encourage inspiration, ideation, and organizational learning, all human-centred values (Brown, 2009; McGowan et al., 2017). Specific applications and methods for design thinking will be briefly described in the following sections.

2.2 Applications of design thinking research

Many applications of the design thinking framework exist in the literature and in practice. Examples include Herbert Simon's design thinking process (1969), which suggests seven stages of design thinking for product design, including *defining the problem, researching, ideating, prototyping, choosing a solution, implementing the solution, and learning*. Plattner et al. (2011) propose a five-step version of the design thinking process that includes *redefining the problem, need finding and benchmarking, ideating, building, and testing*. International design and consulting firm IDEO applies a four-phase process that includes *gathering inspiration, generating ideas, making ideas tangible*, and *sharing your story* (Brown, 2009).

While each interpretation differs slightly from the others, important foundational values of design thinking persist. First, design thinking is solution-based, and most design thinking methods include prototyping and iteration phases. These solutions are human-centred products or services, developed with designers' personal experiences, intellect, empathy, and understanding. Likewise, the design thinking process itself is human-centred, offering methods for inspiration, ideation, and learning to designers (Brown, 2009). Design thinking has been described as a "high order intellectual activity" that "requires practice and is learnable" (Plattner et al., 2011). This description is supported by findings in cognitive psychology. Example methods for studying design thinking are discussed in the following section.

2.3 Methods: Studying designer thinking and design cognition

As previously described, empirical studies of designer thinking are abundant, having matured substantially since the early 1980s. Contemporary applications of the term "designer thinking" generally refer to the study of "cognitive processes and strategies employed by human designers working on design problems (Dinar et al., 2015)." These processes are explored through case studies, think-aloud protocols, controlled experiments, psychometric measurement, and, more recently, through physiological measurement techniques such as functional magnetic resonance imaging (fMRI). Popular research topics in design cognition include the role of sketching and visual representation, the use of analogies, methods for fostering creativity, ideation, and overcoming blocking, approaches for balancing divergent and convergent thinking, and elucidating differences between expert and novice designers. A detailed discussion of these studies and their contributions is beyond the scope of this work. However, a comprehensive review of empirical studies of designer thinking is provided in the paper by Dinar et al. (2015).

A critical point here is that "thinking" research in the design engineering tradition has successfully integrated theory and methods from cognitive and other social sciences. Studies on engineering systems thinking, a similar concept developed for application in systems engineering organizations, might look to advance in a similar way. Only recently have research efforts expanded to include non-engineering factors such as design cognition in the analysis of engineering systems design (Davidz and Nightingale, 2008; Griffin, 2010; Frank, 2012). The following section describes the history of the EST concept, tracing its evolution from a physics-based modelling method to the more interdisciplinary approach observed in practice today. Contemporary values, applications, and challenges are also discussed.

3 THE "SYSTEMS APPROACH" TO COMPLEXITY MANAGEMENT

3.1 A brief history of the systems approach

The history of the "systems approach" for dealing with design complexity is long and diverse. The following section provides a brief overview of several major schools of systems theory, beginning with Ludwig von Bertalanffy's General Systems Theory (1940). von Bertalanffy's work was quickly expanded to describe cybernetic systems (Wiener, 1948) and dynamic systems (Forrester, 1961), and has also informed traditional operations research, systems engineering, and management science (Checkland, 1981). Later work examined the application of general systems concepts to human social systems. While general systems theory was somewhat useful for analysing social and organizational systems, traditional physics-based models did not always adequately represent human factors that influence system performance (Forrester, 1994). These findings prompted the development of "soft operations research (OR)"—a collection of methods 'designed to help with the understanding, clarification, and communication of problems' in industrial engineering and design. Engineering systems thinking is considered a method for soft OR (Forrester, 1994). Because EST evolved in the OR tradition, its empirical study has been limited to the perspectives and methods of systems engineering, management science, and quantitative decision-making, with limited insights from cognitive and other social sciences.

3.1.1 General systems theory and cybernetics

The term "systems theory" was coined by Ludwig von Bertalanffy in 1937 and describes the interdisciplinary study of systems in general. Systems theory emerged as an attempt to uncover patterns and principles common to all levels of all types of systems, again with an emphasis on generality. The primary goal in developing systems theory was to provide a useful framework for describing a broad range of systems using the same terminology, in contrast to existing discipline-specific systems models in biology, engineering, and psychology (von Bertalanffy, 1940).

