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A framework for designing policies for networked systems with uncertainty

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ABSTRACT

This paper presents a framework to design policies for networked systems. The framework integrates model building, stability analysis of dynamic systems, surrogate model generation and optimization under uncertainty. We illustrate the framework using a transportation network benchmark problem. We consider bounded rational users and model the network using software agents. We use Largest Lyapunov exponents to characterize stability and use Gaussian process model as an inexpensive surrogate, facilitating computational efficiency in policy optimization under uncertainty. We demonstrate scalability by solving a traffic grid policy design problem and show how the framework lends itself towards carrying out stability versus performance tradeoffs.

1. Introduction

During the past decade there has been a growing interest in developing conceptual, methodological and analytical approaches for studying large scale inter-disciplinary problems that are embedded in networks at multiple levels and multiple domains [36]. Such systems typically consist of networks that have multiple decision makers and exhibit operational and managerial independence, geographical distribution, and emergent behavior [15]. Modern transportation and supply networks, critical infrastructure networks, energy and power networks [36] display such properties. For example, transportation networks in US metropolitan cities typically have multiple modes of transportation (roadways with passenger cars, buses, and subway and ferry system). Collections of these individual networks are used by numerous users, who display different kinds of user behavior (risk averse, risk taking, rational, bounded rational). The individual networks are managed by independently governed units with managerial independence and are affected by changes in the surrounding uncertain environment resulting in distinct flow patterns (on each of these systems). Similar properties are observed in supply networks in which multiple independent organizations displaying heterogeneous behavior while operating under an uncertain environment to fulfill customer demand, display distinct patterns of product and information flow and changing topological structures.

While research in the field of policy design for real life networked system has evolved from the initial days of drawing influence diagrams [35], it is still considered a challenge to integrate the above mentioned dynamisms within a policy design framework that can accommodate complex network topologies, diverse user behavior and rich set of system-user interactions [36]. In this paper we suggest an approach that follows the same trend of model building, model analysis and decision making as used by multitude of researchers [3,7,8,24,30,34–36] and presents comprehensive additions in the form of stability analysis and surrogate model representation to better address the non-linearity and dynamism in real life networked systems. The four step approach can be summarized into a logical framework as (See Fig. 1):

1. *Modeling* of system behavior along with user behavior: while our framework is not limited to any particular modeling methodology we demonstrate our example problems using agent based simulations to capture how system response changes as individual users interact with the network in order to achieve their goal, and how the individual user behavior is impacted by the system state.
2. *Analyzing* system response behavior for stability conditions: recent literature on large scale system design [3,37] suggests that optimal solutions in networked systems should be carried out in the stable region of operations in order for the optimal policy to be effective. Design of policy in chaotic regime defeats the purpose of an optimal policy design approach. Thus we ensure that the set of

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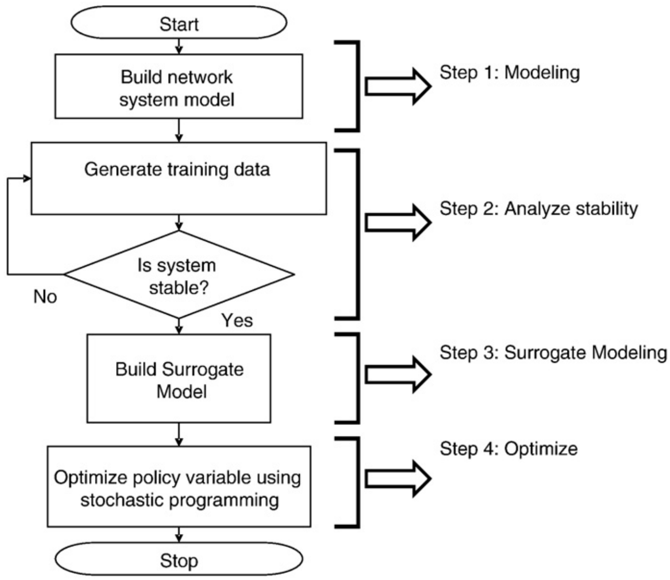

Fig. 1. Framework for policy optimization in network systems.

input and decision variables being considered yields stable system response behavior before optimizing policy variables.

