RESEARCH STATEMENT

Current research in complex systems, e.g., modeling and simulation, is challenging because of the complex causal relationships between local interactions and the global system performance. Further, the study of complex systems requires synthesis of knowledge from multiple disciplines. To address these challenges, my long-term *research goal* is to establish scientific foundations for complex systems engineering and design by developing and synergistically integrating theories from different domains. To this end, my research is focused on establishing framework and approaches for modeling and analyzing how the collective dynamics of complex systems results from the decisions made by individual entities (agents). These approaches utilize analytical models based on utility theory, game theory, stochastic process modeling and behavioral experimentation. I have applied the approaches for a variety of applications, including social product development, air transportation system and the Internet (see Figure 1).

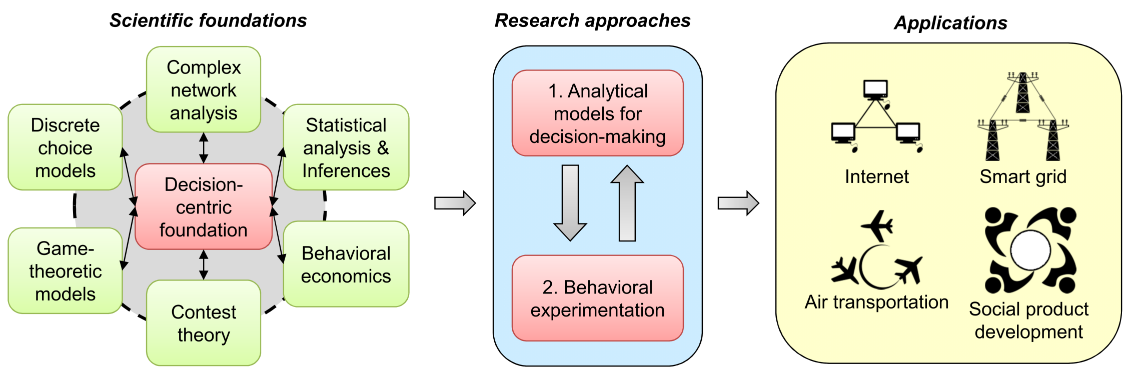

Figure 1: Research Overview

The *central hypothesis* of my research is that the system-level performance in complex systems engineering and design is a result of local interactions and decision-making behaviors of individual entities. The underlying dynamics of complex systems can be abstracted as five levels shown in Figure 2. A paradigmatic example of such systems is the Internet in which the autonomous systems (ASes) make peering decisions to route data based on commercial relationships. The ASes peering decisions play a central role in determining the Internet's topology and its overall performance, as quantified by transit speed and routing efficiency. Similar relationship between local decisions and system-level performance also exists in the air transportation system and social product development. In order to achieve desired system-level performance and/or design requirements, the complex systems should be engineered in a bottom-up manner by influencing the behaviors of local entities. To this end, it is crucial to have an explicit understanding about individual preferences and behavior, which calls for the approaches to (i) model the decision-making behaviors of individual entities, (ii) elicit their decision-making preferences in engineering process, and (iii) analyze the impact of decision-making preferences on the structure and performance of systems. My dissertation is focused on these three aspects. In the following, I summarize my research experience and contributions in detail.

Research Experience and Contributions

The preferences of decision-makers in systems design can be inferred through surveys or interviews to decision-makers. However, direct access to decision makers is always difficult. An alternate way is to infer the preferences indirectly from the data about the decisions that have been made in real choice situations. In my research, I have established two decision-centric approaches for understanding how decisions made by individual entities affect a system's structure and performance. In the first approach, *field data* about the system structure are used to statistically estimate the decision-makers' preferences using discrete-choice models based on utility maximization. These preferences are then used to model bottom-up evolution of the

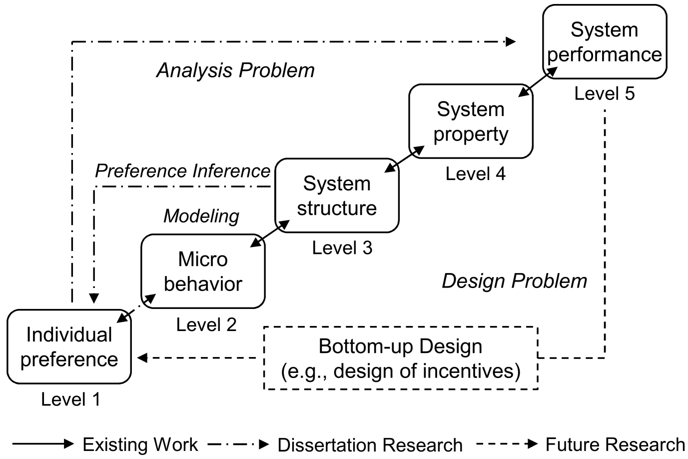

Figure 2: Five-level abstraction of underlying dynamics in complex systems

complex networked systems. In the second approach, human-subject experiments are designed to acquire *targeted data* on decisions made during the design process. The results from behavioral experiments are then synthesized with predictions from analytical game-theoretic models, and the approach is applied to crowdsourcing in engineering design. Details of the my dissertation research are discussed below.