A central tenet of systems theory is self-regulation, and systems theory is often applied to describe systems that self-correct through feedback. These types of systems are found in nature, in local and global ecosystems, and in human learning processes at both the individual and organizational level. Early work in self-regulating systems eventually led to the development of cybernetics – the formal study of communication and control of regulatory feedback (Wiener, 1948). Cybernetics offers approaches for exploring natural systems, mechanical systems, physical systems, cognitive systems, and social systems; cybernetics is applicable in the analysis of any system that incorporates a closed signalling loop. While the cybernetics framework can be applied to analyse non-engineering systems, engineering theory and methods are still used to represent the system.

Systems dynamics, a related field pioneered by Jay Forrester at MIT, emerged in the mid-1950s as application of electrical control theory to the analysis of business systems. Forrester developed a mathematical modelling technique to help corporate managers improve their understanding of industrial practices. By simulating the stock-flow-feedback structure of an organization, Forrester demonstrated that instability in organizational employment was due to internal structure of the firm, and not to an external force such as a business cycle (Forrester, 1961). Forrester's work on applied system dynamics marked a major paradigm shift in engineering by successfully demonstrating that mathematical models are useful for representing, understanding, and predicting outcomes for non-technical systems engineering problems.

3.1.2 From 'system dynamics' to 'systems thinking'

System dynamics is a foundational method in systems engineering (SE)—an interdisciplinary field of formalized approaches for designing and managing large-scale, complex engineered systems (LSCES) throughout the life cycle. Like design science, the need for systems engineering arose with the increase in complexity of military-industrial systems in the 1940s: as projects increased in size and scope, computational tools for modelling and simulation, requirements analysis, reliability, logistics, coordination, scheduling etc. were necessary for successful system design, implementation, and decommission. Systems engineering methodology offers a process for technical management of LSCES— sophisticated quantitative techniques are used to organize and coordinate work activities, evaluate technical systems interactions, and assure system quality and performance. To address human factors that influence LSCES design, systems engineering has drawn from operations research and management science to develop mathematical models of human performance. Examples of classical quantitative approaches to management include Markov analysis; linear/dynamic programming; decision theory; and game theory, among others.

Systems engineers are well-trained to manage technical system consolidation, but the associated changes between social and organizational units are more difficult to govern in practice. Existing analytical methods from hard OR methodology are inapplicable or ineffective for solving this problem (Forrester, 1994). Nonetheless, systems engineers are expected to play ambidextrous roles and have the professional responsibility of "systems thinking," i.e., serving as big picture "visionary designers" who manage technical as well as social and organizational constraints in dynamic environments (Brooks et al., 2011). The complexity of this task and its implications for system performance, cost, and schedule led to the development of soft operations research— an extension of traditional operations research that places less emphasis on mathematical modelling of business and social systems and more on thoroughly defining system boundaries and problems, resolving conflicting viewpoints, and reaching consensus on future action (Forrester, 1994). Soft OR methods such as ST characterize systems on a variety of qualitative dimensions — e.g., physical vs. social, causal vs. probabilistic, degree of complexity, or susceptibility to control— and utilize discussion and intuition rather than quantitative methods to analyse systems engineering and design processes (Forrester, 1994).

3.2 Engineering systems thinking

Understanding how systems engineers evaluate technical and social relationships—and leverage this information to successfully design and manage complex systems—is a challenge in modern systems engineering practice. Research efforts in recent decades have explored this activity, attempting to elucidate both individual traits, skills, and attitudes as well team properties that contribute to the "capacity for engineering systems thinking (Frank, 2000, 2006, 2012; Williams and Derro, 2008; Brooks et al., 2011)."

Several general trends in the study of EST can be identified, and conceptual themes are described in more detail in Sections 3.3. First, it is important to note that engineering systems thinking is primarily studied through behavioural observation and defined in behavioural terms in the literature. One notable example is a 2008 study conducted by NASA's Office of the Chief Engineer, in which "highly-valued" systems engineers—those identified by NASA centres as "go-to" people with regards to systems engineering— were interviewed, shadowed, and observed, and findings summarizing their behaviour were organized and distributed as an interagency report (Williams and Derro, 2008). The study resulted in rich descriptions of individual attitudes, problem solving strategies, technical acumen, and systems thinking capabilities required to do systems engineering at the highest level, and described leadership, communication, and other social skills as equally important for systems thinking and systems engineering. These findings are mirrored in several other studies from industry and academia (Davidz et al., 2005; Rhodes et al., 2008; Frank, 2000, 2006, 2012).

