Educating Designers For Generative Engineering (EDGE)

Executive Report

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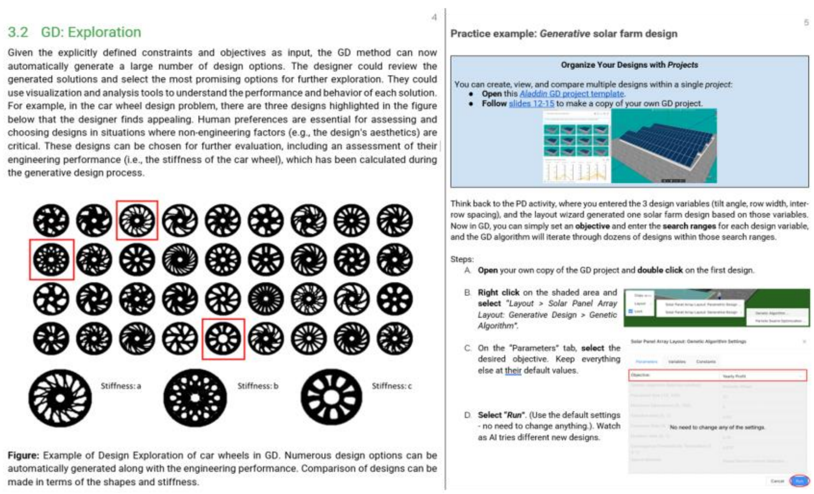
Executive Summary

The goals of this project are to define, implement, and disseminate generative design thinking to facilitate the teaching and learning of generative design at undergraduate levels. Our major activities in Year 4 were influenced by the key suggestions from the Year 3 Advisory Board meeting. These activities included:

First, we **created design curriculum materials** and refined the design challenge in Aladdin to support **data collection and evaluation of the curriculum**. We progressed from using a single design challenge as both the learning activity and the assessment instrument to using a dedicated curriculum as the learning activity and using the design challenge solely as the assessment instrument. To this end, we developed an engineering design curriculum to teach the evolution of design paradigms from traditional design to parametric design and finally generative design. We revised the previous design challenge so that it served as a measurement of students' learning outcomes after going through the design curriculum. We conducted think-aloud sessions as students read the curriculum and completed the activities to collect data on the efficacy and student opinions of the curriculum. By collecting data on student thought processes in the curriculum and in the open-ended design challenge, we can compare these two processes to understand how the curriculum translates to open-ended problems. We can also compare thought processes between each design thinking procedure to generate qualitative insights on the differences between traditional, parametric, and generative design thinking.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3.2 GD: Exploration

Given the explicitly defined constraints and objectives as input, the GD method can now automatically generate a large number of design options. The designer could review the generated solutions and select the most promising options for further exploration. They could use visualization and analysis tools to understand the performance and behavior of each solution. For example, in the car wheel design problem, there are three designs highlighted in the figure below that the designer finds appealing. Human preferences are essential for assessing and choosing designs in situations where non-engineering factors (e.g., the design's aesthetics) are critical. These designs can be chosen for further evaluation, including an assessment of their engineering performance (i.e., the stiffness of the car wheel), which has been calculated during the generative design process.

Stiffness: a

Stiffness: b

Stiffness: c

Figure: Example of Design Exploration of car wheels in GD. Numerous design options can be automatically generated along with the engineering performance. Comparison of designs can be made in terms of the shapes and stiffness.

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Practice example: *Generative* solar farm design

Organize Your Designs with *Projects*

You can create, view, and compare multiple designs within a single *project*:
- **Open** this Aladdin GD project template.
- **Follow** slides 12-15 to make a copy of your own GD project.

Think back to the PD activity, where you entered the 3 design variables (tilt angle, row width, inter-row spacing), and the layout wizard generated one solar farm design based on those variables. Now in GD, you can simply set an **objective** and enter the **search ranges** for each design variable, and the GD algorithm will iterate through dozens of designs within those search ranges.

Steps:

A. **Open** your own copy of the GD project and **double click** on the first design.

B. **Right click** on the shaded area and **select** *"Layout > Solar Panel Array Layout: Generative Design > Genetic Algorithm"*.

