EDUCATING DESIGNERS FOR GENERATIVE ENGINEERING (EDGE)

2023 Advisory Board Meeting Research Report

Click Here for the NSF Project Page

Prepared by:

Dr. Zhenghui Sha	zsha@austin.utexas.edu
Dr. Darya L. Zabelina	dlzabeli@uark.edu
Dr. Molly H. Goldstein	mhg3@illinois.edu
Dr. Onan Demirel	onan.demirel@oregonstate.edu
Dr. Charles Xie	charles@intofuture.org
Elena Sereiviene	elena@intofuture.org
Xingang Li	xingang.li@utexas.edu
John Z. Clay	jzc298@utexas.edu
Elisa Koolman	hek448@utexas.edu

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Project Overview

Key Personnel - Research Team

Dr. Zhenghui Sha, University of Texas at Austin, Principal Investigator

- Dr. Zhenghui Sha is an Assistant Professor in the Walker Department of Mechanical Engineering at the University of Texas (UT) at Austin. His research focuses on system science and design science as well as the intersection between these two areas, with an emphasis on design theory, human-machine interaction, swarm manufacturing, and complex sociotechnical systems.

Dr. Darya L. Zabelina, University of Arkansas, Co-Principal Investigator

- Dr. Darya L. Zabelina is an Assistant Professor of Psychology at the University of Arkansas. Her research focuses on understanding creative cognition, imagination, and other related processes, and how these processes are linked with more traditional subfields of cognitive psychology, such as attention and executive functions. The long-term objective of Dr. Zabelina's research is to create a theoretical foundation upon which to develop methods to enhance creative thinking and problem-solving abilities.

Dr. Molly H. Goldstein, University of Illinois Urbana-Champaign, Co-Principal Investigator

- Dr. Molly H. Goldstein is a Teaching Assistant Professor in Industrial and Enterprise Systems Engineering at the University of Illinois. Her research focuses on student designer trade-off decisions through the study of their design actions and thinking. Her studies often involve educational and professional contexts with cross-disciplinary collaborations.

Dr. Onan Demirel, Oregon State University, Co-Principal Investigator

- Dr. Onan Demirel is an Assistant Professor of Mechanical Engineering at Oregon State University. His research focuses on understanding human elements in the design process, and developing multi-disciplinary design theory and methods to explore inter-dependencies and co-evolution of the human element in engineering systems. His goal is to develop computational and experimental human-centered design theory and methodology to incorporate human factors engineering principles early in the design for product development.

Dr. Charles Xie, Institute for Future Intelligence, Co-Principal Investigator

- Dr. Charles Xie is the founder, President, CEO, and Chief Scientist of the Institute of Future Intelligence. His current work is focused on evolutionary computation

algorithms that can be used to create artificially intelligent design tutors embedded in CAD and CAE software. He is also the creator of Aladdin, Energy2D, iFlow, Infrared Explorer, and Quantum Explorer, and a co-developer of Infrared Street View and Telelab.

Elena Sereiviene, Institute for Future Intelligence, Director of Outreach and Dissemination

- Elena Sereiviene is the Director of Outreach and Dissemination at the Institute for Future Intelligence. She is responsible for project dissemination, including school implementations of developed materials. Her previous experience includes organizing educational events, and promoting collaboration within multicultural teams to promote social change.

Xingang Li, University of Texas at Austin, Student Researcher

- Xingang Li is a Ph.D student in the System Integration and Design Informatics Laboratory, studying under Dr. Zhenghui Sha. His research focuses on generative design and human-AI design collaboration.

John Z. Clay, University of Texas at Austin, Research Assistant

- John Z. Clay is a post-undergraduate Research Scientist Assistant in the System Integration and Design Informatics Laboratory, working under Dr. Zhenghui Sha. His research focuses on generative design thinking, i.e., the cognitive processes underlying generative design.

Elisa Koolman, University of Texas at Austin, Student Researcher

- Elisa Koolman is a Ph. D. student in the Center for Engineering Education and the System Integration and Design Informatics groups, working under Dr. Maura Borrego and Dr. Zhenghui Sha. Elisa's research focuses on engineering education, specifically student interactions in makerspaces, accessibility in STEM, and student teaching tool efficacy.

Key Personnel - Advisory Board Members

Dan Banach, Autodesk, Inc.

- Dan Banach works at Autodesk, Inc. as a Senior Technical Manager. Mr. Banach is a nationally recognized expert in Mechanical Computer-Aided Design, and has authored 25 books on the Autodesk 3D mechanical design software.

