Multiple Participant Models of Urban Infrastructure Performance and Decision Support

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Abstract. Representations of an infrastructure network model and its state space equations are presented to analyze resilience of a system over time. A simplified example is utilized to demonstrate application of these methods. Connecting these models to agent-based conflict models to generate scenarios for decision support is discussed.

Keywords: Graph Models; Multiple Participants; State Space; Urban Infrastructure Resilience.

1 Introduction

Urban infrastructure systems are composed of networks of facilities and services that underlie the functions of cities. A facility such as a water treatment plant or power substation is an infrastructure system within an infrastructure system. Moreover, infrastructure systems including water management infrastructure or energy infrastructure are also part of a larger network of dependencies [15]. This larger network of dependencies consists of other infrastructure, users, operators, and other socio-economic, political and environmental interconnections. Informed decision making within this web of complex interactions among systems and participants within these systems requires understanding of this larger context, as well as, how this context changes over time. In the short-term, for example, the event of a natural hazard changes the operating conditions of a system. In the extreme case, infrastructure systems are pushed to their design limits and beyond, as happened to the levees and flood walls of New Orleans during Hurricane Katrina [13]. Over longer timescales, for example, the complexity of systems increase as more connections are created among its components [14], which can amplify expected events to unexpected proportions, such as the 2003 Northeast blackout affecting at least 50 million people [1][17]. Due to the high capital investments needed to maintain and revitalize...
infrastructure, strategic planning is required of our political leaders and managers of urban infrastructure [16]. In strategic planning, participants recognize the mission of decision making processes within a vision, how the decision context may change, and hence consider variable options for achieving their goals under a changing context.

The objective of this paper is to present multiple participant decision making models for strategic infrastructure planning using a combined complex adaptive systems and conflict resolution approach, which was presented at GDN2013 [4]. Based on the socio-ecological framework to study evolution of cities and their resilience in [4], adaptive cycles conceptualize the resilience context of an urban infrastructure system, while conflict models describe the strategic context of participants involved in and affected by infrastructure management decisions. The purpose of this paper is to further operationalize the approach in order to inform decision making within a strategic planning construct. To this end, network models and state space equations are formulated to analyze resilience of a system over time. These functional models are then integrated with agent-based models to synthesize interactions among participants to generate scenarios for decision making.

In Section 2, representations of a network model and its state space equations are presented. A simplified example is utilized to demonstrate application of these methods. Connecting these models to agent-based conflict models to generate scenarios for decision support is discussed in Section 3. Finally, Section 4 concludes this paper with future work on developing decision support tools for disaster response on one hand, and urban energy resilience and sustainability on the other.

2 Infrastructure networks and state space equations

Infrastructure is built for a purpose and in order to fulfill that purpose it relies upon external influences and support to continue [11]. A coal fired generating plant, for example, depends on the freight industry for delivery of coal; the freight industry depends on well-maintained roads to transport physical goods; roads depend on storm water drains or storm sewers to clear away precipitation, as well as electric power to regulate traffic flow with traffic control signals; electric power distributors depend on coal fired generating plants, as well as nuclear, gas, hydro and wind power plants. Conversely, energy suppliers depend on energy consumers; the construction and maintenance of roads depend on drivers to use the roads; and storm sewers depend on precipitation to justify their capacity.

In a network model, nodes represent infrastructure facilities and services, as well as resource-bases and end-uses which are defined by boundaries of the overall modelled system. Arcs represent dependencies. A ‘directed edge’ (denoted by an arc with an arrow) into node \( i \) represents a dependency, which means that node \( i \) requires a flow of resources or information from the upstream node. An arc out of node \( i \) means that node \( i \) can impact the downstream node directly and any other downstream node indirectly. End-uses are considered external to the system model boundary and delineate the consequences that decision makers consider important. Resource-bases are also considered external to the modelled system. The infrastructure network is
thus described as an open system. Fig. 1 illustrates the basic components of a network model of urban infrastructure.

The operation of networks of interdependent infrastructure involves many measures of operation. The dynamics of each node’s measures dictate not only its own recovery after a shock, but also the recovery of the network as a whole as changes propagate along the dependency pathways between nodes. Consider, for the time being a measure called performance, the exact meaning of this measure is intentionally general at this point, but it can be assumed to mean financial performance, or the capability of a plant. As Fig. 2 illustrates, this recovery of performance can take many forms following an event.

In the first case (a) Steady recovery is a typical performance curve that many operators aim for when devising their resilience plans. The middle case, (b) Failed recovery, is a near-worst case scenario whereby the recovery to past performance never occurs. This may happen if the devastation is so great or the response so poor that recovery becomes impossible. Finally, in (c) Overshoot recovery, a quick return to high levels of performance is achieved that even for a time overshoot previous levels. At first glance, this seems like a positive scenario, yet a network-wide result of such recovery is not necessarily positive if it induces conflict among nodes due to

Fig. 1. Network model of dependencies and impacts of an infrastructure component

Fig. 2. Selected varieties of node response to a disturbance or shock over time (t = 0 corresponds to the time of the shock).
limited resources. If a given node’s recovery needs are so great as to rob other nodes of key resources, then chains of dependency can propagate performance deficiencies [12]. Such a situation is increasingly likely if there are a number of nodes whose recovery overshoots what is actually required of them from a network-wide perspective. The recovery of all of the nodes, ideally, is synchronized to reduce network-wide down time and losses. Whether recovery takes the form of cases (a), (b) or (c) establishes a large portion of the context under which group decision making and negotiation must occur among stakeholders and operators of different nodes.