I. Decision-Centric Foundations for Modeling and Analysis of Complex Systems

The study of networks is at the core of systems science since the formation of network topology reveals how systems evolve. In my study the nodes in a network are modeled as rational decision-making entities who maximize their own utility while linking to target nodes. Under this assumption, an approach based on discrete choice models augmented with complex network analysis is proposed to estimate the node-level preferences and behavior. The approach has been applied to estimate the peering preferences of autonomous systems in the Internet [J2 in CV]. The resulting model is an improvement over existing network evolution models because it explicitly accounts for agents' decision-making preferences in a way that is consistent with decision theory. The approach has also been applied to the air transportation system (ATS) for estimating airlines' decisions on route planning [R1 in CV]. The estimated decision models enable the forecast of the evolution of ATS. Among the routes that are planned to be added and deleted, such models predict successfully about 40% and 80%, respectively. This prediction accuracy is higher than that of existing models. Currently, I am extending this approach into a multidimensional network-based framework in support of understanding the across-level interaction in socio-technical systems, such as the passenger-airlines decisions in ATS and costumer-product relations in engineering design.

II. Social Product Development for Engineering Design with Crowdsourcing

Currently, there is an increasing interest in engaging a vastly large pool of talent to democratize the design innovation process. One of the mechanisms is to outsource sub-tasks through crowdsourcing competitions. The objective of this part of my research is to establish a rigorous framework for understanding the designers' decision-making behavior in crowdsourcing competitions, and its effects on design outcomes. Specifically, I designed a behavioral experiment for crowdsourced design to complement analytical models based on game theory [J1 and R2 in CV]. The results indicate that specific formulations of the game lead to different Nash Equilibria of contestants' behaviors. The experimental data reveals deviations from rational human behaviors, e.g., biases that are not structurally included in the game-theoretic models. Through this study, I showed that (i) the contestants' preferences are heterogeneous in nature, and (ii) their behavior is attributed to three factors: the cost of solving a problem, the quality of that solution and the uncertainty of problems needed to be solved in the future. These results provide insights for systems engineers and managers to design effective and low-cost crowdsourcing competition to achieve desired design objectives.

Future Research

In the next five years, I will build on my doctoral dissertation by developing new knowledge on how individual decisions can be influenced to achieve desired system performance through theoretical and experimental studies. Specifically, I plan on initiating the following two research projects:

I. Holistic Decision-centric Framework for Complex Systems: Theoretical and Experimental Studies

The design of successful complex systems rests with decisions of stakeholders at different levels, such as users, manufacturers, distributors, market, and environment. Therefore, it is crucial to understand how stakeholders compromise, coordinate and/or cooperate with other stakeholders. Research opportunities exist in how these decisions made by different stakeholders can be synthesized to facilitate the study of the entire system. The *research objective* will be to create such decision-centric design framework by coupling decisions of stakeholders at different design phases. The *research approach* relies on (i) multi-dimensional network theory for modeling hierarchical decision-making among stakeholders in complex systems, and (ii) decision-oriented big data analysis for acquiring the model parameters (i.e., quantified decision-making preferences). The *expected outcome* is a domain-independent framework for identifying design specifications in large-scale engineering systems. The study will also benefit in developing decision-support techniques and tools. The *potential applications* are design-manufacturing ecosystem and power grids.

II. Improving Design Efficiency and Quality: A Bottom-up Design Thinking

During the last decade, there have been many successful cases of social product development, and intensive research in analyzing the participants' behavior and community structure in this new paradigm. However, there is little understanding on how incentive structures should be designed to improve design efficiency of the process and the quality of resulting designs. Research opportunities exist in creating knowledge about designing of mechanisms and/or incentive structures in social product development. The *research objective* will be to design incentive structures to steer the product development to a desired direct. Detailed research tasks include (a) use analytical game theory to analyze the impact of mechanism design options and incentive structures on the quality of design outcomes, (b) perform human-subject experiments to verify improved incentives structures, and (c) evaluate the effectiveness of the resulting mechanisms. The study would benefit other engineering design problems involving strategic decisions, such as design for market systems, where only analytical game-theoretic models have been used. Such studies would provide opportunities for the integration of research into classroom environment, e.g., the senior design projects. I believe this would be a valuable opportunity for broadening students' perspective on product development and design.

Potential Funding Sources: Recently, various government agencies have recognized the need for research in system science. As the International Council on Systems Engineering highlights

"*Engineered systems increasingly derive their behavior from complex interactions between tightly coupled parts, covering multiple disciplines. It is therefore important to develop a scientific foundation that helps us to understand the whole rather than just the parts, that focuses on the relationships among the parts and the emergent properties.*[1]"

NSF has recently started a new System Science (SS) program in Civil, Mechanical and Manufacturing Innovation (CMMI) division to support fundamental research leading to a theoretical foundation for design and systems engineering. Besides, the Engineering and System Design (ESD) program in NSF CMMI division and Cyber-Physical Systems (CPS) program in Electrical, Communications and Cyber Systems (ECCS) division are the potential funding opportunities. Additionally, the Systems Engineering Research Center (SERC), which is a University-Affiliated Research Center of the US Department of Defense (DoD), is a penitential funding source. Other domain-specific agencies with interests in complex systems engineering, such as Department of Energy (DOE), Federal Aviation Administration (FAA) and National Aeronautics and Space Administration (NASA), are some of the other potential funding sources.

[1] A World in Motion, System Engineering Vision 2025, *International Council on Systems Engineering*, 2014.