Educating Designers For Generative Engineering (EDGE)

2024 Executive Summary

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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 hosted the Generative Design in Engineering Research and Education Workshop with industry collaborators PTC Inc. at their headquarters in Boston, MA in May. Seventeen in-person attendees met with three workshop goals: (1) discuss best practices in teaching generative design and generative AI in engineering; (2) exchange ideas on the development of curriculum for teaching generative design; (3) promote collaboration between partners in industry and academia for generative design research and education in engineering. An Industrial Session featured a hands-on demonstration of the in-development GD software Onshape from PTC, and a showcase of Aladdin, a major contribution of the EDGE project. Presentations from attendees were related to generative design thinking and ethical industrial applications of generative design, and followed by two roundtable discussion sessions on 1) best practices for implementing engineering education curriculum modules and 2) research in engineering and engineering design education. See here for a formal summary of the workshop.

Figure 1: The Generative Design in Engineering Research and Education Workshop attendees at PTC Inc.'s headquarters in Boston, MA, May 25th, 2024.

Second, we have shared the outcomes of our project, including: the updated Aladdin software, a generative design curriculum with Aladdin design challenges, Fusion360 instructional modules developed in Year 5 and modules from previous years, engineering education research based on these curriculum materials, exploration of multimodal LLMs for 3D CAD generation, and an operational definition of generative design thinking, through major technical and educational conferences and peer-reviewed journals. Publications included “A Study on Generative Design Reasoning and Students' Divergent and Convergent Thinking," published in the flagship Journal of Mechanical Design. We also participated in the 2024 ASEE NSF Grantees Poster session to receive community feedback and display project work at one of the leading engineering education conferences. See the **Products** section on pages 16-17 for more details on the publications that have resulted from this project.

Third, we continued the **development and refinement of curriculum materials** in Aladdin and Fusion360 to teach generative design and related concepts, and conducted **human-subjects data collection** to test curriculum materials and explore generative design thinking. In Aladdin, last year we developed an engineering design curriculum to teach generative design and fundamental engineering design concepts via a text-based curriculum accompanied by CAD practice activities in Aladdin. This year we completed two pilot studies by conducting think-aloud sessions from students reading the curriculum and completing the activities. The results of the pilot studies were used to guide further refinements to the curriculum in which we added text to explain basic engineering design concepts to increase accessibility to a wider range of students, and developed auxiliary teaching documents to aid the dissemination and implementation of the curriculum. A new “Teacher's Handbook” divides the curriculum into five separate Learning Goals, each of which is accompanied by a PowerPoint slideshow curated to teach the concepts in a classroom setting, and a Glossary and Index for each major concept in the curriculum. Finally, we have developed pre-recorded lectures for each Learning Goal and are implementing these materials on our website to aid collaborative educational research.

In Fusion360, in the previous years we have worked to integrate generative design technologies into existing design courses via the development of course modules to teach GD. We have continued to use these GD modules in Year 5, and nearly 1,000 students have completed the Fusion360 modules in an undergraduate course at UIUC (Engineering Design Graphics). A new study was also conducted to explore the difference in the quality of designs generated via Fusion360’s generative capabilities vs. those designed with a traditional, human-driven approach. Twenty student designers were prompted to use

CAD to design two objects (suspension and excavator) using traditional design for one and generative design for the other (order was randomized; Figure 2). Analysis confirmed the initial hypothesis by uncovering a significant difference in the quality (as judged by a rubric developed by the researchers). Specifically, designs created via generative design showed a significantly higher quality on average than those designed via the traditional, human-driven process. Finally, the paper which explored divergent and convergent thinking during generative design which was submitted to the Journal of Mechanical Design last year was accepted and published in Year 5.