C. On the "Parameters" tab, **select** the desired objective. Keep everything else at their default values.

D. **Select "*Run*"**. (Use the default settings - no need to change anything.). Watch as AI tries different new designs.

No need to change any of the settings.

Figure 1: An example of a section and practice activity from the Generative Design chapter of the design curriculum developed in Year 4.

Second, we conducted collaborative research to develop a Human-Centered Generative Design Framework for injecting human factors into GD, and **continued data collection** on students' learning in Fusion360 GD modules. In Year 4, we published a key journal paper that demonstrates our collaborative research efforts in formulating a human-centered generative design framework that injects human factors early in the design for rapid-and-approximate concept creation and evaluation. In this paper, we disseminated three case studies overviewing our ongoing multidisciplinary efforts. Strategies from a computational design perspective, such as data-driven generative design, digital human modeling, and mixed-reality validation, are discussed as alternative approaches that could be implemented to augment designers.

In Years 1 and 2, we started the exploration of integrating generative design technologies in existing design courses and developed GD course modules for students to practice generative design (GD) technologies and learn GD thinking. In Year 3, effort was continued by further refining the course modules, and the homework and project assignments. In Year 4, we continued using the generative design modules and so far, there are more than 650 students who have completed the generative design modules through their undergraduate courses (Engineering Design Graphics).

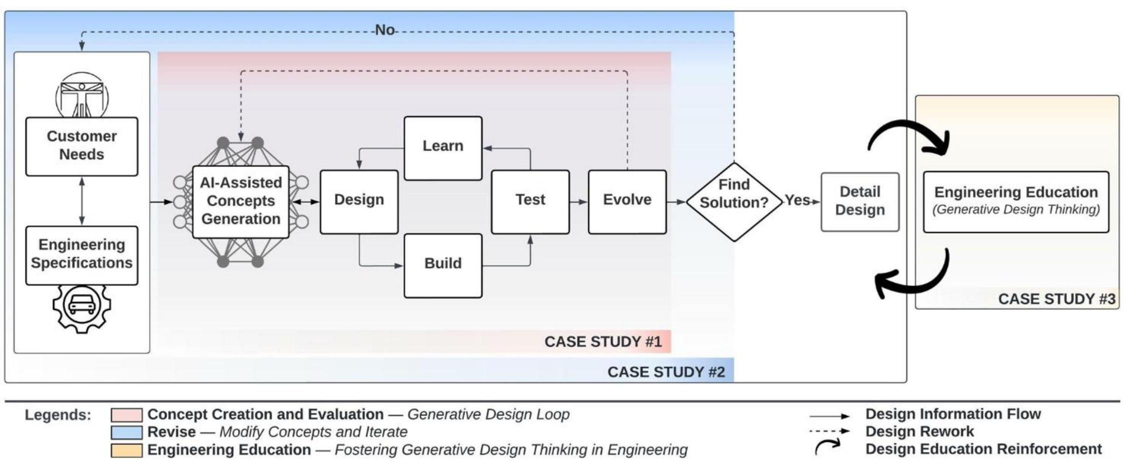

Figure 2: Illustration of the conceptual GD-based human-centered design framework.

Third, we developed a new approach for identifying appropriate vectorized design representation to support rapid engineering performance evaluation for structure-aware generative design. This technique can **support GD software development** and **enable fast computer-aided engineering analysis** in supporting GD concepts comparison and selection. To support the development of generative design for Aladdin, in Year 4 we conducted a systematic review of deep learning methods for cross-modal tasks (DLCMT) to have a better understanding of the current development of data-driven generative design methods that involve multiple design modalities. The DLCMT methods have the potential to improve engineering design education and democratize product development by allowing intuitive inputs such as text descriptions. In Year 4, this review work was published by Journal of Mechanical Design. Furthermore, we investigated data-driven evaluation methods for structure-aware generative design. This involved addressing a previously unexplored research question: How can we identify the suitable vectorized design representation for evaluating 3D shapes produced through structure-aware generative design? This work has been published in the Design Science journal.

