Analysis and Design of Sociotechnical Systems

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Modern engineered systems are increasingly connected, with complex interactions among social and technical aspects, both during the design process and after fielding. For example, autonomous vehicles, smart cities, sharing economy platforms, and more broadly, emerging systems enabled by AI and the internet of things, cross traditional cyber and physical, machine and human, boundaries with their performance largely determined by how they interact with society. In the light of these trends, sociotechnical systems can be defined by the dynamic interaction between technical systems (hardware, software, and AI agents) and human agents (at the individual, social, and organizational levels). They are often multi-stakeholder, highly heterogeneous in terms of the needs and behavior of users and stakeholders, and are only weakly controllable, due to the presence of different types of autonomy within the system. These factors result in high levels of complexity, cast new challenges at the design stage, and call for incorporating certain elements of system governance into the design process.

While traditional engineering design often focuses on designing an optimal technical artifact, there is an increasing recognition that social and organizational aspects of how designers collaborate and create, and how systems co-evolve with the human and built environments through use, are equally important drivers of value. Of course, considering humans in engineering system design is not new or unique to sociotechnical systems; after all, system-level requirements are often linked to what humans value, what they expect, and how they use engineered systems. Nonetheless, past work has often considered the human as a *boundary condition*. Instead, the sociotechnical systems approach extends the system boundary to include many actors as critical components, integrated throughout the entire design lifecycle and explicitly co-evolving with the system they are a part of.

These interactions are particularly important as the AI agents continue to transform many of the systems we engage with daily, for example in intelligent transportation systems, advanced manufacturing systems and industry 4.0, supply-chain logistics. Automated agents are creating a dynamic interaction between the technical and social sides of such systems where multiple AI-agents interact with multiple humans, adjust their behaviors based on such interactions in the short term (machine learning), and result in longer term changes in the modes of human usage and expectations (social learning). Our understanding of such co-evolution of social/organizational and technical components during the lifecycle of a given system is currently limited, however, it is crucial to integrate this dimension into the design of sociotechnical systems.

Additionally, the rise of new sources of data and increased availability thereof creates many opportunities to extend design research into the sociotechnical realm. The prevalence of a wide range of low-cost physical and behavioral sensors and user-generated data about different products translates into a (near) real-time access to dynamic information about preferences,

consumption patterns, and changes in sentiments, market norms and demand. As discussed before, these new sources of high frequency data can be used beyond shaping the design boundary conditions and be integrated into different stages of the lifecycle by introducing methods for collecting and learning from new sources of data, incorporating human individual and group behavior into design, and developing models and tools to govern them.

Dealing with the aforementioned challenges is beyond the research scope of a single discipline. Some essential elements of research will continue to be pursued by disciplinary research in a diverse set of fields such as psychology, economics, and computer science. There are however, several crucial interdisciplinary research directions relevant to the Systems Engineering and Design (SE&D) community that encompasses various scholars within several communities, including American Society of Mechanical Engineers(ASME), International Council on Systems Engineering(INCOSE), Council of Engineering Systems Universities(CESUN) and Institute for Operations Research and Management Sciences (INFORMS). Responding to that, this special issue brings together fundamental scientific contributions that the SE&D community are already making and lays out a path for our future engagement with this important topic. As we will discuss in the following sections, some of these areas are already actively pursued by SE&D researchers, and this special issue aims at collecting and classifying a group of representative papers in such areas. In what follows, we will also make a case for a few other interdisciplinary research areas that can be further pursued by the SE&D community in the coming years.

Overview of papers in the issue

The special issue consists of 15 papers which provide insight into the many ways that the SE&D community is already contributing to this important area. The contributions are concentrated around four key themes: 1) *Integrating human preferences and behavior (individual and group) into the design process.* 2) *Quantifying non-functional & human-centric performance measures (resilience, evolvability, flexibility etc.).* 3) *Empirical methods and data collection to study complex sociotechnical system design.* 4) *Risk and uncertainties in sociotechnical systems.* Naturally, there is some overlap between these categories; for instance, studies on resilience and flexibility (category 2) include certain elements of uncertainty modeling (category 4), or those with the goal of integrating human preferences and behavior into the design process (category 1), might include data collection elements (category 3). For clarity, we assign each paper to only one category. Here, we provide a short description of each category followed by a summary of contributed papers under that category.

- 1) **Integrating human preferences and behavior (individual and group) into the design process:** Maximizing the delivered value is the central goal of engineering design. This value ultimately depends on the preferences of stakeholders and behavior of users, both highly heterogeneous and dynamic throughout the lifecycle in sociotechnical systems. This special issue includes five (5) papers in this category, briefly discussed below:

In “*Combining Direct and Indirect User Data for Calculating Social Impact Indicators of Products in Developing Countries*”, Stringham et. al. present a framework for the quantitative evaluation of the social impact of products. The framework uses deep learning to integrate

indirect user data, collected in real time using sensors, with direct data obtained from user surveys. The resulting social impact indicators can either be used to determine the social impact of a product, or to understand the social condition in a region. The framework is demonstrated using an example of water hand pumps in Uganda.

