Design Science

Guest Editorial

Network-based Modeling and Analysis in Design

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In the last two decades, network science has emerged as a vibrant interdisciplinary field and has affected our understanding in many domains, including biology, physics, computer science, economics, and social sciences. One might claim that *networks* are now considered as a common metaphor to describe various aspects of our social and economic lives, as well as many new technologies of the last decade. Despite its success, applications of network science have, to a large extent, focused on *understanding* various mechanisms related to complex systems, and to a lesser extent on using this understanding as an engineering tool. As network science is coming of age, and as engineering systems are becoming more complex, it is an appropriate time to highlight network-based modeling and analysis as an important area in design research. It is in light of such a need that we introduce this Thematic Collection.

Networks and network methods can contribute to the existing science and practice of design in multiple ways, and they can offer significant contributions to design science. Existing research in network-based modeling and analysis in design generally falls under the following three areas:

(I) **Networks and Architecture**: Networks can help us create abstract models of structural dependencies within products and systems. More importantly, they can help us to have dynamic models of physical and cyber architectures of systems. As a result, network-based modeling can help us to understand better the structural dynamics of systems in the face of various kinds of failure and exogenous shocks, and the evolution of products in response to technology changes.

(II) **Networks and Design Decisions:** Networks can also help us to better model, understand, and engineer the design process. Networks can not only represent design decisions and their dependencies, but they can also represent designers and their communication, cooperation, and competition with each other. Key questions here are related to understanding the dynamics of the design process for each of those networks (i.e., networks of design decisions and networks of designers), as well as the interaction dynamics of these two types of networks.

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(III) **Networks and Design Ecosystems**: Networks can help us to understand the social, economic, and institutional environment in which the products and the design processes are embedded. They can help us to model the dynamics of markets and consumer preferences, innovation processes, knowledge transfer and design education, market competition, and policy forces that directly or indirectly affect the design processes.

With this in mind, we organized this Thematic Collection to gather state-of-the-art research in network-based modeling and analysis in design, with the goal of identifying new research frontiers in this area. We classify the papers in the collection into four groups based on common themes: (1) customer preference modeling and design, (2) design ideation, (3) system performance, and (4) broader applications in design.

These four categories exemplify the main areas we discussed earlier. Papers in the first category look at customers' preference as an example of characterizing product markets, a key element of the design ecosystem (Area III). The second category includes papers related to Area II, i.e., the formation and dynamics of designers' decisions. The papers under the third category, system performance, discuss network structural consequences of systems on their attack tolerance, process robustness, and design team dynamics. These papers are related to both networks and architecture (Area I), as well as networks and design decisions (Area II). Finally, the papers under the broader applications category study two other examples related to networks and design ecosystems (Area III) by discussing design education and the knowledge evolution process using networks of *educational* entities, and academic paper co-authorship networks.

Customer preference modeling and design. As a part of the preference elicitation in design, customer preference modeling bridges the gap between modeling user preferences and predicting market demand as a function of product design attributes and target market descriptions. Two papers from the same author group have illustrated the use of the network modeling approach for modeling customer preferences through customer–product interactions.

In their first paper, *Wang, Chen, Huang, Contractor, and Fu* (https://doi.org/10.1017/dsj.2016.11) propose a novel conceptual framework of multidimensional network analysis (MNA) for modeling customer preferences. Customer–product interactions are viewed as a socio-technical system where separate entities of 'customers' and 'products' are simultaneously modeled as two layers of a network and multiple types of relations, such as consideration and purchase, product associations, and customer social interactions, are modeled as links between these entities. The exponential random graph model is employed as a unified statistical inference framework to interpret complex preference decisions. Their approach broadens the traditional utility-based logit models by considering dependency among complex customer–product relations, such as the similarity of associated products and 'irrationality' of customers induced by social influence.

In the second paper by *Wang, Sai, Huang, Contractor, Fu, and Chen*, the authors demonstrate how the MNA approach is capable of predicting complex co-consideration relations of products as a network and predicting market competitions in response to potential technological changes by using both descriptive analyses and predictive models. The paper shows that the descriptive network analysis approach provides an effective visual representation of the underlying market structures, and facilitates the evaluation of the correlation between customers' consideration preferences and product attributes as well as customer demographics. A vehicle design application is presented in both papers to illustrate the potential of using customer preference predictions to support attribute decision-making in the design of complex systems such as vehicles.

Design ideation. Network analysis is a useful tool for research in design ideation. The following two papers illustrate the use of networks in understanding how designers generate ideas and establishing mechanisms to support them during the ideation process.

