Journal of Mechanical Design

# Guest Editorial

## Special Issue: Emerging Technologies and Methods for Early-Stage Product Design and Development

The early-stage product design and development (PDD) process fundamentally involves the processing, synthesis, and communication of a large amount of information to make a series of key decisions on design exploration and specification, concept generation and evaluation, and prototyping. Although most current PDD practices depend heavily on human intuition, advances in computing, communication, and human–computer interaction technologies can transform PDD processes by combining the creativity and ingenuity of human designers with the speed and precision of computers. Emerging technologies like artificial intelligence (AI), cloud computing, and extended reality (XR) stand to substantially change the way designers process information and make decisions in the early stages of PDD by enabling new methods such as natural language processing, generative modeling, cloud-based virtual collaboration, and immersive design and prototyping. These new technologies are unlikely to render the human designer obsolete, but rather do change the role that the human designer plays. Thus, it is essential to understand the designer's role as an individual, a team, and a group that forms an organization. The purpose of this special issue is to synthesize the state-of-the-art research on technologies and methods that augment the performance of designers in the front-end of PDD—from understanding user needs to conceptual design, prototyping, and development of systems architecture while also emphasizing the critical need to understand the designer and their role as well.

The research articles that comprise this special issue focus primarily on three major early-stage PDD activities that new technologies and methods can potentially transform: (1) design problem exploration, (2) design concept generation, and (3) design concept evaluation. Articles in the first collection gravitate toward AI methods that facilitate the elicitation of user needs and product usage context, exploration and identification of design problems, and specification of design guidelines. The second collection of research articles contributes new AI methods that enable the automated generation of novel design concepts in various forms, such as textual descriptions, images, and 3D shapes, along with a thorough analysis of the resulting changes in the designer's role. The third collection of articles investigates new methods based on AI and XR that aim at automating or facilitating design concept evaluation. While these articles break new ground in augmenting the front-end of PDD through new technologies and methods, designers remain the principal actor in this process. It is, therefore, of paramount importance to explore the evolving role of designers in the PDD process and the nature and necessity of their partnership with technology. This special issue also presents research articles that explore biases, beliefs, attitudes, and intentions, as well as the means and method to facilitate the collection, extraction, and organization of their knowledge to support design. The remainder of this Guest Editorial elaborates on the collections of research articles presented in this special issue.

### Design Problem Exploration

The research articles in this collection of early-stage PDD activities focus on various fundamental problems concerning the specification of the design problem to be solved, including design problem identification and definition, elicitation of user needs and product usage contexts, and specification of design objectives and outcomes.

In the article "A Computational Approach to Identifying Engineering Design Problems," Obieke, Milisavljevic-Syed, Silva, and Han present a method based on Markovian models and machine learning to support engineering design problem exploration, a process of identifying or coming up with a new problem or need at the early stage of design. The authors investigate the natural models and phenomena that explain this process, such as rational and garbage can models, and the emerging technologies that can support this process along with the associated challenges. A case study involving 43 international participants from the engineering design communities in academia and industry shows the effectiveness of the proposed method in supporting novice and experienced design engineers in the problem-exploration process.

In the article, "A Hybrid Semantic Networks Construction Framework for Engineering Design," Cheligeer, Yang, Bayatpour, Miklin, Dufresne, Lin, Bhuiyan, and Zeng develop a method based on recursive object modeling, Word2Vec technique, and a domain-specific language model to build semantic networks for a project to design aircraft braking systems. The semantic networks are built on the abstracts of scientific papers retrieved from Semantic Scholar API to address the design problem implied in the seed design statement, following an environment analysis from environment-based design methodology. The semantic network proposed in this article can be used for design information retrieval, computer-aided design idea generation, cross-domain communication support system, and designer training.

The article "Attribute-Sentiment-Guided Summarization of User Opinions from Online Reviews" by Han, Nanda, and Moghaddam presents a novel computational method for abstractive summarization of user opinions from online reviews guided by specific product attributes and sentiment polarities. The article is motivated by the rapid growth of user-generated reviews, the lack of formal mechanisms to guide the generative process with respect to different categories of product attributes and user sentiments, and the lack of annotated training datasets needed for the supervised training of abstractive summarization models. The authors develop a hierarchical multi-instance attribute-sentiment inference model for assembling a high-quality synthetic dataset, which is utilized to fine-tune a pretrained language model (PLM) for an abstractive summary generation. The proposed method is validated through numerical experiments on a large dataset from three major e-Commerce retail stores for apparel and footwear products.