3. *Constructing* an inexpensive surrogate for the expensive agent-based simulation: The computational effort associated with the use of agent-based modeling (ABM) for optimization in the presence of uncertainty is enormous. Three types of iterative analyses are required: system and user simulation, uncertainty analysis and optimization. Construction of a surrogate model reduces the computational expense and facilitates the estimation of expected value of the system response behavior which can then be used further in the optimization process.
4. *Optimizing* policy variables through stochastic optimization: as described above network systems typically have multiple types of uncertainties associated with them. In order to design an optimal policy for such systems a stochastic optimization approach where the problem formulation includes system response variables, the input variables and the decision (policy) variables and their stochastic characteristics is necessary. Use of a surrogate model representation further reduces the complexity of implementing optimization routines as full grid searches become feasible. We demonstrate this with our two examples later in the paper.

In order to illustrate our framework we use a popular benchmark problem as a verification problem in the transportation network literature called the Braess network [6] that has been widely used by researchers [12,13,25,36,37,42,53]. The Braess network consists of a single origin-destination (OD) pair and four nodes. We later use a single random input (random demand) and a single policy control variable (flow split at the origin node) to illustrate each of the four steps mentioned above. First we use an agent-based modeling (ABM) approach for modeling the Braess network with multiple users with bounded rational behavior [54]. Second, we compute the Largest Lyapunov exponent (LPE) [20,46,47,50] to analyze the stability of the system response behavior. Next, we estimate a closed functional form of the overall system cost (system response behavior) using a Gaussian process (GP) surrogate estimation technique [43]. Finally we perform stochastic optimization to find the value for the flow-split policy variable that minimizes the total system cost in the network. We then illustrate scalability of our framework by designing policies for a traffic grid with 25 signalized intersections, 80 links and 10 times the number of users as compared to the verification problem. We also introduce stability response surfaces as a trade off tool while selecting policies for a network system.

While the individual tools used in this framework are proven and tested individually; to the best of our knowledge, they have never been used together to methodically approach policy design problems for networked systems. The primary contribution of this paper is the synthesis of model-based network system representation, stability analysis of dynamic systems, surrogate model reconstruction and optimization under uncertainty (OUU) within an overarching framework, enabling design of stable policies for network systems. Strengths of this framework include the ability to use any modeling approach for representing the system. We impose no constraints except for the requirement that a system model can be used to generate training data for stability analysis and surrogate model reconstruction (in the form of time series representation of dependent and independent variables). A novel aspect of this research is the stability analysis of the dynamic system responses and surrogate reconstruction of a stability surface. As shown in the later sections with one of our complex network (a hypothetical urban traffic grid) demonstrations, stability surfaces can be used for making tradeoffs between different policy aspects in a networked system along with ensuring that the designed policies are selected from a stable operating zone. The integration of Gaussian Process Models (GP) in this framework enables construction of the stability surface while also allowing us to use a cheap surrogate representation of the system in the optimization process. The inexpensive computation time provided by the GP model allows us to use very simple optimization routines such as line searches and full grid searches.

Section 2 presents the background literature on network system modeling and simulation. Section 3 introduces the Braess network (verification problem) and policy design formulation. Section 4 presents detailed step by step illustration of the agent-based model for the Braess system. Section 5 presents the LPE analysis while Section 6 discusses the surrogate model construction. Section 7 presents a stochastic optimization approach for finding the optimal design value for the policy variable. Section 8 then illustrates scalability of our framework. Section 9 concludes and suggests future research.

2. Background

Researchers from diverse domains such as transportation system design [13,53], supply network design [11,36], and more recently super network (overlapping transportation and supply networks) [37,42] and emergency response network design [3] have attempted to design optimal economic and operational control policies for network systems. For example, in transportation network and supply network design, the approaches include: system and user equilibrium behavior models (logit and probit models) [13,53], variational inequality formulations that consider multiple user types and multiple classes of networks (super networks), and system dynamics formulations for time dependent problems [37]. Several solution approaches such as stochastic programming, discrete time and discrete event simulations and multidisciplinary optimization methods [24,27,40] have been considered. Additionally researchers in facility network layout design [14,17,44] have considered uncertainty associated with demand generation, fixed costs, transportation between nodes etc. while suggesting numerous solution approaches for designing optimal solutions/policies such as dynamic programming [28], lagrangian heuristics [1], genetic algorithms [4], and tabu-search [2] to name a few.

Carley and Kamneva [8] have developed a dynamic network analysis and optimization approach for improving organizational policy design while addressing some of the above mentioned issues. They represent network systems in the form of a relationship matrix between the nodes of the network and use Monte Carlo and simulated annealing-based heuristic optimization methods to