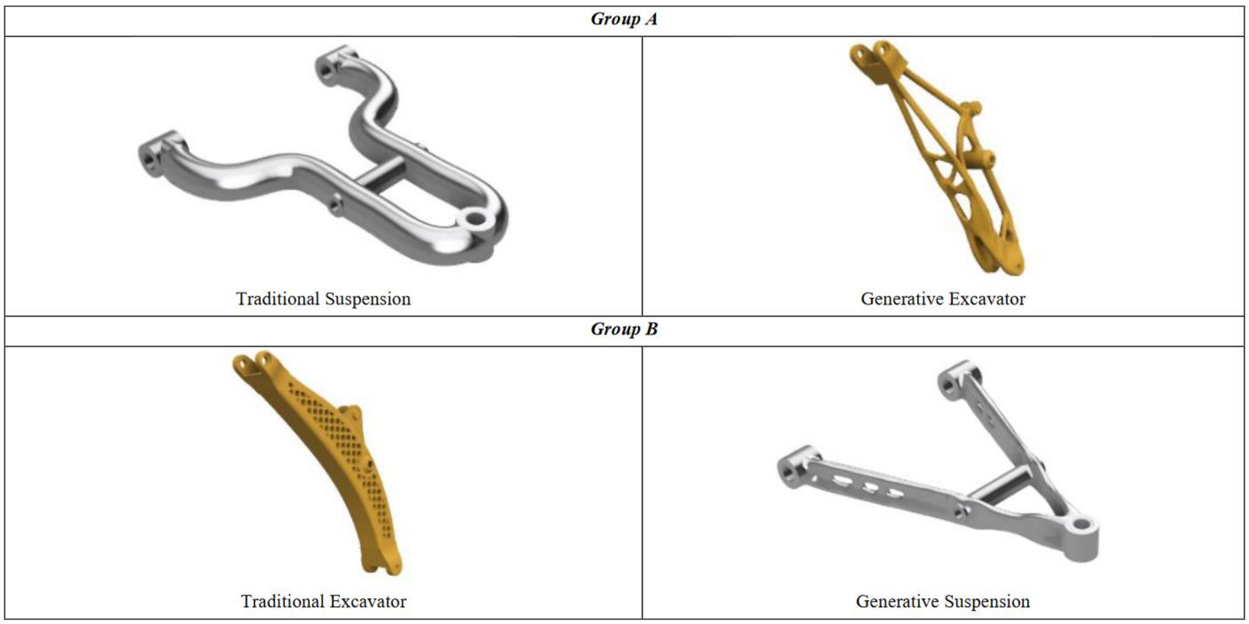

Figure 2: Student designers used Fusion360 to design two objects (suspension and excavator) using either traditional design for one and generative design for the other (order was randomized).

Fourth, IFI has continued to develop the features of the cloud-based, open-source Aladdin CAD/CAE software with generative design capabilities. One new feature is the use of project filters, which allow the user to select a subspace of the solution space to analyze designs within. In the Project's Design Gallery, a filter can be used to select those solutions that fall within certain ranges. Inspired by Autodesk's GD work in urban planning, we are also making cuboids in Aladdin stackable so that we can create city blocks more easily. Compared with buildings with roofs, windows, and walls, cuboids are approximations that may be necessary to speed up rendering and simulations, which is essential in GD considering the bottleneck of computational power.