  

The article "Constructing Product Usage Context Knowledge Graph Using User-Generated Content for User-Driven Customization" by Wang, Liu, and Kara proposes a knowledge graph construction method to identify product usage context from user-generated content for user-driven customization. The authors aim to enable a design paradigm where customers act as co-designers to configure products based on their needs while avoiding designing products incompatible with their environment and needs. The proposed method can convert crowdsourced corner cases into structured usage context knowledge graphs to facilitate the personal usage context prediction, summarization, and reasoning by designers.

In the article "Task-Oriented Methodology Combining Human Manual Gestures and Robotic Grasp Stability Analyses: Application to the Specification of Dexterous Robotic Grippers," Escorcia-Hernandez, Grossard, and Gosselin present a task analysis method based on human-centered gestures analysis and object-centered grasp stability analysis to provide guidelines for the design of dexterous robotic grippers. The main design objectives include versatility to perform various tasks, simplicity of manufacturing, and reduced kinematic complexity. The proposed method provides designers with tools that help specify the number of fingers, the number of degrees-of-freedom, and the placement of tactile sensors, along with guidelines for the specification of the actuation system. The authors validate the method by defining technical specifications for designing a multifingered robotic gripper intended to perform the tasks involved in a sterility testing process.

## Design Concept Generation

The first two articles related to design concept generation help frame the role of designers concerning technology and its potential for integration into the process. With advances in AI and other technologies, this collection of articles is centered on integrating technology into the PDD process to augment the designer's ability to generate concepts via methods that might enhance the novelty, quality, and quantity of concepts that express the needs and requirements of a potential solution. A common thread among these articles is the inclusion of data, be it consumer reviews or inspiration from biological systems, which provide a catalyst for including adjacencies into concept development and related activities. The final two articles in this subtopic give examples and demonstrations of novel technology-driven design concept generation methods.

In the article "Generative Design: Reframing the Role of the Designer in Early-Stage Design Process," Saadi and Yang explore how using these generative design tools may impact the design process, designer behavior, and overall outcomes. This qualitative article reports on the results of in-depth interviews with practicing and student designers from different disciplines who use commercial generative design tools, detailing the design processes they followed. This article proposes a provisional process diagram for generative design and its uses in the early-stage design process. The proposed framework and approach can help designers understand when and where new tools, such as generative design, can be best utilized in the early stages of design.

In the article "Deep-Learning Methods of Cross-Modal Tasks for Conceptual Design of Product Shapes: A Review," Li, Wang, and Sha conduct a systematic review of the retrieval, generation, and manipulation methods for deep learning of cross-model tasks (DLCMT) that involve three cross-modal types: text-to-3D shape, text-to-sketch, and sketch-to-3D shape. The review identifies 50 articles from 1341 papers in computer graphics, computer vision, and engineering design. The article reviews the state-of-the-art DLCMT methods that can be applied to product shape design and identifies critical challenges. The authors then discuss potential solutions to these challenges and propose research questions that point to future directions of data-driven conceptual design.

The next two articles provide examples of how technology can augment the designer's role and tasks. In the article "DDE-GAN: Integrating a Data-Driven Design Evaluator Into Generative Adversarial Networks for Desirable and Diverse Concept Generation," Yuan, Marion, and Moghaddam propose and validate a new GAN-based generative design model with an offline design evaluation function to generate samples that are not only realistic but also diverse and desirable. A multimodal data-driven design evaluation (DDE) model is developed to guide the generative process by automatically predicting user sentiments for the generated samples based on large-scale user reviews of previous designs. The proposed method illustrates how technology can be inserted into the design process to automatically assist the designer in integrating and utilizing customer data to improve the generation of new concepts.

In the article, "Biologically Inspired Design Concept Generation Using Generative Pre-Trained Transformers," Zhu, Zhang, and Luo propose a method that integrates bio-inspired design (BID) into the process. This article presents a generative design approach based on the generative PLM to automatically retrieve and map biological analogy and generate BID in the form of natural language. Three design concept generators are identified and fine-tuned from the PLM according to the looseness of the problem space representation. The approach is evaluated and employed in a real-world project of designing light-weighted flying cars during its conceptual design phase. The results illustrate that BID can generate novel designs with good performance.