Second, practicing engineers and engineering researchers are beginning to acknowledge the need for a more rigorous interdisciplinary framework for EST, to understand the social and psychological underpinnings of EST behaviours. Frank (2006, 2012) describes systems thinking as "a high-order thinking skill," and suggests several cognitive processes that might facilitate systems thinking. Work by Rhodes and colleagues Lamb, Nightingale, and Davidz (2008) suggests that enabling systems thinking is a critical step in advancing the development of senior systems engineers, at the same time recognizing that fundamental questions remain about how systems thinking develops in engineers. The authors describe “how” to do systems thinking using tools, methods, models, and simulations, reflecting the traditional systems engineering approach, but identify other important enablers to the development of systems thinking such as experiential learning, education, interpersonal interactions, and training in a supportive environment. The authors also identify some individual cognitive and social processes at work, and recommend additional inquiry in this area.

3.3 Values, applications, and methods in EST research

Engineering systems thinking shares a foundation with systems science; thus, values and applications bear strong resemblance to those of general systems theory, cybernetics, and systems dynamics. The EST framework posits that a system is composed of parts, the system is greater than the sum of its parts, and all parts of the system are interrelated. Systems receive inputs from the environment, execute processes that transform these inputs into outputs, and send these outputs back into the environment in feedback loops. Systems are dynamic and complex, interactions may be difficult to identify or quantify, and emergence is common. Like the earlier approaches, engineering systems thinking is system-centred, i.e., is used for conceptualizing systems, their individual components, and interactions between those components, to help designers anticipate emergent features and design robust and resilient systems.
Contemporary research in EST seeks to make the approach more human-centred. Successful engineering systems thinkers are consistently recognized as being good leaders and communicators and as naturally "curious" or "innovative." Studies suggest that systems thinkers can see and define boundaries; understand system synergy; and balance reductionist and holistic viewpoints. They think creatively, overcome fixation, and tolerate ambiguity. ESTs ask "good questions"; can understand new systems and concepts quickly; can consider non-engineering factors that influence system performance; and understand analogies and parallelism between systems (Frank, 2012; Williams and Derro, 2008; Davidz and Nightingale, 2008; Davidz et al., 2008; Rhodes et al., 2008; McGowan, 2014). While these human-centred values are described at a high level in EST research, few formal methods exist in systems engineering for applying or studying them with precision.

4 "CONCEPT MODELS" FOR COMPARING DESIGN THINKING AND ENGINEERING SYSTEMS THINKING RESEARCH

Previous sections described design thinking and engineering systems thinking using four general themes: history, values, applications, and methods. This section organizes these themes into "concept models" that visually represent different perspectives on the relationship between design thinking and engineering systems thinking. The first model, called the Distinctive Concept Model, positions DT and EST as separate concepts, each with a unique history, set of values, practical application, and methods. The second model, the Comparative Concept Model, suggests that DT and EST are similar underlying concepts with different applications and methods. The third model, the Inclusive Concept Model, describes engineering systems thinking as a specific application of design thinking, in which design thinking principles, methods, and processes are applied to complex systems design problems. The final model, the Integrative Concept Model, suggests that design thinking might be the critical skill for design at both the product and system level, and that EST might not be practically distinguishable from DT. Again, these models do not suggest any single "correct" representation of the DT/EST relationship. Additional work will be required to make definitive claims.

4.1 The Distinctive Concept Model

The distinctive concept model of design thinking and engineering systems thinking describes two unique concepts with different histories, values, themes, and applications (Figure 1). This model suggests that DT and EST were developed for different purposes, with different guiding principles.

