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A model for simulating adaptive, dynamic flows on networks: Application to petroleum infrastructure

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ABSTRACT

Simulation models can improve decisions meant to control the consequences of disruptions to critical infrastructures. We describe a dynamic flow model on networks purposed to inform analyses by those concerned about consequences of disruptions to infrastructures and to help policy makers design robust mitigations. We conceptualize the adaptive responses of infrastructure networks to perturbations as market transactions and business decisions of operators. We approximate commodity flows in these networks by a diffusion equation, with non-linearities introduced to model capacity limits. To illustrate the behavior and scalability of the model, we show its application first on two simple networks, then on petroleum infrastructure in the United States, where we analyze the effects of a hypothesized earthquake.

1. Introduction

If we consider an infrastructure as a system used to produce and distribute a widely-used commodity, large infrastructure disruptions are of concern because they can suddenly reduce commodity availability over significant areas for a period of weeks to months. Recognizing that all disruptive events cannot be prevented, there has been a focus on evaluating and measuring system resilience [1,2]. There are many definitions of resilience proposed to meet specific objectives [3,4,5]. Definitions that emphasize the capacities of the system to mitigate consequences by absorbing impacts, adapting to changing conditions, and restoring the system to pre-disruption conditions [1], are useful in many cases.

Resilience definitions typically consider a system's functioning throughout a disruption lifecycle, including pre-disruption investments, disruption, and recovery. Focus on the dynamics of the system response, and on its interactions with the other systems implicated in its disruption and reconstruction, mean that resilience assessment frameworks often call for coupled dynamical models that include human interactions with physical infrastructure [1]. Some frameworks define a single overarching model formalism for all processes (production and transmission of commodities; monitoring and control systems; response and recovery) such as networks of state indicators [3,6]; others envision an ensemble of discrete and dynamic models [2].

Because infrastructure components are expensive, infrastructures typically have a limited capacity to produce, store, or transmit a commodity. The importance of capacity limits and the spatial distribution and connectivity of the system's components in shaping response has led us, along with many others, to conceptualize the infrastructure system as a network.

The performance of infrastructures during disruptive events depends not only on physical constraints of capacity limits, but also on the business decisions of infrastructure operators and the behaviors of consumers of the commodity provided by the infrastructures. To estimate disruption consequences, we need a socio-technical model that represents the interaction between physical and behavioral aspects of the infrastructure network. Vespignani [7] describes the challenge of forecasting performances of socio-technical systems. He notes that steady-state data can be used to describe normal conditions, but during catastrophic events, such as natural disasters, systems are driven out of equilibrium into a state in which adaptive behaviors play an important role.

Various approaches have been used to study infrastructure networks including optimization [8–10], first-principle engineering models [11,12], and flow models based on conservation laws [13–16], or heuristics [17,18]. Ouyang [19] provides an extensive overview of the modeling approaches that have been used to model and simulate infrastructure systems. However, none of the previous approaches are well suited to combining the physical and behavioral aspects of infrastructure performance during disruptions. Specifically, we found that engineering approaches that solve fluid dynamic equations to represent the physical part of the socio-technical system are not well suited for three reasons. First, it is not practical to build models of large networks (e.g., the U.S. crude and product petroleum network) because the engineering details of system components are not available outside of the private companies that own and operate them. Second, if such a model could be con-

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structed, it would be extremely complicated and expensive to develop, use, and maintain. Third, a model of system response requires a model of operator behavior. Models for this essential half of the socio-technical system cannot be specified with certainty. Coupling detailed engineering models to uncertain operator and market models only provides an appearance of improved accuracy. Although several researchers have pointed out the desire for dynamic flow-based simulations of national-scale networks, they have noted that such simulations are challenging or not practicable because of the need for large computational resources and data sets [6]. The behavioral part of the socio-technical system is often implicitly addressed by assuming that individual business decisions aggregate to produce optimal behaviors in a market in which there is complete sharing of information about the system state. This assumption is perhaps well suited for undisturbed conditions, but seems inappropriate when considering short-term response to unexpected large-scale disruptions. Monforti and Szikszai [18], in contrast, represent individual decisions as random selections from a set of rule-based behaviors. Their approach is intended to explore large numbers of possible system-level responses to disruptive events without assuming optimal or coordinated behavior. Behavioral considerations can be incorporated through agent-based modeling, as recently outlined by Nan and Sansavini [1]. In the context of this general framework for resilience assessment, the behavior of system operators and emergency responders is of interest because errors in their ability to execute prescribed functions can exacerbate the disruption and impede restoration and recovery. Because of their focus on specified functional roles, it is possible to formulate agent behavior as stress-compromised execution of articulated responsibilities or response plans. For the infrastructure systems we consider, operators are not executing defined roles, but are making judgements about storage or release of inventory in the face of novel challenges.