Fourth, we refined the Evolving Design Thinking (EDT) model and **planned a systematic review** of the concepts with the goal of **synthesizing a comprehensive definition of generative design thinking**. Additionally, **collected data on student generative design reasoning** via divergent and convergent thinking. We built upon and refined our approach to defining GDT by conducting a literature review of the topics referenced in the updated Evolving Design Thinking (EDT) model from Year 3, specifically those related to the design thinking and design cognition layers of the model. We are currently conducting a systematic review of the Design Technology and Design Thinking layers from the EDT model, specifically the technologies and cognitive processes used in traditional and parametric design. After highlighting how design technologies shape design cognition in these paradigms, we will leverage these insights to show how GDT may be influenced by GD technologies.

We also completed a study to advance our understanding of the relationship between aspects of generative design thinking and traditional thinking, namely students' generative design reasoning through their divergent and convergent thinking. This study, originally developed and conducted as a Master's Thesis, was submitted to the Journal of Mechanical Design, and our revision of the work is currently in review.

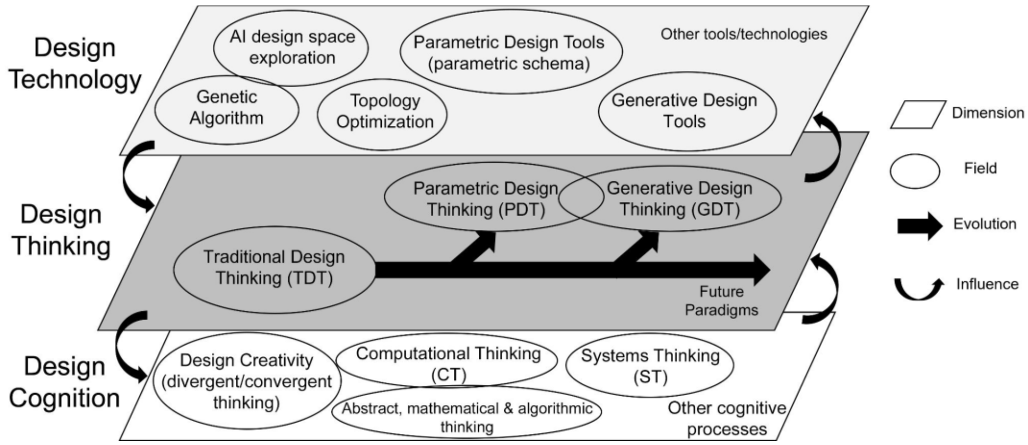

Figure 3: The updated Evolving Design Thinking (EDT) model.

Lastly, we **updated** the cloud-based, open-source **Aladdin with generative design capabilities** and the ability to analyze a curated set of alternative designs. In Year 4, IFI continued to develop the generative design capabilities of the cloud-based, open-source Aladdin CAD/CAE software. It now features a new solution space explorer that allows the user to curate a number of alternative designs and analyze them as a whole with interactive visual analytics, including finding the designs on the Pareto front. You can access Aladdin through this link: https://intofuture.org/aladdin.html. **Figure 4** shows the scalarization method for solving multi-objective optimization within generative design. It reformulates the multi-objective optimization problem into a single-objective optimization problem such that the optimal solutions to the latter correspond to the Pareto optimal solutions to the former.

