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Author(s):
Dubaniowski, Mateusz Iwo; Stojadinovic, Bozidar

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Modelling complex and interdependent STE systems
Agent-based modelling and simulation for the assessment and design of STE systems

Nested multi-input-output model of interdependent infrastructure and socioeconomic systems in urban areas

Mateusz Iwo Dubaniowski[1*], **Božidar Stojadinović**[1]
[1]*ETH Zurich, Future Resilient Systems, Singapore-ETH Centre*
[*]*corresponding author: iwo.dubaniowski@frs.ethz.ch*

Summary
Urban areas are constantly expanding as people gravitate towards cities. As a result, cities become more complex, interconnected, and dependent on essential infrastructure systems. These systems are stressed and suffer more disruptions. In turn, these disruptions have larger impacts due to higher urban density and increasing number of interdependencies present. Consequently, it is vital to ensure that the infrastructure systems are resilient. We present a framework for modeling impacts of disruptions on infrastructure systems, businesses, and households in urban areas. Our novel model addresses the gap of adequately modeling non-homogenous urban areas. These areas might benefit from more detailed representations in regions of particular interest. We outline the approach and key issues in this space, such as mapping of resources between models of different granularity and defining the most adequate granularity levels. Finally, we describe the main challenges and possible further studies focused around the application of this model in practice.

Keywords
Infrastructure modeling; system-of-systems; agent-based modeling; infrastructure resilience; model granularity

Introduction
Over the past years people gravitated towards cities as a result of technological advancements and the concentration of employment, housing as well as most socioeconomic institutions in urban areas. This trend is expected to continue in the near future: the UN predicts that over 60% of people globally will live in urban areas by 2030 [1]. Consequently, trends accompanying this rapid urbanization are immensely important. These include development of large amounts of dense infrastructure systems. These systems enable societies to operate by providing them with the essential functions such as transportation, water supply, energy supply, communications. These services are vital to modern societies, which cannot operate without them, especially so in urban areas. As a result, the efficient operations of these services and provision of resources that these systems are producing and delivering are crucial. It is important that governments and decision makers develop, plan, manage, and maintain these infrastructures in a way that ensure their smooth running.

The development of infrastructures, as well as the abovementioned rapid urbanization, however, stress infrastructure system and lead to increasing numbers of disruptions in such systems, along with increased impacts of these disruptions. This is due to several factors. First, the density of urban areas and infrastructures increases, which leads to more events happening in the same area, and similarly to growing impact of events that affect the same area. Second, modern infrastructures become extremely interdependent forming a complex mesh of networks and systems that depend on each other. Third, these systems undergo rapid transformation and form a cybernetic organism that results in cascading and emergent impacts of seemingly separate events[2].

This poses a question as to how to design, manage and plan these, thus continuously developing, more interdependent and complex infrastructures in a way that ensures their resilience and ability to survive any disruptive events. To achieve this, we need a modeling approach that adequately represents interdependencies between infrastructure systems and socioeconomic agents of the society, which can be used to evaluate the resilience of these complex urban systems with accounting for the interdependencies between constituent systems. Hence, the aim of our work is to present a novel contribution to modeling interdependencies between infrastructure systems and socioeconomic agents, such as households or businesses, as well as the impact of disruptions, which would enable to better represent impacts of disruptions in diverse, spatially non-homogenous urban areas.

The challenge of modeling infrastructure systems and the impacts of disruptions has been attempted by several authors [3][4][5][6][7]. An interesting approach was proposed by Dubaniowski and Heinimann[8][9], who developed a multi-input-output framework for modeling impacts of disruptions on infrastructure systems, households, and businesses. Their approach combined Leontief's input-output model [10] with complex network analysis [11]. However, this approach was limited in its coverage of spatially non-homogenous areas, such that more and less densely populated areas had the same granularity of the model. Hence, our aim is to extend this model by allowing combination of several nested models of varying granularities. This would allow for varying levels of granularity to be included in one model comprising of various models with different granularities within it. The issue is also evident in other fields such as food production [12]. In this abstract, we present the preliminary study of this novel approach.