The National Petroleum Council [20] describes the types of changes in process rates, transportation rates, and inventory levels at individual facilities that result from the business decisions of independent companies as they respond normal minor stresses, such as a refinery shut down for maintenance, or to more severe stresses. These market-driven responses are possible because, under undisturbed conditions, the full capacity of a network component to store, process, or transport crude oil or refined products is typically not fully utilized. For example, the U.S. Government Accountability Office (GAO) reports that undamaged refineries increase output during Gulf Coast hurricanes to compensate for closed refineries [21]. In addition, nearly all transmission pipelines are common carriers meaning that, like airlines, no shipper can receive preferential access to a pipeline. The common-carrier operation of pipelines ensures that companies have the flexibility of multiple routes to ship crude oil and refined products throughout the petroleum supply network [22]. The National Petroleum Council [20] noted that the availability of inventory at various points in the supply network is an important aspect of the system flexibility. Together, market incentives, excess capacity, availability of inventory, and flexibility in transportation modes and routes allows system-level rebalancing to move crude oil and refined products from where they are relatively abundant to where they are more scarce.

Decision makers are interested in understanding and controlling the extent and duration of reduced availability of resources caused by disruptions. We present a simulation model that is designed to help them build this understanding and evaluate mitigations by deriving patterns of commodity availability that might follow from disruption scenarios. We discuss a novel method to simulate dynamic, adaptive flows, that has been successfully applied to national-scale infrastructures [27]. Our model is unique in that it represents physical constraints and dynamic, adaptive, behaviors during disruptions.

Our work concerns the petroleum fuels sector, which we use for illustration in this paper. However, the problem of shortfall following disruption is common to other individual and interconnected infrastructures, and our intent is that the model we present generalizes to other commodities whose availability is determined by constraints on the capacity of transportation and storage facilities.

Our model supports the evaluation and improvement of the resilience of infrastructure systems having certain general properties. It is designed to cover the range of conditions typically considered in resilience assessments: pre-disruption, disruption, response, recovery, post-disruption equilibrium) but does not attempt to represent connected infrastructures nor the operation of supporting infrastructures implicated in response, such as transportation of replacement equipment, communication of system state to responders, etc. It includes models of the reactions of key human operators, however in contrast to other formalisms that internalize behavior, it does not attempt to articulate their behavior in terms of response rule that may operate with some reduced reliability. The behaviors that concern us are the locally optimizing responses of individual asset managers, and our formulation is motivated by the need to have a parsimonious description that allows us to explore a range of possible responses.

We address the challenge of forecasting the performance of a socio-technical system, described by Vespignani [7], adopting the National Petroleum Council's conceptualization of a supply network [20], in which market transactions, business decisions of many independent companies, and (sometimes) regulatory actions work together to mitigate shortages of supplies by adjusting utilization of existing resources within capacity constraint. We represent dynamic infrastructure behavior by analogy to flows in physical systems in which storage and flow are driven by gradients of a potential; examples include heat flow from regions of higher temperature to regions of lower temperature, and hydraulic systems in which fluids flow along pressure gradients.

In work that is mathematically similar to our study, Svendsen and Wolthusen [16] describe a general network flow model for simulating interdependent infrastructures. Their study emphasizes the importance of simulating time-dependent dynamic effects by incorporating storage, the application of conversation laws, flows driven by gradients of a state variable (e.g., fluid pressure in their natural gas example), and the specified intent to not represent the detailed physical effects commonly included in engineering models of individual infrastructures. In contrast to Svendson and Wolthusen [16], we envision flows to occur along gradients of potential that represent the relative scarcity of commodities in different parts of the supply network instead of representing a measurable physical quantity. In this sense, our model simulates the results of market and business behaviors by moving crude oil and refined products from where they are relatively abundant to where they are most needed.

We first develop a general mathematical model and define system performance metrics for commodity service delivery and inventory in Section 2. To examine the sensitivity and dependence of the socio-technical system on behavioral parameters, we use trivial stylized systems and analyze the effects of change in behavior on model results. In Section 3, we show the application of the model to the United States petroleum infrastructure, and analyze its response if damaged by a large earthquake. This case example shows that sufficiently detailed model representations of large infrastructure systems can be constructed, and that these systems can be simulated with modest computational resources.

2. Theory

We are interested in estimating the availability of a commodity supplied by a national- or regional-scale infrastructure following unexpected disruption of one or more of its components. The large scope of the disruptions of interest produce changes in availability lasting days to weeks. Consequently, we do not try to resolve daily variations in system state and do not include the long-term processes that cause infrastructures to evolve as assets are added and removed according to owners' planning decisions.