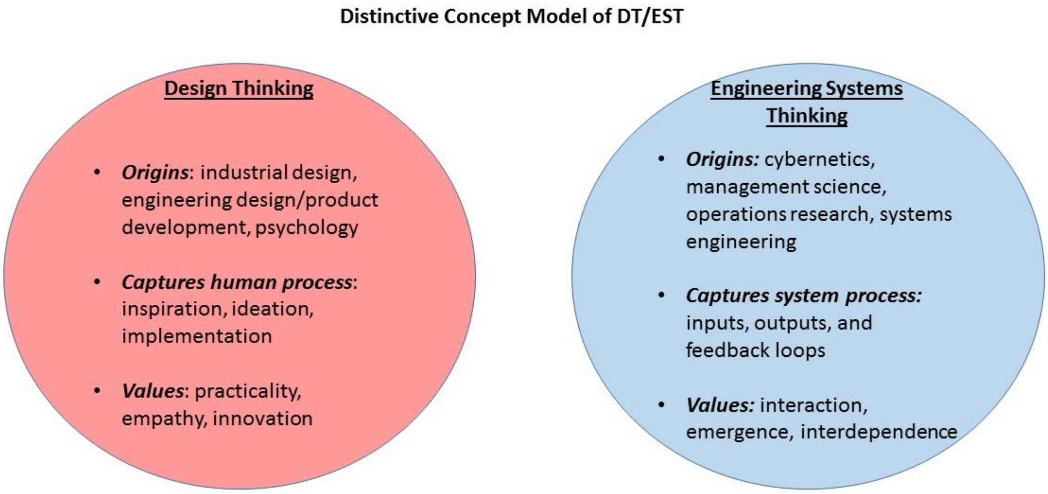

Figure 1. Distinctive concept model of design thinking and engineering systems thinking. DT/EST are distinct concepts, with different histories, approaches, and goals

Design thinking has origins in psychology, industrial design, and product development, and is a method for generating innovative, user-centred products and services. Empathy is a key driver of the design thinking process. Systems thinking, on the other hand, originated from cybernetics and operations research and is intended to capture stock and flow structures and feedback loop dynamics. It is system-focused and used for identifying potential interactions between system elements that might result in unintended system performance. Put succinctly, the goal of design thinking is to create innovative, user-friendly products and services. The goal of systems thinking is to uncover as many relevant factors and interactions between system elements as possible, so that systems can be designed to be resilient and robust.

4.2 The Comparative Concept Model

A second conceptualization of design thinking and engineering systems thinking positions the two concepts as distinct, but with several major overlaps (Figure 2). While DT and EST have different origins, applications and approaches, both require a similar cognitive skill set in practice: design thinkers and engineering systems thinkers alike must be creative, flexible, curious, and emotionally intelligent. Design thinkers and engineering systems thinkers both utilize divergent and convergent thinking strategies, use analogical, visual, and spatial reasoning, and embrace ambiguity and emergence. However, design thinking is a somewhat more linear and bounded process, in that it leads to concrete, physical prototypes. Systems thinking is more cyclical and abstraction-driven, and does not emphasize tangibility through prototyping in the same way that design thinking methodology does.

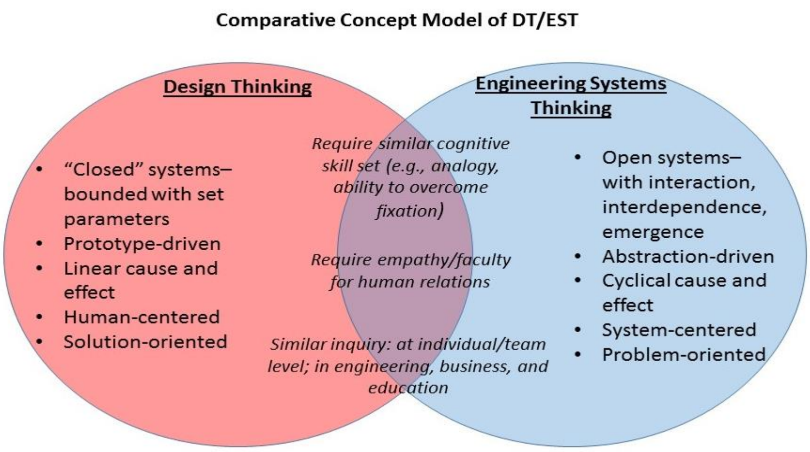

Figure 2. Comparative concept model of design thinking and engineering systems thinking. Underlying mechanisms are similar, but concepts have different applications and utilize different methods

4.3 The Inclusive Concept Model

The inclusive concept model suggests that engineering systems thinking might not be a standalone methodology, but rather the specific application of design thinking principles to the design of large-scale, complex engineering systems such as software enterprise systems, aerospace vehicles, or nuclear power stations (Figure 3). DT and EST are both approaches for addressing design complexity, defining and solving wicked problems, and understanding the role of cognitive and social processes on system design and performance. Systems thinking has been described as a necessary skill for design thinking (Long, 2012). The key distinction here is the emphasis placed on abstraction, interdependence, and emergence in EST, versus tangibility, prototyping, testing, and redesign in DT.