Since the complex dynamics among nodes relate strongly to the dynamics of each node, dependency representations must capture node dynamics. This requires characterizing the relationship among the inputs and outputs of a node as well as the state of the node [10]. Following, a state space representation is proposed to model a focal node in a dependency network. The purpose of the state space model is to capture the interrelationships among inputs, outputs and node state. A short example then illustrates the usefulness of this approach for specifying the impact of shocks on dependency networks, and where the leverage points are for making decisions to alter these impacts to increase the resilience of a city.

2.1 Network and state space representation

The network of infrastructure dependencies can be represented as a graph comprised of vertices (nodes) $\mathbf{v} = \{1, \ldots, N\}$ and directed edges (or arcs) $\mathbf{E} = \{(i, j) \mid i, j \in \mathbf{v}\}$. An arc $(i, j)$, where node $i$ is the source node and node $j$ is the destination node, has an associated vector $\mathbf{d}_{i,j}$ of length $q_i$, the number of output measures of node $i$, comprised of zeros (0) and ones (1) indicating whether a given output of node $i$ is an input to node $j$. Hence, $\mathbf{d}_{i,j}$ indicates the dependencies of node $j$ on node $i$, or conversely the impacts of node $i$ on node $j$.

A discrete state space representation of node $i \in \{1, \ldots, N\}$ is proposed as follows:

$$\mathbf{x}_{t+1}^i = \mathbf{A}^i \mathbf{x}_t^i + \mathbf{B}^i \mathbf{z}_t^i + \mathbf{\Gamma}^i \mathbf{h}_t^i$$

(1)

$$\mathbf{y}_t^i = \mathbf{A}^i \mathbf{x}_t^i + \mathbf{\Phi}^i \mathbf{z}_t^i + \mathbf{\Theta}^i \mathbf{h}_t^i$$

(2)

where the focal node is identified as node $i$ and $t$ is the current time step. In the following explanation of Equations 1 and 2, the superscript $i$ and subscript $t$ are implied. The state of the focal node is described by $\mathbf{x}$, which is a $n_i \times 1$ vector where $n_i$ is the number of state variables of node $i$. As $t$ increases, the state variables are updated. A $n_i \times n_i$ state transition matrix $\mathbf{A}$ feeds the current state into the new state $\mathbf{x}_{t+1}$. The new state is also affected by the change in the performance of node $i$’s

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1 Assuming the typical simplification of considering differentials in a linear regime of the state space [18].
dependencies denoted by \( \mathbf{z} \) (a \( m_i \times 1 \) vector where \( m_i \) is the number of output measures from other nodes \( j \neq i \) that are directed into node \( i \)) and the change in the realized hazard levels on node \( i \), which are represented by \( \mathbf{h} \) (a \( r \times 1 \) vector where \( r \) is the number of hazards). Hazards, as well as dependencies, can induce stress or shock on node \( i \). As hazards are considered independent variables, a stress caused by a hazard would be modeled with a ramp function that approaches a certain threat boundary, whereas a shock due to a hazard would be captured with an impulse or step function that exceeds the threat boundary. How dependencies and realized hazards impact the focal node’s state is described by \( \mathbf{B} \) a \( n_i \times m_i \) matrix and \( \Gamma \) a \( n_i \times r \) matrix, respectively. The current state of the focal node will in turn influence the node’s outputs. The change in the performance of the outputs of node \( i \) that serve as dependencies to other nodes \( j \neq i \) is represented by \( \mathbf{y} \), a \( q_i \times 1 \) vector where \( q_i \) is the number of outputs of node \( i \); \( \mathbf{A} \) is a \( q_i \times n_i \) matrix describing the impacts of node \( i \)’s state on its outputs. The focal node’s outputs may also be directly affected by changes in the performance of its dependencies and realized hazard levels if the node anticipates changes. If a decision maker can forecast changes in dependencies and hazard levels based on current data, then the outputs of an infrastructure system can be influenced in advance through feed-forward compensation. This capability is modeled by \( \Phi \), a \( q_i \times m_i \) matrix describing the influence of the current performance of the focal node’s dependencies on its own outputs, and \( \Theta \), a \( q_i \times r \) matrix describing the influence of the current hazard levels on the outputs of node \( i \).