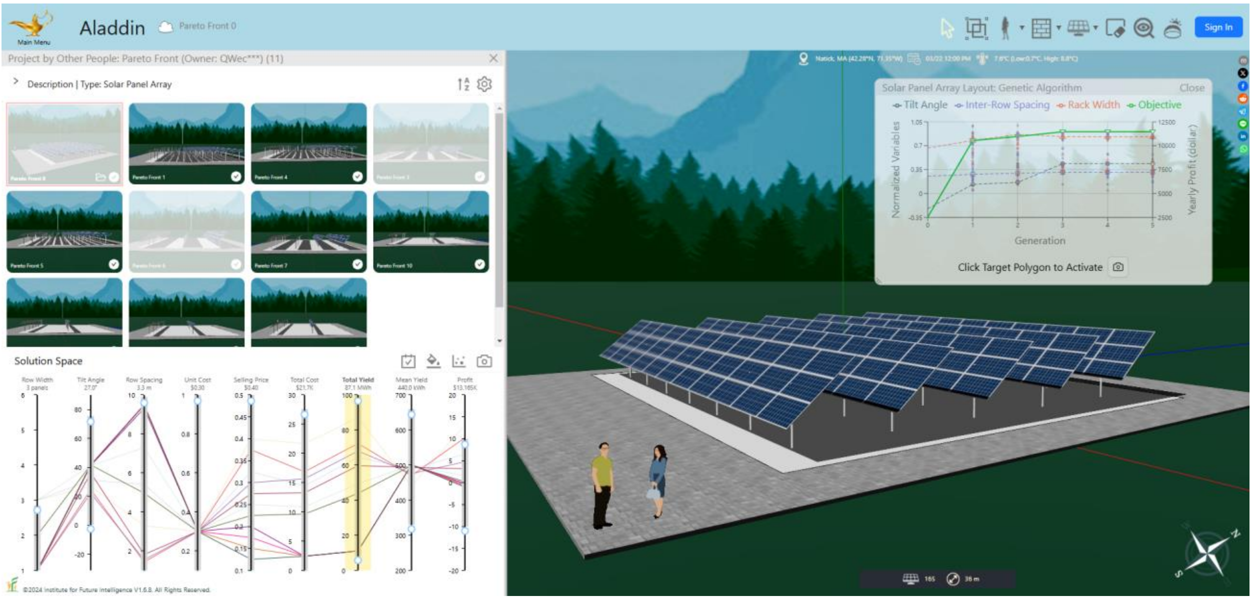

Figure 3: Aladdin's Design Gallery feature which allows users to easily view, open, edit, and compare different models.

Finally, we also continued to explore data-driven generative design towards the generation of 3D CAD models in Year 5 through the use of large language models (LLMs), specifically, multimodal LLMs which can process multiple input modalities, e.g., text and images. To 1) explore how multimodal LLMs generate 3D design objects when employing different design modalities or a combination of various modalities, and 2) explore strategies to to enhance the ability of multimodal LLMs to create 3D design objects, we developed an approach to enable two LLMs (GPT-4 and GPT-4V) to generate 3D CAD models and perform experiments to evaluate their efficacy (Figure 5). GPT-4 and GPT-4V showed significant potential in the generation of 3D CAD models. We also tested four input modes for GPT-4V: text-only, text with sketch, text with image, and a combination of text, sketch, and image. GPT-4V's performance with text-only input surpassed that of the other three multimodal inputs on average, a surprising observation which challenges the common belief in multimodal machine learning that incorporating varied input modalities always improves a machine learning model's predictive accuracy due to increased information for learning and inference. The preliminary results of this study were presented at the ASME 2024 IDETC/CIE Conference. The journal version is currently under review by the Journal of Computing and Information Science in Engineering.

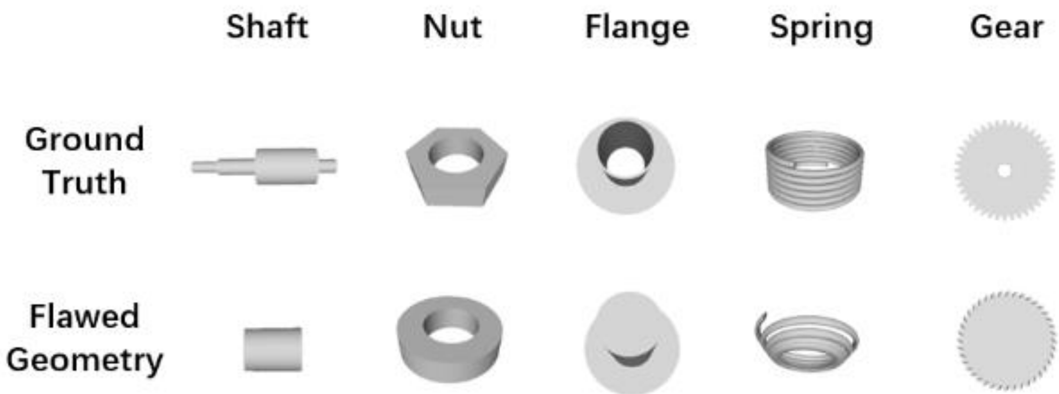

Figure 4: Examples of flawed geometry generated by the GPT-4V model.