Dr. Lydia Chilton, Columbia University

- Dr. Lydia Chilton is an Assistant Professor of Computer Science at Columbia University. Dr. Chilton's research focuses on human-computer interaction within computational design, with the goal to build AI tools that enhance human productivity.

Dr. Yan Fu, Ford Motor Company

- Dr. Yan Fu is a Senior Manager in Strategy and Enterprise Analytics at Ford Motor Company. Dr. Fu's research is focused on AI and advanced optimization technologies, and her work has resulted in 2 US patents, 4 Ford Trade Secrets, and 1 Defensive Publication.

Dr. John Gero, University of North Carolina at Charlotte

- Dr. John Gero is a Research Professor in Computer Science and Architecture at the University of North Carolina at Charlotte. Dr. Gero's research spans many disciplines, including design science, design computing, AI, computer-aided design, design cognition and design neurocognition. Dr. Gero has authored over 50 books and over 750 papers throughout his career, and is a leading figure in design research.

Susan Shaw, Ford Motor Company

- Susan Shaw is a Customer Research Lead in Advanced Driver-Assistance Systems at Ford Motor Company, and was previously a Senior Engineer at the Hyundia-Kia America Technical Center, Inc. Ms. Shaw's research focuses on human-machine interface and usability of vehicle systems.

Rachel Switzky, University of Illinois Urbana-Champaign

- Rachel Switzky is an Assistant Professor at the University of Illinois Urbana-Champaign. Ms. Switzky's research focuses on human-centered design curriculum and education, and advanced AI and machine learning methods to conduct molecular research.

Goals and Research Questions

Project Goals: To define, implement, and disseminate **generative design thinking** to facilitate the teaching and learning of generative design at undergraduate levels.

- *RQ1.* **Theoretical perspective:** What are the essential elements of generative design thinking that students must acquire in order to work effectively at the human technology frontier in engineering?
- *RQ2.* **Practical perspective:** To what extent and in what ways can the project products support the learning of generative design as indicated by students' gains in generative design thinking?
- *RQ3.* **Affective perspective:** To what extent and in what ways can AI affect the professional formation of engineers as indicated by the changes of students' interest and self-efficacy in engineering?

Work Plan

Define generative design thinking by assimilating computational thinking to augment and reshape design thinking, thereby setting up 1) a theoretical foundation for research, 2) learning goals for students, and 3) the developmental goals for the project.

Develop the open-source Aladdin software with the goal to support the learning and teaching of generative design. The focus is on supporting students as they learn basic concepts of generative design, and allowing researchers to find ways to improve this human-AI collaboration.

Develop curriculum modules in Aladdin using project-based learning. To engage students, we will adopt authentic engineering projects that can be realistically solved using generative design.

Conduct educational research through collaboration with ten other participating colleges and universities. With these collaborators, we will explore the strategies and methods for integrating instructional modules and embedding the educational research into introductory engineering and CAD courses.

Collect and analyze student data using instruments such as demographic surveys, questionnaires, self-efficacy measures, design reports, screencast videos, software logs, classroom observations, and participant interviews.

Disseminate the products of this project, including an operational definition of generative design thinking, the Aladdin software, and the instructional modules.

Collaborate with the Advisory Board to evaluate and advance the project through the evaluation given by the board members.

2022 Advisory Board Meeting Insights and Suggestions

The key suggestions from the Year 3 Advisory Board meeting were that we should focus our Year 4 efforts towards measuring the effect of developed materials on student learning outcomes, and that the PI and Co-PI's should show closer collaboration to achieving the project goals. By considering these suggestions and the research plan outlined in the original proposal, we have conducted the following research activities in Year 4:

- Closely collaborated to develop a design curriculum that teaches traditional, parametric, and generative design. We are collecting student data via a think-aloud protocol to gather preliminary results on the efficacy of these materials and to guide their refinement.
- Closer collaboration with the project members to develop a human-centered GD framework to inject human factors into the AI intensive GD process.

Year 4 Research Activities

1. **Development of curriculum documents** to teach traditional, parametric, and generative design concepts, and refinement of the design challenge-based **human-subject experiment** for the collection of students' learning and design behavioral data using Aladdin.

Based on the feedback from the Year 3 Advisory Board meeting, in Year 4 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 then 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.