### 2.2 Example implementation of network and state space representation

An example network and state space representation of a simplified real-world infrastructure dependency is presented. A partial dependency network is illustrated in Fig. 3, in which a natural gas power plant is the system-of-interest. This sample is useful for illustrating the interplay among different nodes under the realization of a particular hazard, namely a heat wave. Using node 1 as the focal node, a state space representation is demonstrated in practice considering the impact of a heat wave on the performance of the natural gas power plant.

\[2\text{ The matrix } \mathbf{z}_j \text{ is a concatenation of all of the outputs of all other nodes } j \neq i \text{ that are dependencies of node } i \text{. Mathematically it is the concatenation of } \mathbf{y}_j \text{ for all } (j,i) \in \mathbf{E} \text{ where } d_{j,i} = 1 \text{ for all } d_{j,i} \in \mathbf{d}_{j,i}.\]
To simplify the demonstration, it is assumed in this case that there is only one dependency per arc (\( d_{ij} \) has only one non-zero entry) and that the state transition matrix \( (A) \) and the impact matrices \( (B, \Gamma, \Lambda, \Phi, \Theta) \) are assumed to be invariant over the relevant timescale provided that there are no interventions on the part of decision makers. A qualitative version of the state space equations for this scenario is shown in Equations 3 and 4. In this particular case, depending on the impact factors and heat wave hazard level, the power plant may simply be able to respond by raising power output to meet customer demand. It may also be the case that the hazard level is sufficiently high and the impact matrices are exceedingly imposing that the change in power plant capacity is limited; hence the plant cannot respond adequately.

\[
\begin{align*}
\text{New departure from nominal max capacity, } x_i^1 & = \\
\begin{bmatrix} 
\alpha_1 & \beta_1 & \beta_2 & \beta_3 \\
0 & 1 & 0 & 0 \\
0 & 0 & 1 & 0 \\
0 & 0 & 0 & 1 \\
\end{bmatrix} & + \\
\begin{bmatrix} 
\beta_1 \\
-\beta_2 \\
\beta_3 \\
\beta_4 \\
\end{bmatrix} x_i^0 + \\
\begin{bmatrix} 
\rho_1 \\
\rho_2 \\
\rho_3 \\
\rho_4 \\
\end{bmatrix} T & + \\
\begin{bmatrix} 
\rho_5 \\
\rho_6 \\
\rho_7 \\
\rho_8 \\
\end{bmatrix} T & + \\
\begin{bmatrix} 
\mu_1 \\
\mu_2 \\
\mu_3 \\
\mu_4 \\
\end{bmatrix} T & + \\
\begin{bmatrix} 
\eta_1 \\
\eta_2 \\
\eta_3 \\
\eta_4 \\
\end{bmatrix} T & + \\
\begin{bmatrix} 
\nu_1 \\
\nu_2 \\
\nu_3 \\
\nu_4 \\
\end{bmatrix} T & + \\
\begin{bmatrix} 
\xi_1 \\
\xi_2 \\
\xi_3 \\
\xi_4 \\
\end{bmatrix} T & = 0
\end{align*}
\]
The impact matrices, while assumed to be constant under no intervention, are in fact dependent upon decision making processes. For example, through interventions of preparedness, risk mitigation strategies or building of resilience the impact matrices are influenced. The modifications of impact matrices change the impacts of dependency failures and realized hazards, as well as the outputs to other nodes. Decision makers need to account for contextual influences such as the risk context in terms of risk perceptions of various participants, the broader resilience context in terms of the adaptive cycle of the network as a whole, the strategic context of conflicting as well as complementary value systems and objectives of all decision makers, and constraints imposed by the institutional (socio-economic-political) and technological environments.

3 Agent based models for decision support

An agent-based modelling framework may be used to situate a network model and its associated state space representations of nodes within the context of decision making processes. As argued in the previous section, the interplay among nodes defines the responses of nodes and thus the behaviour of the overall system. Due to conflicts among the values and preferences of the stakeholders of separate nodes, individual goals may clash with the achievement of system-wide resilience. Such can be the case with private-sector power plant owners, for example, whose primary responsibility of business is to maximize profits and elected government representatives whose main desire is to garner political support in their own constituencies. Interactive decision support with the Graph Model for Conflict Resolution (GMCR) [7–9] can help stakeholders take into account their own goals, options and preferences along with the goals, options and preferences of other participants to determine potential cooperative outcomes that would not be reached if participants pursued individual goals on their
own. It is also suggested that state space models of risk perceptions and GMCR conflict models of risk management may be connected to incorporate strategic considerations into risk analysis [6]. Moreover, with an agent-based framework to model competitive and cooperative behaviour [3, 5], conflict dynamics can be modelled to project ensembles of potential conflict evolutions which illuminate possible pathways to desired joint outcomes. A decision support system that connects network models and state space representations with agent-based models of conflict dynamics that take into account changing contextual variables would provide participants with a tool to develop and effectively analyze a multitude of scenarios to construct and negotiate contingency plans for desired levels preparedness and response capability of urban infrastructure systems.

4 Future Work

The next goal of this research is to develop a disaster response decision support system for city emergency response in a catastrophe. On the other hand, resilience is but one objective. Other goals, such as sustainability are of similar interest to many urban decision makers and stakeholders. Urban energy networks [2], and other varieties of urban networks could be incorporated into the agent based conflict dynamics model along with the urban dependency network. Similarly, the goal is to provide decision support in multi-objective, multi-participant strategic planning for resilience and sustainability of cities.

References