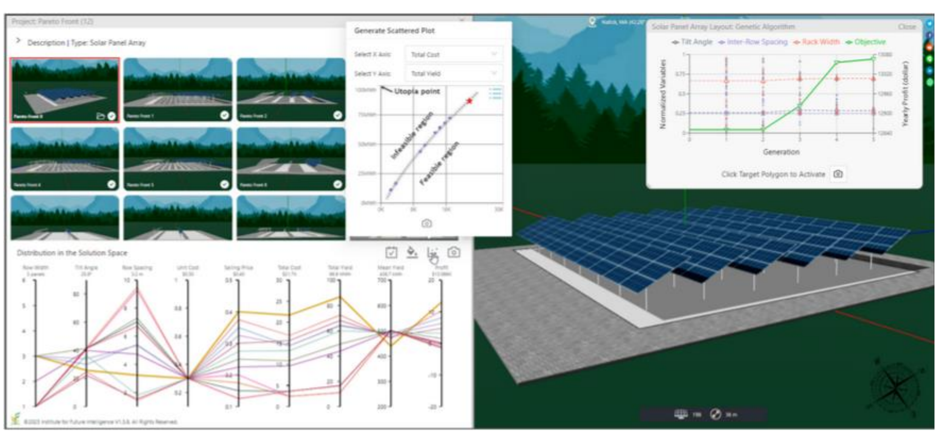

Figure 4. The Pareto front generated using the scalarization method in Aladdin.

Lastly, we broadened the dissemination of the products, including a human-centered generative design framework and updates to our open-source software, Aladdin, and continued journal publications and conference paper and poster presentations. We have shared the outcomes of our project, including an operational definition of generative design thinking, the updated Aladdin software, the Fusion360 instructional modules, and the collaboration driven human-centered generative design framework, through various channels, including online education division, partner websites, conference presentations, and journal publications. One of the Co-PIs participated in the 2023 ASEE NSF Grantees Poster Session and received community feedback. In addition, we published one journal review paper focusing on the methods for deep learning of cross-modal tasks (DLCMT). See the **Products** section on pages 14-15 for more details on the publications that have resulted from this project.

Overall, our research has four broad impacts. First, the **generative design curriculum developed by the team** has already generated an impact on engineering education despite being in the pilot study phase. For example, it has been tested in two mechanical engineering core courses at UT Austin: 1) Engineering Design Graphics, and 2) Mechanical Design Methodology. Following the pilot study and refinement to the curriculum, **we expect to disseminate the materials to a broader community**, which will impact an increasing number of engineering students and teachers in colleges, K-12 STEM education, and more.

Second, we **developed a structure-aware generative design module that can generate various new 3D shapes** taking into account the interconnections between parts. Based on the integrated framework combining structure-aware DDGD for design generation and surrogate modeling for design evaluation, we tested different types of vectorized design representations. We observed that latent vectors directly from the structure-aware generative design module achieved the worst prediction accuracy regardless of the design cases and AutoML frameworks used. **This work can have a broader impact on industry professionals** because the use of appropriate VDR can lead to the improved predictive performance of design automation tools. A better prediction of engineering performance will also help designers make informed decisions in the early design stage when interacting with AI, facing a large number of design alternatives generated, thus potentially shortening the overall design cycle and reducing the development time. On the other hand, **we initiated a sub research topic on "data-driven image-to-CAD sequence"** while we were investigating generative design technologies. The proposed approach holds significant potential to bring about transformative changes in existing CAD systems, revolutionizing the product development cycle. Moreover, it has the capacity to democratize the CAD model reconstruction process, allowing individuals with limited experience or expertise to actively participate. By removing barriers, it can also facilitate customer engagement in design activities, promoting the democratization of design.

Third, the **systematic literature review** being based on the EDT model will **contribute to defining generative design thinking** via the cognitive processes activated during generative design tasks. There are no standard GD curricula in US undergraduate engineering programs, and educators lack knowledge on the cognition underlying GD tasks due to a lack of research. Studying which cognitive processes carry out GD (e.g., creative cognition, computational thinking, and systems thinking) and the role of each process will benefit engineering education via guiding curriculum development and professional training for future engineers using GD technologies. Additionally, identifying GD-relevant cognitive processes may benefit human-AI collaboration efficacy by laying the foundation for analyzing how individual differences in GDT influence human-AI relationship. Lastly, by reviewing psychological and neuroscientific literature our work will allow engineering researchers and educators to leverage psychometric methods to measure and facilitate the GD-relevant cognitive processes.

Lastly, the development of the cloud-based Aladdin has demonstrated how **Aladdin is enabling engineering design of renewable energy solutions for everyone** in the browser. The development of Aladdin software also has the potential to generate a profound impact on the domain of design thinking study because it will support the collection of standard and quality design behavioral data. Given the rising demand for engineers in the field of renewable energy, Aladdin is poised to generate broader impacts in the years to come.