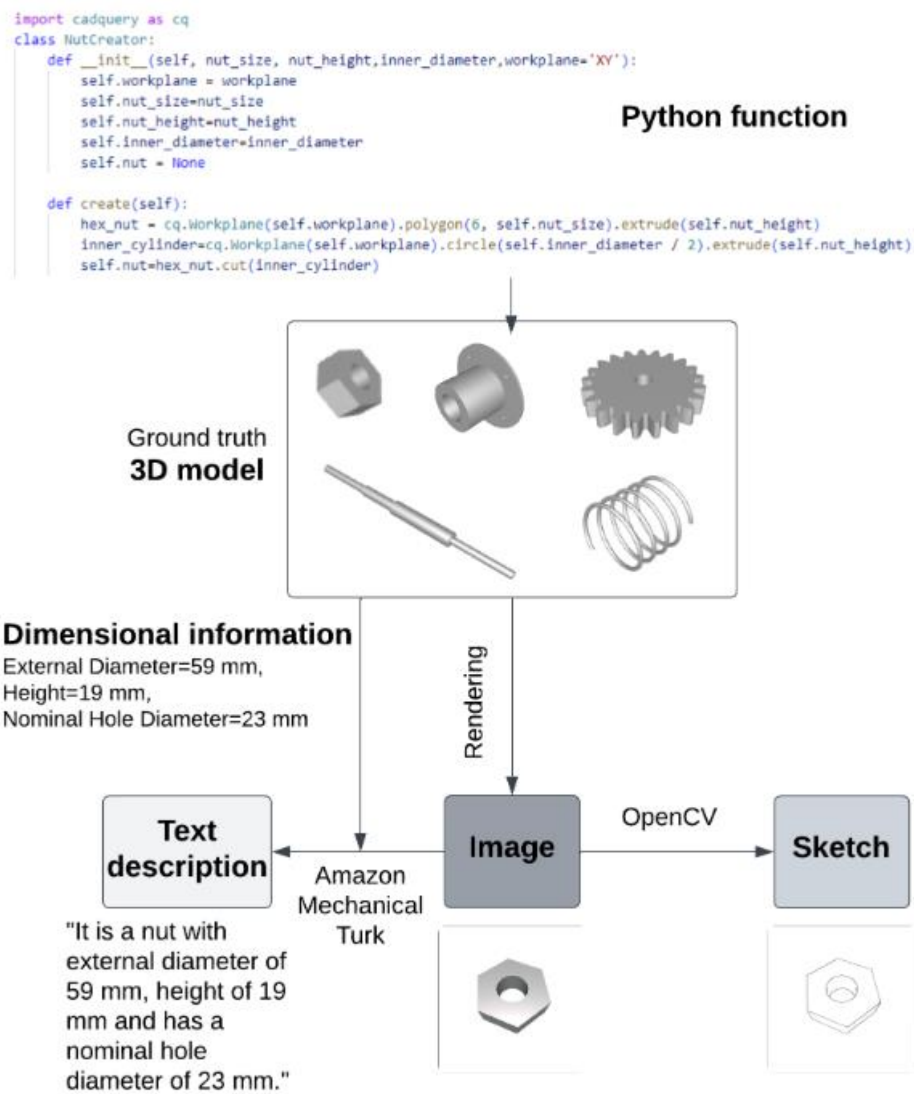

Figure 5: The data synthesis pipeline.

Our work in year 5 has had key impacts in three major areas.

First, we focused significant efforts in Year 5 towards **disseminating project materials and insights** to create broader impacts based on the feedback from the Year 4 Advisory Board meeting and due to being in the later stages of the project. The **Generative Design in Engineering Research and Education Workshop** hosted with industry partners PTC Inc. was the key dissemination activity which allowed us to share our ideas and curriculum materials with a broader audience, and also establish relationships for collaborative educational research.

Second, the **generative design curriculum materials** developed and refined by the team have generated impacts in engineering education research and in classrooms at major universities. Specifically, we have begun **collaboration with local researchers** at UT-Austin **and external researchers** (Lehigh University, Utah Tech University, Hawaii Kapiolani Community College, Texas A&M University, Carnegie Mellon University, and the University of California, Irvine) to implement the Aladdin-based generative design curriculum as modules in their engineering design courses and collect data on generative design thinking from their students. In addition to Aladdin-based educational research, we have continued to develop material and conduct research via the widely-used tool Fusion360. For instance, nearly 1,000 students over the full project have completed the generative design curriculum modules developed in Fusion360, and a new study in Year 5 compared the quality of student designs generated with the help of AI vs. without.

Finally, we **explored multimodal LLMs** (GPT-4 and GPT-4V) **for 3D CAD model generation** using various input modalities (text, sketch, image). The text-only input outperformed multimodal inputs on average, but when examining category-specific results of mechanical components, multimodal inputs start to gain prominence with more complex geometries (e.g., shafts and gears) in terms of the successful parsing rate of the generated CAD programs and the geometric accuracy. From these observations, we see that the current multimodal LLMs are still limited in handling multimodal inputs when applied to LLM4CAD. However, the insights from the category-specific results indicate that multimodal LLMs have great potential benefits in real-world design scenarios characterized by complex objects although it remains challenging for them to generate complex design objects. Improving the capability of these models to process diverse input modalities and proposing strategies to improve their capability to handle complex design objects are promising research avenues.