## Design Concept Evaluation

Historically, the evaluation of design concepts has been a largely manual activity based on input from the design team. While Pugh matrices and quality function deployment integrate customer needs with proposed features and specifications into the decision-making process, these evaluation techniques have historically relied on a limited amount of data and have limitations due to the subjectivity and biases of the evaluators. New technologies can potentially integrate more data into the evaluation and selection process, thereby reducing human-related challenges such as bias and requiring high levels of expertise.

In the article "Attention-Enhanced Multimodal Learning for Conceptual Design Evaluation," Song, Miller, and Ahmed propose an attention-enhanced multimodal learning-based machine learning model to predict five design metrics: drawing quality, uniqueness, elegance, usefulness, and creativity. The proposed model utilizes knowledge from large external datasets through transfer learning, simultaneously processes text and sketch data from early-phase concepts, and effectively fuses the multimodal information through a mutual cross-attention mechanism. The proposed method highlights the potential benefit of using multimodal representations for design metric assessment.

In another article with a similar scope but a significantly different method, entitled "The Influence of Hand Tracking and Haptic Feedback for Virtual Prototype Evaluation in the Product Design Process," Palacios-Ibáñez, Alonso-García, Contero, and Camba report the results of a study where a group of participants evaluated three designs of a product (i.e., umbrella stands) when viewed in a real setting, virtual reality (VR), and VR with passive haptics. Their goal was to observe the influence of visual media in product perception and how the use of a complementary item (i.e., a physical umbrella) for interaction and user design expertise influence product assessment. The article highlights that using VR with passive haptics could be an effective tool for product evaluation, as illustrated by the study of umbrella stands and young consumers.

## The Evolving Role of Designers in Early-Stage Product Design and Development

Despite the potentially transformative role of technology in the front-end of PDD, as described earlier, design is still inherently a human activity that relies heavily on the ingenuity and creativity of designers. To better understand how engineering designers and engineering design technologies can work together and complement each other, it is, therefore, necessary to further explore human designers' unique capabilities and limitations in PDD. The last collection of research articles featured in this special issue is centered on the role of designers in PDD, the impact of human traits such as empathy and bias on design outcomes, and the technologies and methods that can foster innovation in design teams and organizations.

The article "Error Management Bias in Student Design Teams" by Fillingim, Shapiro, and Fu investigates cognitive bias in design teams with consideration for the intent of error management through the lens of adaptive rationality. The results of a survey-based data collection activity conducted in a graduate-level design course indicate five types of bias in design activities, including bandwagon, availability, status quo, ownership, and hindsight biases. The authors draw conclusions on trends and statistical correlations from survey data and course deliverables. This article highlights the most common forms of bias in design teams and provides directions for developing ways to mitigate such biases.

In the article "Not Good Enough? Exploring Relationships Between Novice Designers' Trait Empathy, Their Beliefs, Attitudes, and Intentions Toward Sustainability, and the Self-Evaluated Sustainability of Their Solutions," Prabhu, Alzayed, and Starkey investigate designers' ability to empathize with those affected in a secondary or tertiary capacity and the influence of designers' internal traits, such as beliefs, attitudes, and intentions, on their emphasis on environmental sustainability. Through a human subject experiment involving student designers, the authors compared changes in their trait empathy and their beliefs, attitudes, and intentions toward sustainability before and after a hands-on sustainable design workshop. Results show that participants experienced an increase in their beliefs and intentions toward sustainability and a decrease in personal distress after the workshop. They also reveal that trait empathy significantly predicted the self-evaluated sustainability of solutions on the following dimensions of sustainable design: disposal, recycling, and finding wholesome alternatives. The authors conclude the article by providing future research directions on the influence of designers' differences on their approach to sustainable design.

In the article "Embedding Experiential Design Knowledge in Interactive Knowledge Graphs," Wang, Goridkov, Rao, Cui, Grandi, and Goucher-Lambert study the knowledge organization practices of a group of professional designers as they virtually engage with data collected during a teardown of a consumer product to understand knowledge organization during an experiential activity and how it can be transformed into a scalable representation. The authors develop a searchable knowledge graph to represent experiential knowledge and handle complex queries. Two extended examples are used to validate the knowledge graph and uncover insights and patterns from design knowledge. This article is a preliminary step toward creating design knowledge bases that accurately reflect designer behavior and enable effective data-driven support tools for design.

