System Dynamics: Selected Doctoral Theses

"Enhancing methods for modeling and estimation of complex socio-technical systems"
Author: Tianyi Li (2021)
Committee: John Sterman (co-chair), Hazhir Rahmandad (co-chair), Munther Dahleh (MIT IDSS), Rogelio Oliva (Texas A&M University)
Abstract:

Chapter 1: We study parameter estimation methods in the context of epidemic models. We compare standard least-squares estimation with a panel of alternative estimation schemes in which we test various likelihood functions as well as the use of Kalman filtering. We explore the performance of these methods under different assumptions about data availability and quality, including missing data on important variables and measurement error. While all methods perform comparably in terms of bias in estimated parameters, they vary significantly in the quality of the confidence intervals they yield. Naive least-squares estimation performs poorly, while a negative binomial likelihood or the application of Kalman filtering yields more reliable results. The results should apply not only to epidemics, but to models of social contagion, innovation adoption and diffusion, and potentially other domains.

Chapter 2: When sufficient data for model specification and estimation are unavailable, how should modelers optimally determine which data should be acquired? Specifically, for a given model and set of variables to collect data on, which next k model variables provide the greatest utility for model calibration? We connect this problem with the sensor placement problem in engineering systems, which leads to a combinatorial optimization. We first translate two established solution approaches from engineering systems to social science simulation models. Then, based on the idea of Data Availability Partition and drawing on insights from existing solutions, we propose a new objective function for the optimization. Analytical results for the optimal placement solution under the new objective function are derived for binary and multi-ary trees. For a general tree structure with n nodes, the optimal placement algorithm is devised, with complexity growing at an upper bound of O(nlog2(n)). For arbitrary model structures with feedback loops, approximate solution schemes are developed. Comparison against existing approaches shows notable advantages of the newly proposed method. These findings provide modelers across domains with an objective method and a useful toolkit to prioritize data acquisition.

Chapter 3: Because SD strive to create realistic, operationally grounded, endogenous explanations of broad-boundary issues, its efforts often result in large complex models that are difficult to understand and leverage at the aggregate level. Recent efforts have formalized the analysis the structural determinants of the system's transient behavior. In this study, we complement these efforts by focusing on the model elements that are ultimately responsible for managing the endpoint levels of the state variables, i.e., control inputs. We borrow from structural control theory and develop a set of algorithms to formally identify the control inputs in a model and assess their capacity to control the system states variables. This post-modeling workflow is summarized as the structural control analysis (SCA) of SD models. The results of these algorithms provide insights into the system controllability and policy design. We illustrate these benefits through several examples and outline potential areas of future research.

“Prevention & Reduction of Opioid Misuse with Systems Exploration: Modelling complex, uncertain problems for policy development”
Author: Tse Yang Lim (2021)
Committee: John Sterman (co-chair), Hazhir Rahmandad (co-chair), Jonathan P. Caulkins (Carnegie Mellon)
Abstract:

The opioid crisis is one of the worst public health crises in America. Annual overdose deaths have been climbing rapidly, to over 50,000 people a year. The crisis is a complex and dynamic problem, with long delays and multiple feedbacks, in which any policy actions risk triggering unexpected resistance or causing unintended consequences. In light of these challenges, the National Academies of Sciences, Engineering, and Medicine called for a quantitative systems model to guide Federal government policy to address the crisis.

Here I present a quantitative simulation model of the opioid crisis developed in conjunction with the US Food and Drug Administration to support policy analysis and decision-making. The model is built on extensive literature review and expert consultation, and calibrated to the US population using 20 years of national-level data. It encompasses misuse of prescription and illicit opioids, opioid use disorder, treatment and remission, and tracks a range of outcomes, most notably overdose mortality.

Our baseline model estimates highlight the role of various drivers of the crisis, including the impact of supply-side changes, behavioural risk responses, and the competing influences of illicit fentanyl and overdose prevention efforts. These estimates yield the most thorough quantitative understanding of the historical trajectory of the crisis available to date, and provide a solid foundation for identifying and analysing policy solutions. In addition, this work serves as an example of simulation modelling in two ways – first, as an empirically-grounded model of a complex and highly uncertain problem, and second, as a model and modelling process developed and deployed explicitly in support of policy decision-making.

“Essays on the counter-intuitive consequences of labor policies in service industries”
Author: Mahdi Hashemian (2020)
Committee: Hazhir Rahmandad (chair), John Sterman, Zeynep Ton
Abstract:

In essays one and two, I examine how unstable schedules affect financial performance. In essay one, using 52 weeks of data from over 1,000 stores and more than 15,000 employees of a specialty retailer, I estimate the effect of unstable schedules on store productivity. I use an instrumental variable approach and a natural experiment to partially address the possible endogeneity of scheduling decisions. I find evidence that increasing the adequacy and consistency of employees' hours improves employee and store productivity and find partial support for the positive effect of predictability. To study the policy impact of these findings, I build a behavioral agent-based model of scheduling in essay two. My model provides a platform to conduct counterfactual analyses and thus increases the external validity of my findings.