Large scale, long lifetime, and complex engineered systems are inherently social systems as they interact with culture and society. As well such systems are designed by many different designers thus making the design of the technical system a social activity. This collective action of the design team is strategy dynamics. In *“Structured to Succeed?: Strategy Dynamics in Engineering Systems Design and their Effect on Collective Performance”* Valencia-Romer and Grogan present research to understand how social elements such as harmony and coexistence impact the outcome of the designed system.

In the paper, *“Representativeness of Model Worlds in Systems Engineering and Design: A Case Study”*, Chaudhari et. al. focus on design of representative model world for large-scale complex systems that take multiple years and involve large number of individuals scattered in different locations. They elaborate on and illustrate a number of research design choices in the context of communication in collaborative design, using a case study from concurrent design facility at NASA.

Technical innovations are often faced with acceptance barriers, especially when adopting them changes people’s modes of production and lifestyle. In technical brief *“A framework for the exploration of critical factors on promoting two seasons cultivation in rural communities in India”*, the authors use an agent-based modeling approach to simulate villager’s acceptance of the second season cultivation and discuss critical factors regarding the improvement of the socio-economic status of the community in short and long term and recommend methods to influence the community innovation adaption behavior.

Finally, *“An exploration of intermediary’s role in participatory product design at the Bottom of the Pyramid: the case of Improvised Pedal-operated Chaak”* is another technical brief that discusses how the various governmental and non-governmental agencies as well as users and experts were involved in a design process for a novel pedal operate pottery wheel for a Bottom of the Pyramid context.

- 2) Quantifying non-functional & human-centric performance measures (resilience, evolvability, flexibility etc.)** As discussed in the introduction, the technical and social sides of sociotechnical systems are constantly co-evolving. Moreover, inclusion of different types and layers of human and AI autonomy, makes such systems susceptible to new forms of disruption that can emerge from the aggregate behavior of autonomous agents, making flexibility and resilience essential system-level characteristics of sociotechnical systems. On the other hand, with the right design and governance, interactions of these agents can create new opportunities for increasing resilience and flexibility at the system-level. We have three (3) papers in this category:

In the paper, *“Revisiting flexibility in design: An analysis of the impact of implementation uncertainty on the value of real options”*, Sapol and Szajnfarder look into the impact of implementation delays when flexibility is embedded in the early design process, as a way to deal pro-actively with uncertainty and improve expected performance. The analysis involves simulations of a representative Army vehicle system. This paper sheds light on important socio-technical considerations of flexibility analysis often not considered in the literature, that relate to how such delays in budget cycles, supply chains, and decision-making power can affect the value of flexibility.

Watson et. al. present a paper titled *“Adding a Detrital Actor to Increase System of System Resilience: A Case Study Test of a Biologically Inspired Design Heuristic to Guide Sociotechnical Network Evolution”*, in which they look at the issue of resilience in sociotechnical systems, looking at them from systems of systems (SoS) perspective. They use a biologically-inspired design method to improve the resilience of networked systems and show the advantages of their model compared to soft and hard resilience improvement methods for the simulated case of a forestry industry.

Authors in *“Impact of Generational Commonality of Short Life Cycle Products in Manufacturing and Remanufacturing Processes”* consider the trade-off between the need for rapid technical evolution of products and the environmental problems caused by the end-of-life of such products. Kim and Kim look at the impact of generational commonality on the production process including remanufacturing step. By quantifying this trade-off, they relate pricing strategies, production plans and recovery to different degree of generational commonality.

3) Empirical methods and data collection to study complex sociotechnical system design:

One of the main research directions in sociotechnical systems is on collecting and learning from new sources of data on preferences and behavior at the individual and group level and incorporating them into the design and governance of such systems.

Considering mass collaboration in design activities as a socio-technical system, Ball and Lewis present a paper (Predicting Design Performance Utilizing Automated Topic Discovery) that studies how each individual competency influences the overall design process. Through studying design performance of student capstone projects, the work uses automated topic extraction of textual data and regressions to propose five predictive models mapping ability and performance of individual contributors.

In *“Mining Design Heuristics for Additive Manufacturing via Eye-Tracking and Hidden Markov Modelling”*, Mehta et. al. perform an empirical study based on eye tracking methods that investigates the design process of a group of novice and expert engineering designers to show how unique mixes of data collection and analysis methods can complement each other in describing design cognition, in the context of redesign for additive manufacturing. They show that experts spend less time removing material and revising than novices, and that high-

performing designers spend less time working with the requirements of the project than those with low-performing design.