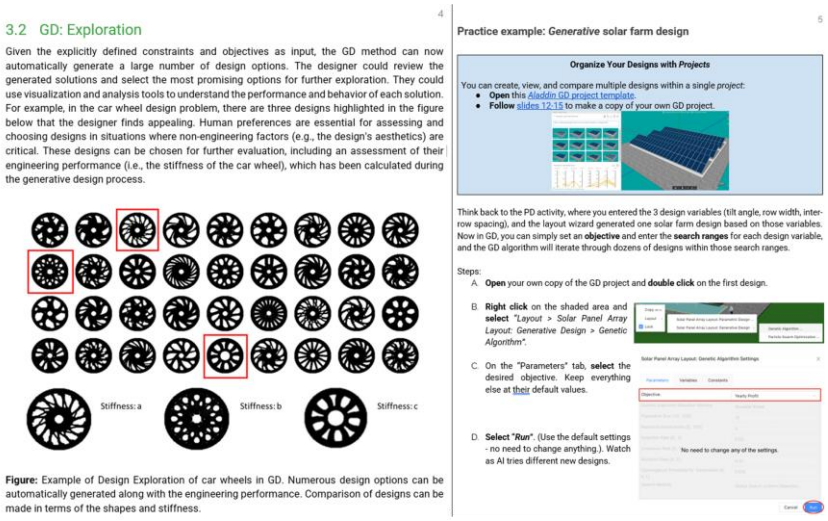

Figure 1: An example of a section and practice activity from the Generative Design chapter of the design curriculum developed in Year 4.

2. **Collaborated** to develop a **Human-Centered Generative Design Framework** to support the role of humans GD**; continued dissemination of generative design education** using the Fusion 360-based generative design lab module and **continued data collection and analysis** of students' learning data using Fusion 360.

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).

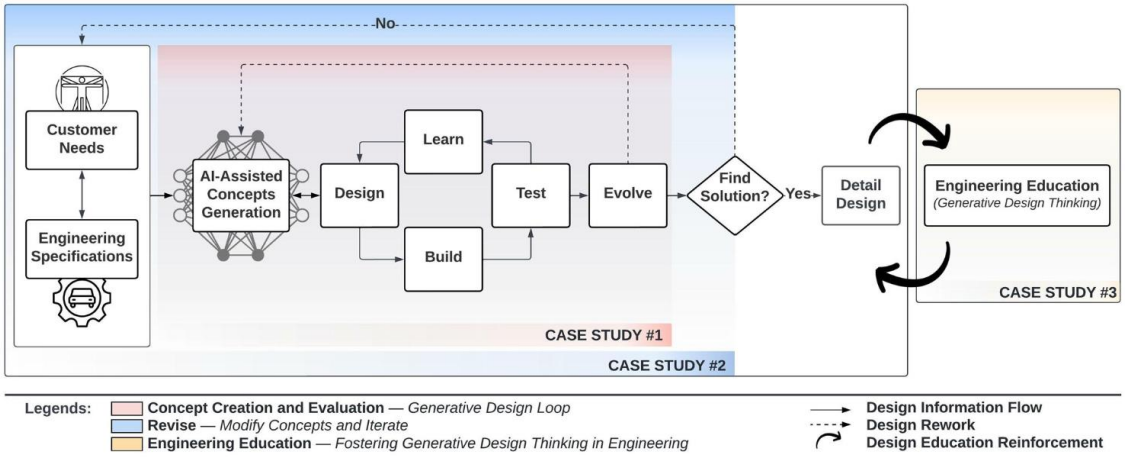

Figure 2: Illustration of the conceptual GD-based human-centered design framework.

3. **Exploration of data-driven methods** for the **realization of generative design** in support of software and tool development.

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.

4. **Seeking an operational definition of generative design thinking** (GDT) through an investigation on the relationship between engineering systems thinking, parametric design thinking, computational thinking, and engineering design thinking; **a study on students' generative design reasoning** and their divergent and convergent thinking.

In Year 4, 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 masters thesis, was submitted to the Journal of Mechanical Design, and our revision of the work is currently in review.

