Exploring Generative Design Thinking for Engineering Design and Design Education

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Keywords

Generative design thinking, evolving design thinking model, faculty paper

Generative design (GD) is a design method that utilizes computational methods and algorithms to generate designs [1]. Under a set of rules and constraints, GD can generate thousands of design options, allowing designers to explore a broader range of the design space to discover new designs compared to traditional design methods. GD can help overcome the design fixation and thus potentially foster design creativity [2]. It is garnering more attention from both academia and industry. Mountstephens and Teo [1] claim that GD in engineering product design research demonstrates considerable progress and promise. Also, there has been a success in applications of GD in the industry (e.g., Airbus A320 partition redesign [3]), which proves the statement that the time of GD has come with the development of cloud computing and additive manufacturing [4]. GD can be seen as a design automation process that can save human labor and time, which requires designers with different skills and mindsets from the traditional design methods. However, like traditional design processes, human designers remain critical in the GD process for at least three reasons: 1) Design options are generated by algorithms that designers create. Although there is some off-the-shelf GD software, e.g., Autodesk's Fusion 360, designers still need to define necessary design parameters and constraints, such as spatial constraints and engineering requirements. 2) Designers need to make trade-off decisions among numerous generated design options, often with multiple conflicting features; 3) The aesthetic requirements cannot be easily encoded into algorithms and largely depend on the subjective perspectives of designers. Due to the essential role of human designers in GD, it is essential to identify the basic constituents of design thinking in a GD process that designers are expected to possess, so they can better operate and apply GD. To that end, we aim to explore and define *Generative Design Thinking (GDT)* in engineering design.

Plattner et al. [5] describe design thinking as a learnable high-order intellectual activity that can also be practiced. This means that design thinking can be taught. Therefore, the identification of the key elements of GDT has a significant implication to engineering design education. However, it is challenging to define GDT because it involves many aspects like GD models, cognitive ability, and engineering design knowledge. In this study, we make the first attempt to define GDT by reviewing the literature of design thinking (DT), engineering systems thinking (EST), and computational thinking (CT), which are believed to be highly related to GDT. In addition, as a computational design method, parametric design (PD) could be a confusing term with GD, so we also want to clarify the differences between PD and GD. PD represents a design using parameters, which allows the creation of different design options by manipulating those parameters and their

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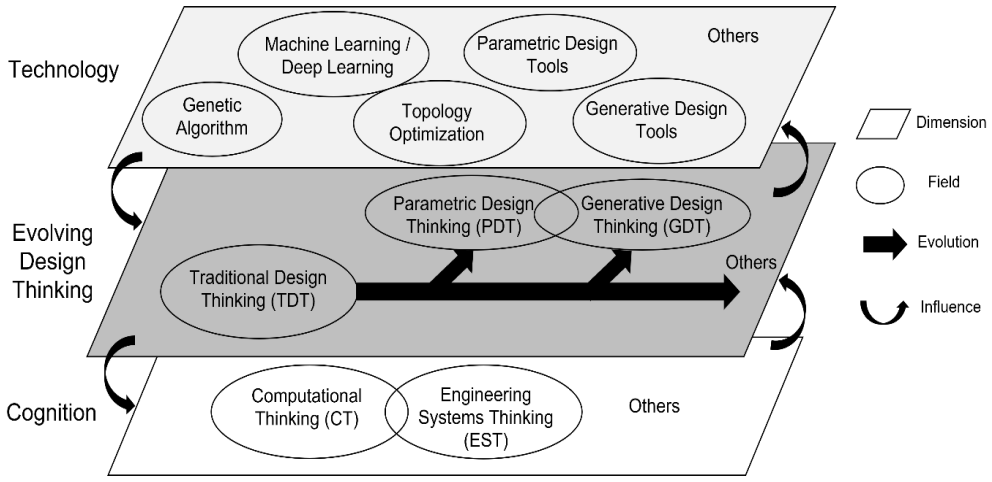

Figure 1: Evolving Design Thinking Model

relationships. PD and GD are different, but PD is orthogonal to GD [6]. Conversely, PD does not necessarily use algorithms to automatically generate design options, even though generative function can be added into PD. On the other hand, GD can use PD for design problems that could be modeled parametrically, but some GD problems could not be done so [6]. Oxman [7] proposed parametric design thinking (PDT) as "a continuity and change within the evolution of design thinking" in the context of architecture design. Similar to PDT, GDT is highly context and tool-based. The inclusive concept model for DT and EST [8] suggests that EST is a necessary skill for DT, which is supported by [8] and [9]. In addition, Lucas et al. [9] claim that CT could also be a new engineering habit of mind envisioning the importance of computation in future design work. However, Shute et al. [10] hold the opinion that CT is an umbrella term that contains DT and ST. There is no agreement for the definition of individual "thinking," let alone their relationships. It is helpful to make those terms and their relationships organized and clearer.

We propose *Evolving Design Thinking (EDT)* as a new representation for traditional design thinking (TDT) that researchers have studied as "*Design Thinking*." DT is expanding and evolving with the development of technology as well as the understanding of designers' cognitive competencies, which is shown by the proposed *Evolving Design Thinking Model* in Figure 1. There are three dimensions: technology (like different design methods and design tools), evolving design thinking, and human cognitive competencies (e.g., CT and EST). EDT is in the middle, which receives influence from and in turn influences the development of technology and the study of human cognition. As previously discussed, PDT is an evolution of the TDT, which is much influenced by the development of digital design tools and technology. GDT should overlap with PDT, but they are also different in terms of cognitive constructs and technology. Research has been conducted to understand the relationships between DT and human cognitive competencies to better understand designers and aid them for better design. However, for generative design, the literature has been primarily focused on developing efficient and effective design methods and tools. To our best knowledge, little research is conducted on understanding the essential cognitive constructs and competencies that form generative design thinking. For example, CT may not be considered important for TDT, but it is indispensable to generative designers because they need to think about how a design problem can be encoded to computer language and solved by algorithms. We believe that a good generative designer should not only grasp design technology and techniques but also have certain cognitive competencies, both of which contribute to the formation of GDT. The

proposed model is not meant to be comprehensive but to serve as a starting point for future research on the exploration of GDT.

In this study, we initialize the first step to explore generative design thinking (GDT) by exploring the literature of different cognitive "thinking" and represent its relationship with design technology. We will continue improving the EDT model and exploring the competencies and psychological constructs for GDT. The understanding of GDT could guide the design of GD curriculums to facilitate the engineering education in schools and universities and professional training of GD in the industry to cultivate successful generative designers. For example, based on the understanding of the core cognitive competencies and required design technology for GDT, we can design a curriculum to include corresponding design tasks to train engineering learners to better acquire that design knowledge and competencies. The *Evolving Design Thinking (EDT*) *Model* can also foster the understanding of the ever-evolving design thinking by considering its relationships with technology and human cognition.

Acknowledgment

The authors would like to gratefully acknowledge the financial support from the U.S. National Science Foundation (NSF) via grants #1918847. Any opinions, findings, and conclusions expressed in this publication or presentation are those of the authors and do not necessarily reflect the view of the NSF.

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