Data science is rapidly integrating into many engineering organizations. In “Data Fairy in Engineering Land: The Magic of Data Analysis as a Socio-Technical Process in Engineering Companies” Isaksson et. al. argue that the process of adopting data science techniques into an engineering organization is a sociotechnical process and use a participant observation case study to discuss the challenges associated with this process. They use this case study to reveal a number of shortcomings and lack of knowledge on different levels and point to the ethical implication of these shortcomings.

In the paper, “*Design and Analysis of New Haptic Joysticks for Enhancing Operational Skills in Excavator Control*”, C S et. al. present a work that aims to reduce human error and improve user experience of excavator operators. The paper introduces a novel joystick design with haptic force feedback. It is designed to enhance operator awareness and prevent overloading related accidents by giving feedback of bucket forces and loading limits during excavator use.

- 4) Risk and uncertainties in sociotechnical systems:** Understanding risk and uncertainty has always been a major central concern of engineering design. This topic however takes additional dimensions when it comes to modern sociotechnical systems, since dynamic human interactions with the system and their strategic and bounded-rational behaviors create additional types of risk, including systemic-risk that is a collective, system-level property, not well understood in current models of engineering risk and uncertainty.

Complex systems need to be architected such that they can simultaneously explore the trade-space populated by competing technologies, while considering potential future changes in technologies, markets and preferences. In the paper, *Optimizing Architecture Transitions Using Decision Networks*, Siddiqi et. al. propose a method to assist in selected preferred system architecture in the face of technological and market changes and apply the method to the design of an autonomous driving system.

In the paper, “*Quantifying the Importance of Solar Soft Costs: A New Method to Apply Sensitivity Analysis to a Value Function*” Syal and MacDonald focus on understanding the interactions between technology and stakeholders in the context of solar energy infrastructure. The authors present a cost model to calculate the levelized cost of energy of utility-scale solar development. Through sensitivity analysis of the cost model, a multi-attribute value model is created, which enables the evaluation of value of different research funding allocation strategies.

In “*Effects of Robust Convex Optimization on Early-Stage Design Space Exploratory Behavior*”, Pillai et. al. analyze the use of geometric programs as design models to deal with uncertainty via robust optimization principles, with application in aerospace systems. The paper shows that robust convex optimization considerations lead to a more complete

evaluation of the design space, while only generating small differences in participants' understanding of their models. It sheds light on important socio-technical considerations of uncertainty during the design process, as it helps engineers consider alternative approaches to deal with uncertainty that do not leave as much "performance on the table" as current design methods.

Future Research Opportunities for the Engineering System Design Community

As editors we were pleased to see the quality and breadth of sociotechnical systems work already in work. This special issue also highlights some new opportunities for the SE&D community to engage with the unique challenges presented by socio-technical systems. For the most part, research remains focused on individual designers and/or small teams. As noted in the introduction, some of the most pressing issues around sociotechnical systems occur at the scale of organizations, communities or larger, and the interaction of these layers with the technical layer. We believe that SE&D researchers are positioned to leverage their systems thinking approach and interdisciplinary methods to extend their current research to larger groups and collective behavioral attributes that impact systems' performance through their role in the level of coordination, cooperation, system-level flexibility, and resilience. Additionally, the SE&D community has so far focused mostly on the design process. However, more and more we are seeing new behaviors emerge after systems are deployed (because of the interactions discussed above). Maximizing delivered value in such cases demands us to extend the notion of engineering design, to include certain aspects of system governance. We believe that by extending the principles of design thinking and engineering design research, our community can inform issues related to governance of sociotechnical systems more than is already happening.

This brings us to adding two more areas of future research in sociotechnical systems, to be added to the four areas we mentioned earlier for which we received contributions in this special issue. These new areas are:

1. **Dynamic interactions and co-evolution of social and technical systems**, which includes social and AI co-evolution, modeling and leveraging distributed innovation systems, and modeling the interaction of systems and (design) organization architecture.
2. **Integrated design and governance for sociotechnical systems**, which includes design methods for multi-stakeholder systems, incorporating incentive structures into the design process, and leveraging system's architecture in governance.

The papers in this special issue make important contributions to state-of-the-art research in the design of sociotechnical systems. The special issue also helped the editors to better formulate new research opportunities in sociotechnical systems for

the SE&D community. It is our hope that this special issue will stimulate further research and discussion on this topic, thus helping the community make new, rigorous advances in modeling and analysis in engineering design.

In the end, we would like the editor of JMD, Prof. Wei Chen, who kindly supported the idea of this special issue and provided valuable feedback throughout the process. We also would like to thank Prof. Dan McAdams from Texas A&M University for his help in coordinating the review for a number of contributed papers. Finally, we like to mention that this special issue wouldn't be possible without the tremendous help by all the reviewers who provided thorough and timely comments that were instrumental in improving the quality of the contributed papers.