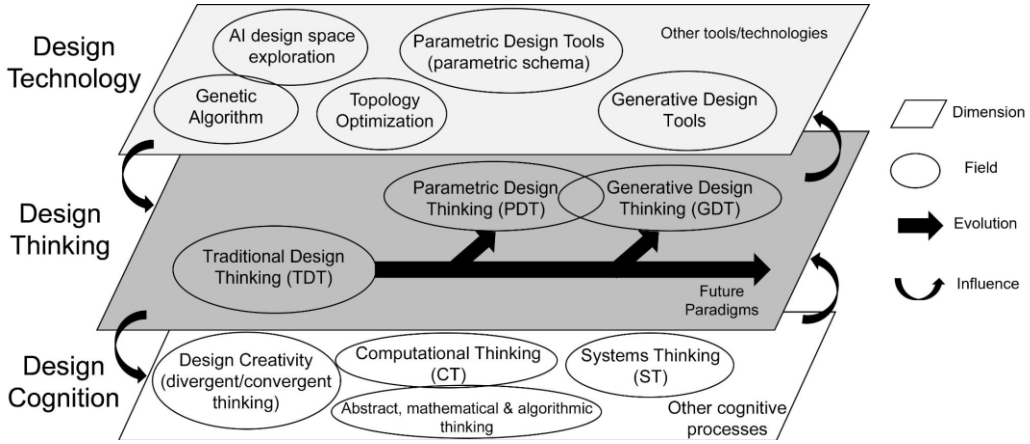

Figure 3: The updated Evolving Design Thinking (EDT) model.

5. **Updates to Aladdin**, an open-source computer-aided generative design and engineering software, with the goal **to support the learning and teaching of generative design**.

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.

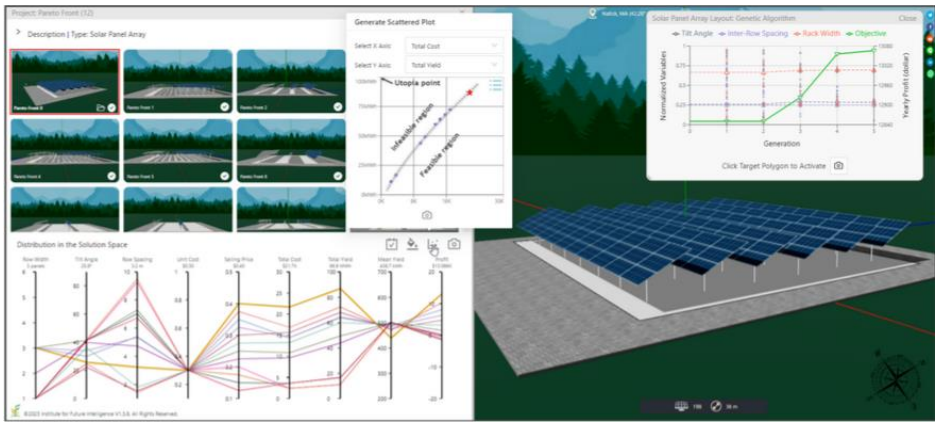

Figure 4. The Pareto front generated using the scalarization method in Aladdin.

6. **Results dissemination** to major technical and educational conferences as well as peer-reviewed journals.

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.

Key Outcomes

Created design curriculum materials and refinement of the design challenge in Aladdin to support **data collection and evaluation of the curriculum**.

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.

Developed a new approach to 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.

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.

Updated the cloud-based, open-source **Aladdin with generative design capabilities** and the ability to analyze a curated set of alternative designs (https://intofuture.org/aladdin.html).

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.

Impact

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.

Future Work

Note: We may refine our Year 5 work plan based on the feedback received from the AB members throughout the November 21st, 2023, meeting.

Software Development: Aladdin

In the next reporting period, we expect to continue to develop Aladdin to provide a research and education platform at the intersection between AI and design. Based on our work to integrate genetic algorithms and particle swarm optimization methods into

the solution space explorer as a generative design implementation for solar farm design in Aladdin, our priority is to advance the parametric and generative design capabilities of Aladdin to other topics while continuing to add more CAD/CAE functionalities (e.g., we start to look into how to incorporate wind energy design)

Approach Development: Data-Driven Generative Design

In Year 5, we plan to continue developing novel data-driven generative design approaches and build a user interface to help students explore the power of AI in generative design and support their learning of GD in conceptual design and creative design. Specifically, we plan to develop new design approaches that can engage humans in the design process to enhance design creativity and human-centered design.

Education Research: Evolving Design Thinking

In Year 5, we will continue investigating RQ1: What are the essential elements of generative design thinking that students must acquire in order to work effectively at the human- technology frontier in engineering? To answer this RQ, we have several activities planned. First, the full-length position paper that was being developed to further define and explore GDT will be expanded to include a systematic literature review of the concepts referenced in the EDT model. Through conducting a systematic literature review we will develop a list of design cognition concepts that define GDT, with an emphasis on how this may be used to benefit education in GD. Additionally, we will continue to use the two developed generative design modules with additional ~200 undergraduate students. Moreover, the UIUC model will be used as the basis for other collaborating institutions, such as Oregon State University, to develop their own instructional modules to support the training of Generative Design Thinking as well as to support the data collection for the proposed education research. Additionally, we will work to develop a generative design content assessment to use as a pre/post-test. This work will be used in our education research.