In the article "Design-as-a-Service Framework for Enabling Innovations in Small- and Medium-Sized Enterprises," Agarwal, Sorathiya, Vaishnav, Desai, and Mears explore the augmentation of the Design-as-a-Service (DaaS) model into the cloud-based design and manufacturing (CBDM), to connect skilled human resources with enterprises interested in transforming an idea into a product or solution. The proposed model presents an approach for integrating human resources with various CBDM elements and end-users through a service-based model. The authors also discuss the challenges associated with implementing the proposed model and provide directions for enterprises and individuals to adopt the model for rapid and economical product discovery.

Lastly, in the article entitled "Prototyping Strategies to Engage Stakeholders During Early Stages of Design: A Study Across Three Design Domains," Rodríguez-Calero, Daly, Burleson, and Sienko aim at identifying patterns in prototyping strategies for engaging stakeholders during the design front-end by conducting semi-structured interviews with a group of design practitioners across three product design domains, including automotive, consumer products, and medical devices. The article is motivated by the lack of studies on prototyping practices that inform problem definition, requirements and specifications development, concept generation, and other front-end design activities. The article reports that the descriptions and examples in the context of prototyping strategies used to engage stakeholders during front-end design can guide the design strategies of both experienced and novice designers.

## Much Is Left to Be Explored

The articles featured in this special issue contribute a wide range of methods enabled by emerging technologies such as AI, cloud computing, and XR to support the front-end of PDD—a process that traditionally depends heavily on human intuition, information processing, and decision-making. The organic emergence of the four collections of articles introduced in this Guest Editorial underscores the role of technology in facilitating activities that involve intensive information processing and decision-making, as well as the necessity of rethinking the roles and capabilities of future designers equipped with these technologies. Yet, this special issue is by no means all-inclusive and should mainly serve as a research agenda for future exploration of new technologies and methods for PDD and their complementary roles in conjunction with designers, design teams, and organizations. There are still limitations on AI systems performing human-like tasks such as latent need generation, creative ideation, and an empathetic understanding of users. The issue of algorithmic bias needs further investigation. Existing generative design models are still limited, expensive to run, and not easily controllable. For concept evaluation, there are still questions surrounding best practices for how best to use automated evaluation to drive the creation of novel solutions. Finally, the role of designers and engineers is ever-changing and, in many cases, evolves in tandem with the emergence of new technology. The future relationship between design practice and the set of technologies featured in this issue is fraught with challenges. It is still unclear how we can best translate this research into truly useful tools and platforms that will augment and improve, but not necessarily replace, the human. The articles presented in this special issue indicate what is possible, but there is a lot more to be explored.

We would like to take this opportunity to thank all authors who submitted their original contributions to this special issue and all reviewers for their effort in providing constructive feedback to the authors. We are grateful for the support and guidance of Professor Wei Chen, the Editor-in-Chief of the Journal of Mechanical Design. Special thanks to Amy Suski for her generous assistance throughout this editorial process.

Mohsen Moghaddam
Department of Mechanical and
Industrial Engineering;
Khoury College of Computer Sciences,
Northeastern University,
Boston, MA 02115
e-mail: m.moghaddam@northeastern.edu

Tucker Marion
D'Amore McKim School of Business;
Department of Mechanical and Industrial Engineering,
Northeastern University,
Boston, MA 02115
e-mail: t.marion@northeastern.edu

Katja Holtta-Otto
Department of Mechanical Engineering,
University of Melbourne,
Parkville, VIC 3010, Australia
e-mail: katja.holttaotto@unimelb.edu.au

Kate Fu
Department of Mechanical Engineering,
University of Wisconsin–Madison,
Madison, WI 53706
e-mail: kfu26@wisc.edu

Alison Olechowski
Department of Mechanical and Industrial Engineering,
University of Toronto,
27 King's College Circle,
Toronto, ON M5S, Canada
e-mail: olechowski@mie.utoronto.ca

Christopher McComb
Department of Mechanical Engineering,
Carnegie Mellon University,
Pittsburgh, PA 15213
e-mail: ccm@cmu.edu