Song, Srinivasan, and Luo (https://doi.org/10.1017/dsj.2017.27) employ network analysis techniques to understand designers' preferences in utilizing patent stimuli during design concept generation. The authors model the technology space as a network and use community detection techniques to determine whether a technology class belongs to the home field, the near field, or the far field. They utilize data from an ideation exercise to locate patents and corresponding technology classes that designers found useful. The paper provides insights about which patents are typically used as stimuli for concept generation, and how the quality and novelty of generated concepts depend on the proximity of patents to different technology classes.

Following the theme of design ideation, *Ahmed and Fuge* present a network-based framework to discover new connections between domains, which fosters creative idea generation. They build upon Bisociative Information Networks, and represent design ideas as sets of topics connected to each other in a network based on conceptual similarity between ideas. Using a dataset from OpenIDEO challenges and human subject experiments, the authors show that the discovered links between domains are useful as creative stimuli for design ideation.

System performance. Network science provides new capabilities to understand the structural implications of system architecture, design processes, and organizational structures on their performance. Three papers in this collection illustrate how network structure can be utilized to analyze the failure tolerance of complex systems, the robustness of design processes, and the performance of participants in crowdsourced designs.

Walsh, *Dong*, and *Tumer* establish network-based representations of complex engineered systems from their behavioral description, and they use these representations to understand failure tolerance of the systems. The authors experimentally study forty engineering systems to analyze the impact of attacks on the degradation of the system. They find that attacks on nodes that bridge different modules of a system result in significantly larger system-level behavioral degradation than attacks on non-bridging nodes. The study highlights the vital role of bridging nodes in system degradation.

Piccolo, Lehmann, and Maier (https://doi.org/10.1017/dsj.2017.32) use data from a large design process and a bipartite network analysis of people and activities to investigate process robustness. Although the process is resistant to random failures, the authors show how the process is vulnerable to problems in resource availability and activity failures simulating targeted attacks to people bridging different modules or highly connected activities. A series of network simulations generalizes this behavior as dependent on the degree distributions. With an additional simulation of cascades as error propagation, the authors show how improving the assignment of people to activities can lead to more robust and resilient processes, thus highlighting the central importance of people for design process robustness.

Ball and Lewis (https://doi.org/10.1017/dsj.2017.26) propose a simulation framework that connects a team's network structure with individual designers' competencies in order to evaluate the potential performance of a project team in the context of open and distributed mass collaboration environments. Using a random intersection model of individuals as nodes in the network and their potential interactions as edges in the network, e.g., through shared design components, the authors simulate 1000 design teams randomly assigned competencies, such as the design discipline. The authors find that when comparing the top performing team with the worst performing team, it appears that greater connectivity, increased skill distribution, and increased level of information flow tend to create higher performance.

Broader applications in design. Beyond enriching specific research areas within design, network analysis opens up new ways of looking at design education and the evolution of the research community. Two specific studies presented in the collection include the use of network modeling for educational mapping and collaboration with the human-centered design community.

Willcox and Huang (https://doi.org/10.1017/dsj.2017.18) present a network modeling approach to educational mapping. Current mapping processes in education typically represent data in forms that do not support scalable learning analytics (e.g., a curriculum map in a table). Their proposed network modeling approach overcomes this limitation through explicit modeling of the relationship among different educational entities, such as courses, concepts, outcomes, departments, and degree programs in a graph structure. Viewing the elements of an educational curriculum through the structured lens of a network model provides insight into learning pathways and permits gap analysis of curriculum coverage, supporting curricular design, student course planning, and student advising. The work shows the promise of using network analysis for data-driven advising, adaptive learning, and personalized learning in engineering education.

To explore the landscape of research related to human-centered design for development (HCD+D), *Li, Kramer, Gordon, and Agogino* build a co-authorship network from a dataset of papers related to HCD+D research and quantified interactions among researchers using social network analysis based on co-authorship. They find that influential authors in HCD+D play a large role in shaping HCD+D, yet there are few such influential authors who are in a position to connect and influence collaborative research. Their network analysis gives rise to implications including an increased need for cross-disciplinary collaboration and the need for a stronger core of HCD+D practitioners.

The papers in this Thematic Collection make important contributions to all three areas mentioned earlier in this editorial and cover a wide range of discussions, including process robustness and failure tolerance, system behavior, processes for innovation, qualitative methods for better understanding and capturing user needs, and quantitative methods for modeling consumer choice. While each of these topics leaves out important questions and requires further research, future research may not only build on the concepts embodied here but also branch into new and exciting research opportunities in crowdsourcing, social computing, web-based user analysis, human-centered design, richer network abstraction of system architecture, and machine learning, to name a few. It is our hope that this Thematic Collection will stimulate further research and discussion on this topic, thus helping the community make new, rigorous advances in modeling and analysis in engineering design.