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BOARD # 263: IUSE: Research on Generative Design Thinking: Design Cognition, Tools, andEducation

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Introduction and Motivation

A paradigm shift has occurred in engineering design which drastically changes the role of the human designer by adding generative artificial intelligence (AI) algorithms (e.g., genetic algorithms, variational autoencoders, generative adversarial networks, large language models) to the Traditional Design (TD) process [1] – [3]. A key feature of design problems is that the variables and constraints of the design space are initially unknown to the designer, i.e., these problems are "ill-defined" [4]. Thus, one of the central roles of the designer in TD is to co-evolve both the design space and the objective space by iteratively generating new design artifacts by arranging different combinations of variable parameters and testing their performance [5]. This is what we term *Forward Design*, which occurs when a (team of) human(s) leads the design process and objective-design space co-evolution by manually generating design artifacts in the design space and subsequently evaluating them in the objective space. However, design featuring generative AI-based tools, i.e., Generative Design (GD), requires the human designer to take an inverse approach to co-evolving the design and objective spaces. GD tools prompt the designer to begin by computationally defining the objective space through the variables to use during generation, material, and manufacturing constraints to consider or avoid, and one or more goals to optimize towards. An AI agent will reference these inputs as it exploits the design space by considering all solutions feasible to the given goal(s) and presenting the human designer with optimal designs for selection and/or further iteration. Thus, GD differs from TD by prompting the designer to employ *Backward Design* when generating solutions.

Design is a cognitive activity which occurs within the mind of the designer(s) [6]. The terms *design thinking* and *design cognition* have been used (with some overlap) to study (respectively) the high-level cognitive approach taken by designers or the low-level cognitive processes, personality traits, and experiences that are relevant to design [7]. However, design's inherent reliance on tools to physically/digitally manifest artifacts means that *design thinking* must be considered in relation to the paradigm (e.g., TD or GD), which differ in the types of tools (e.g., sketching, genetic algorithms) and methodologies (*Forward* vs. *Backward Design*) being used. The knowledge accumulated from researchers studying *design thinking* in TD falls under what we call *Traditional Design Thinking*. However, the recent proliferation of GD throughout engineering opens the need to study *Generative Design Thinking*: how human designers mentally approach the design process using GD tools and methodologies. Additionally, the importance of GD to future industry practices is not yet reflected in the curricula being taught to the next generation of engineers. Thus, the motivation of our multi-institutional project is to define and disseminate *Generative Design Thinking* in three research gaps: design thinking and design cognition to explore high/low-level cognitive behavior during GD, design education to create and test materials to teach GD, and developing GD tools and methods.

Design Thinking and Design Cognition

The first areas that our research addresses are to explore *design thinking* and *design cognition* relevant to GD. First, we devise and present the Paradigmatic Design Thinking Model which novelly defines design thinking as being situated within three factors, each with a bidirectional relationship with the other two: 1) **Design Cognition** (low-level cognitive behaviors and previous experiences relevant to design), and the Paradigm, which consists of 2) **Design Tools** (used to create an artifact), and 3) the **Design Methodology** (i.e., the role of the designer during design-objective space co-evolution). We identify three paradigms (Traditional Design, Parametric Design, and Generative Design) and describe how these factors interact within each paradigm to present a nuanced definition of the type of paradigm-specific (i.e., paradigmatic) *design thinking* required for different tools and methodologies for design. To do this, we are systematically reviewing literature using the terms *design thinking* and *design cognition* within the contexts of TD and PD. We will leverage the insights on how previous paradigms influence *design thinking* while considering GD tools/methodologies to define *Generative Design Thinking*. In our early findings [8], we have compared analogies as a mental heuristic/strategy for creative idea generation in human-driven TD vs. AI-driven GD. Analogies may be used by designers to re-frame the variables of an initial problem representation by *mapping* (i.e., overlaying) the characteristics of a different concept (typically, a previously flawed but subsequently fixed problem representation) [9]. A designer in TD would use analogies to re-frame the lower-level variables to create a new artifact in the Design Space to be tested in the Objective Space. However, analogies in GD require the human designer to take a higher-level approach and computationally represent the analogy rules for an AI agent to optimize within.