It is important to note that EST is included as a subset of DT and not the other way around. This is partly because design thinking has an established interdisciplinary methodology, certifications, short courses, etc., compared to the more casual exploratory studies and descriptions of EST skills. Likewise, systems thinking is sometimes mentioned in the design thinking literature as a requisite skill for design thinking, while there is little mention of design thinking in the engineering systems thinking literature. However, an inverse form of this model is plausible as a "systems view" is required for user-centred design.

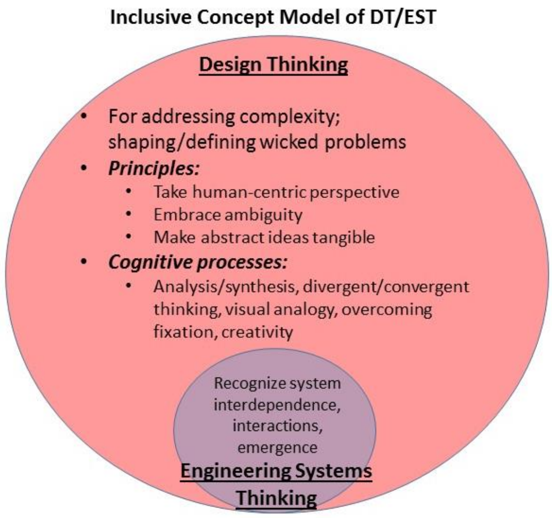

Figure 3. Inclusive concept model of design thinking and engineering systems thinking. EST is represented as the specific application of design thinking principles to the design of large-scale, complex engineered systems

4.4 The Integrative Concept Model

The final model suggests that these philosophies might be better understood as part of a single overarching framework with distinctions for product design, LSCES design, and the design of services (Figure 4). Design thinking could be the fundamental skill required for design across all contexts and levels of complexity; engineering systems thinking might not be distinguishable from design thinking in practice. It is plausible that DT and EST evolved as separate concepts only because of a methodological gap between academic design research and the practice of professional systems engineering.

Integrative Concept Model of DT/EST

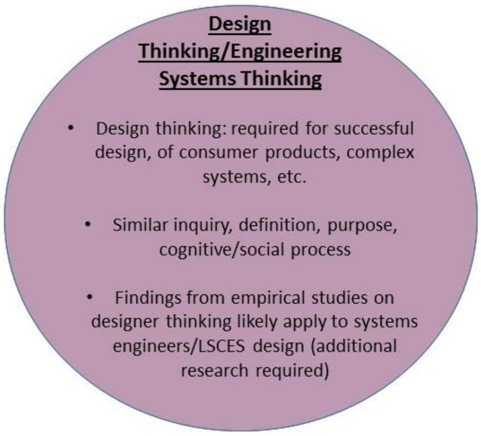

Figure 4. Integrative concept model of design thinking and engineering systems thinking. Despite historical/ conceptual differences, DT and EST utilize the same cognitive processes and have the same practical application

5 CONCLUSIONS AND OPPORTUNITIES FOR FUTURE INQUIRY

Design thinking and engineering systems thinking are similar frameworks for exploring principles and processes of engineering design. Further research is required to fully understand the intricacies of DT and EST, and to draw definitive conclusions about the relationship between the two. The primary contribution of this work is that it represents an early attempt at comparing perspectives on engineering design thinking and engineering systems thinking. Its purpose was not to provide a complete analysis of the literature nor to propose a new definition of either concept, but to instead serve as a reference for framing future research and to highlight the need for an integrated research effort. A more formal literature review, coding, and meta-analysis will be necessary.

This work posed several plausible models of the relationship between design thinking and engineering systems thinking, by comparing the historical development, values, applications, and methods of each approach. Comparing the historical context and values underlying each approach is useful for explaining why design thinking and engineering systems thinking evolved independently into what they are today. Exploring contemporary applications and methods is useful for identifying opportunities to share knowledge and tools between communities in the future.

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