Research Dissemination and Organizing Workshops

All involved institutions will collaborate with each other to pilot-test the software, modules, and instruments with students at UT Austin, UIUC, and OSU. As the development of the open-source Aladdin software, particularly its GD module, becomes more and more mature, we become more involved with our participating colleges for the dissemination of the software product and instructional materials. In the next year we plan to hold two workshops to disseminate our educational products (i.e., the generative design curriculum) and research outcomes. In the first workshop (planned to be held in May 2024), university and community college instructors will be invited and introduced

to our GD curriculum and the preliminary data collected from the classroom. We hope our introduction and demonstration can help them adopt our products in their classes of engineering design and CAD to better prepare their students for future jobs. Based on the teachers' involvement and feedback in this workshop, we expect to refine the curriculum and course materials that are under development. In the second workshop (planned to be held during the 2024 IDETC/CIE conference), we plan to invite professionals to present current GD technologies from an industrial perspective and our team will present our development of Aladdin and the findings of GD research. We expect this workshop will provide us with new ideas and feedback on how our GD technologies can be further improved.

Year 4 Products

Journal Publications

Demirel, H.O., Goldstein, M., Li, X., and Sha, Z., "Human-Centered Generative Design Framework: An Early Design Framework to Support Concept Creation and Evaluation," International Journal of Human–Computer Interaction, pp: 1-12, 2023.

Li, X., Wang, Y., and Sha, Z., "Deep-Learning Methods of Cross-Modal Tasks for Conceptual Design of Product Shapes: A Review," Journal of Mechanical Design, volume 145, issue 4, pp: 041401 (20).

Xie, C., "Beyond Solar Cookers: Modeling and Designing Concentrated Solar Power as Engineering Projects in Physics Classrooms," Phys. Teach. 1 September 2023; 61 (6): 447–452.

Li, X., Xie, C., and Sha, Z., "Design representation for performance evaluation of 3D shapes in structure-aware generative design," Design Science, 9, E27. doi:10.1017/dsj.2023.25.

Refereed Conference Papers

Li, X., Wang, Y., and Sha, Z., "Deep Learning of Cross-Modal Tasks for Conceptual Design of Engineered Products: A Review." Proceedings of the ASME 2022 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference. Volume 6: 34th International Conference on Design Theory and Methodology (DTM). St. Louis, Missouri, USA. August 14–17, 2022. V006T06A016. ASME.

https://doi.org/10.1115/DETC2022-90696.

Clay, J., Li, X., Demirel, O., Goldstein, M., Jiang, R., Xie, C., Zabelina, D., and Sha, Z., "Thinking Inversely in Engineering Design: Towards an Operational Definition of Generative Design Thinking," The 130th ASEE Annual Conference & Exposition, Baltimore, MD, June 25-28, 2023.

Conference Abstracts and Posters

Sha, Z., Zabelina, D., Goldstein, M., Demirel, O., Xie, C., Clay, J., Li, X., Jiang, R., "Educating Generative Designers in Engineering," NSF Grantees Poster Session, The 130th ASEE Annual Conference & Exposition, Baltimore, MD, June 25-28, 2023.

Thesis/Dissertation

Barnaby-Brown, A., "Understanding the Role of Generative Design in Undergraduate Students' Design Thinking," Masters Thesis (2022). University of Illinois Urbana-Champaign.

Other Products

The cloud-based Aladdin CAD/CAE software. Aladdin is an experimental platform for reimagining design in the coming era of AI in the context of renewable energy engineering. The power of Aladdin derives from two different sources: generative design and machine learning, with attaining explainable AI (XAI) to support human-machine collaborative intelligence as an important goal.

https://intofuture.org/aladdin.html

Design Curriculum: Educating Designers for Generative Engineering. We developed an engineering design curriculum to teach the evolution of design paradigms from traditional design (TD) to parametric design (PD) and finally generative design (GD). The curriculum is split across three chapters, one for each of the three paradigms (TD/PD/GD), and after each chapter the participant is asked to design solutions for an open-ended solar design problem via Aladdin. The design statement is identical for each of the three chapters, and participants are given a rubric in the form of an Objective Space to plot the solutions they design based on their Yearly Profit (y-axis) and Yearly Output (x-axis). Participants (and researchers) can easily evaluate and compare the solutions they designed using each of the paradigms.