Design Education

Second, our work addresses research gaps in design education. We have developed and tested two sets of curriculum materials in different CAD platforms (Aladdin and Fusion360) to address the lack of educational materials which teach GD. The text-based curriculum accompanied by CAD activities in Aladdin [10] (see Design Tools and Methods section) is divided into three chapters based on three major design paradigms: Traditional Design, Parametric Design, and Generative Design [11]. Students learn key concepts of each paradigm's approach to the design process and gain first-hand experience through project-based learning modules in pre-set CAD models. Each chapter is divided into four identical subsections which represent a simplified design process: *Problem Definition*, *Exploration*, *Evaluation*, and *Iteration*. The end of each chapter contains an identical open-ended design problem which prompts students to generate multiple CAD solutions for a multi-objective design statement using the tools and methodologies of the chapter's paradigm. Additionally, a Teacher's Handbook divides the curriculum across five learning goals and provides the following for each: a PowerPoint slide deck to aid in teaching the concepts from each section, a pre-recorded video lecture for the slides, and an ungraded, short quiz. Our intention for repeating the chapter structures and the open-ended problem was to highlight the major differences between each paradigm, e.g., the direction that the designer takes during *Exploration*: either moving *Forward* from the Design Space to the Objective Space (in TD and PD), or *Backward* from the Objective Space to the Design Space (in GD).

We have run several rounds of human-subjects data collection with participants completing our materials to aid in curriculum development and to check if students learn the concepts we intend to teach. During the pilot study conducted to check if students understood the curriculum, we utilized the think-aloud protocol to explore student's thoughts while completing the materials. We compared their responses and design behaviors collected from the CAD platform between each paradigm to investigate differences in design thinking in TD, PD and GD. In short, results suggested that student approaches to GD were influenced by their experiences in TD and PD [12]. We are currently conducting another round of data collection as we disseminate these materials both at the institutions of the PI/Co-PI's and at collaborative institutions.

Additionally, our team has developed educational modules to teach GD in Fusion360 and implemented these into existing design courses. We recently conducted a study to explore differences in the quality of CAD artifacts designed using Fusion360's generative AI-based features compared to those designed by human designers leading ideation [13]. Twenty students each designed two objects (suspension and excavator) in CAD using TD for one and GD for the other. Results found a significant difference in the quality of designs in which those generated by AI shower higher on average quality than those designed via a human-driven process.

Design Tools and Methods

Finally, our work addresses research gaps in creating tools and methods for GD educators and practitioners. First, project collaborators at the Institute for Future Intelligence developed and support Aladdin, an open-source CAD/CAE platform with TD/PD/GD features for designing, simulating, and evaluating the efficiency of solar energy structures (e.g., buildings, solar farms) [10]. Aladdin enables researchers and educators to develop experimental tasks and project-based learning modules for participants and students to complete. It allows nuanced analysis of designer behaviors via collecting a fine-grained sequential log of each user action. Second, we have developed data-driven methods for GD using multimodal (e.g., inputting text and images) large language models (LLMs) to generate 3D CAD models based on user inputs [2], [14].

Specifically in [2], we compared the efficacy of two LLMs (GPT-4 and GPT-4V), the latter with four different input modes: text-only, text with sketch, text with image, and a mix of text, sketch, and image. Both models showed high potential with only zero-shot learning; specifically, GTP-4V with text-only input outperformed the other models in some cases, but multimodal inputs showed higher importance when generating geometries of higher complexity. In a later study [15], we developed fine-tuned models based on GPT-3.5 for CAD generation tasks and open-sourced our dataset and experiments for broader dissemination.

Broader Impacts

Two major steps towards creating broader impacts include a workshop and collaboration with additional institutions to conduct educational research and implement the developed curriculum materials. First, we teamed with industry partners PTC Inc. to organize and host the Generative Design in Engineering Research and Education Workshop at the company headquarters in Boston, MA [16]. Workshop goals were to: 1) discuss methods for teaching GD, 2) exchange ideas on GD curriculum development, and 3) boost collaboration between academia and industry. Attendees listened to presentations on the topics of generative design thinking and ethics in generative design and participated in two roundtable discussion sessions related to curriculum implementation and design education research. Second, we are collaborating with several institutions (Utah Tech University, Lehigh University, Carnegie Mellon University, Texas A&M University, and Hawaii Kapiolani Community College) to disseminate and collect data from students completing our curriculum materials and to initiate new methods of teaching GDT.

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