Results suggest that standard scheduling practices, under certain conditions, may have negative, direct labor cost consequences despite their intended rationale for aligning service capacity and demand. Findings highlight the unintended consequences of a narrow focus on matching labor supply to customer demand; designing more employee-friendly schedules could not only create better jobs but also improve firm performance. In essay three, I build a simulation model to explain why Startups play a major role in establishing many new markets when existing firms have more resources and the relevant core and peripheral capabilities. I explore how the strong link between startups' past performance and the resources available for their future capability building conditions their growth prospects. I show that this reinforcing loop leads to entrepreneurial financial markets rapidly focusing on more promising startups.

The strength of this mechanism can allow startups to over-take projects within incumbent firms that are initially better endowed. Using an online experiment, I test the key requirement for our mechanism, showing that the strength of the reinforcing loop is larger for start-ups than in-house projects.

"Essays on Autonomous Vehicles and the Future of Mobility"
Author: Sergey Naumov (2019)
Committee: Charles Fine (chair), John Sterman, David Keith
Abstract:

Automated vehicle (AV) and electric vehicle (EV) technologies are expected to substantially reduce the negative externalities of driving. Combined with ubiquitous ride-hailing platforms that facilitate ride-sharing (pooling), AVs promise to make automobile transportation faster, safer, cheaper, more convenient, and environmentally friendly. Yet the endogenous impacts of AVs on demand for driving are not well understood. My first paper explores the effect of AVs and pooling on the performance of both roads and public transit in a bimodal transportation system. I develop a dynamic model that describes how commuters choose between driving a car or riding public transit in response to the changing attractiveness of these modes in the presence of AVs and pooling. I show that the well-intentioned move to promote pooling may have the unintended consequences of leading to both worse public transit quality and more rather than less traffic congestion if the public transit downward spiral is triggered. In my second paper, I use conjoint analysis to estimate consumer preferences for the attributes of ride-hailing services. I show that consumers have an inherent aversion to pooling, and prefer cheaper trips, meaning that consumer choice of pooling is likely to drop in the future if the cost of driving falls with the introduction of AVs as some predict. In my third paper, I study the role of the accelerated vehicle retirement programs ('cash-for-clunkers') in reducing transportation fleet emissions. I use a model of vehicle fleet turnover in the United States to show that achieving climate goals will likely require cash-for-clunkers policies that incentivize the accelerated retirement of older less-efficient vehicles and the purchase of EVs, combined with the rapid transition to renewable electricity. I demonstrate that such policies can be an effective way to make the on-road fleet less emission-intensive, but that the costs of implementation could be expensive. I show that a gas tax might help offset the costs incurred while also limiting driving demand, helping to achieve a low-emissions transition.

"Why Clinical Practice Guidelines Shift Over Time: A Dynamic Model with Application to Prostate Cancer Screening"
Author: Özge Karanfil (2016)
Committee: John Sterman (chair), Hazhir Rahmandad, Jack Homer, Richard C. Larson
Abstract:

Essay 1: A Dynamic Model for Understanding Long-Term Trends in Prostate Cancer Screening Cancer remains the second leading cause of death in the U.S. after heart disease. After 35 years of routine cancer screening, we still have only a limited understanding of screening dynamics. There is evidence of over-screening and resulting overtreatment in certain cases, and significant provider variation and fluctuations over time in screening criteria. Here I present empirical data for fluctuations in official screening guidelines and in actual practice for the use of the prostate-specific antigen (PSA) test. I explore how these dynamics are affected by the main guideline-issuing organizations in the U.S. and by clinicians, patient groups, and the media.

Essay 2: Our Walk to the End of Cancer? Understanding Long-Term Trends in Medical Screening In this study we develop the first integrated, broad boundary feedback theory and formal model to explain the dynamics of medical screening. The theory includes a decision-theoretic core around harms and benefits including the fundamental tradeoff between sensitivity and specificity; and feedbacks that condition guidelines and actual practice. To provide context we use the case of PSA screening for prostate cancer as a motivating example, but our model is generic and applicable to other contexts. We present a behaviorally realistic, boundedly-rational model of detection and selection for health screening that creates oscillations in policy

recommendation thresholds of formal guidelines. This core model, entailing only the evidence generation and translation processes, demonstrates how oscillations are natural to this category of problems due to inherent delays in evidence-based screening. These fluctuations lead to long periods during which screening guidelines are suboptimal.

Essay 3: A Dynamic Model for Understanding Long-Term Trends in Prostate Cancer Screening

Whereas guidelines for routine screening should be based on medical evidence, evidence often has relatively little impact on practice. This situation has led to ongoing controversy and conflict over appropriate guidelines among scientists, clinicians, and patient advocacy groups. There are significant variations in clinical practice, including evidence of over-screening for some diseases, and under-screening for others. To explain the patterns of over-screening, fluctuations, low adherence to guidelines, and conflict, I develop the first explicit broad boundary feedback theory of the dynamics of medical screening, tested in a formal mathematical model. The model presents an extended case study specific to PSA screening for prostate cancer, including realistic presentations for the fundamental tradeoff between test sensitivity and specificity, the natural progression of the disease, and respective changes in population size and composition.