Model specification

The modeling framework utilized in this study consists of a system-of-systems model of several infrastructure systems, businesses, and households. This is an agent-based model, based on multi-layer complex network approach, where each node corresponds to a business, household, or an infrastructure system provider, and each link corresponds to an infrastructure link between these agents. Under this model, infrastructures are presented in two ways: (1) through infrastructure links between agents, or (2) through agents providing the infrastructure. Each node is formed primarily of an input-output model production process, which represents production process as a transfer of a given set of goods and services into another set of goods and services that could be produced at that agent. Transportation of goods and services happens over links, and is coordinated with a price mechanism, which ensured that cheapest resources are always utilized at each agent in a production process. The price mechanism ensures that system responds to any disruptions by rearranging the supply chains of resources in line with the disruption. The high-level view of the model is shown on Figure 1.

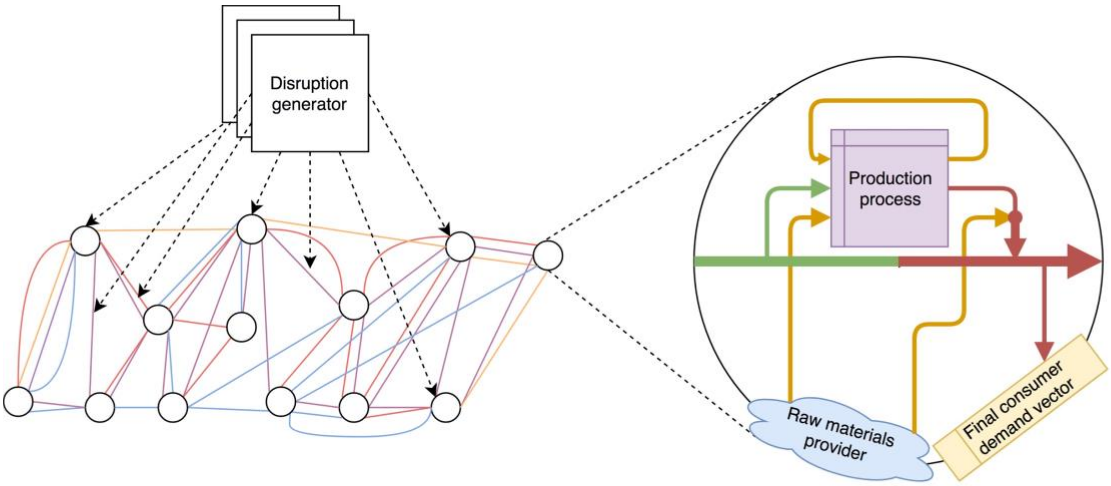

Figure 1: Multi-input output model for modeling disruptions between households, businesses, and infrastructure systems. Each node represents an agent, corresponding to a business or a household, these agents are connected with infrastructure system links.

The model described above could be used to represent urban areas in terms of infrastructure systems, businesses, and households. This is achieved by mapping a certain area to the model by assigning cells of the geographical region to individual nodes of the network. The urban area is divided in the grid, where each cell is represented by an agent-node. However, this approach makes it difficult to represent non-homogenous urban areas. For example, an industrial region consisting of a large amount of closely located factories has very different characteristic compared to a green region with sparse houses. To tackle this challenge, we propose combination of sub-models of varying granularities within one overarching model. In this approach, we represent one or more cells of a coarser granularity model with a much finer granularity model of the same type rather than with an agent-node. The finer granularity model would, for example, include more resources thus providing a better representation of the area. The coarser granularity, overarching model is still used to represent the overall urban area. This approach is presented on Figure 2. As we can see from this figure, an urban area is divided into a grid of cells. Each cell corresponds to a node of the network under the modeling framework. However, certain cells are modeled as an individual instance of the model themselves, rather than as an agent. This results in a better duality with the real-world, where more significant parts of the urban area can be presented as individual sub-models, and hence in more detail. This benefits the overall accuracy of the simulation, which is a desired outcome.

The implementation of the above simulation is achieved using the High Level Architecture (HLA) framework by combining several sub-models into one overarching model. The main challenges that need to be addressed are focused around the interfaces between different granularity models, and their levels. In particular, this includes issues such as mapping finer granularity resources to coarser granularity model's resources, and vice versa in a simulation. Similarly, it is important to formulate the adequate thresholds of granularity that should be devised in order to create an optimal simulation.

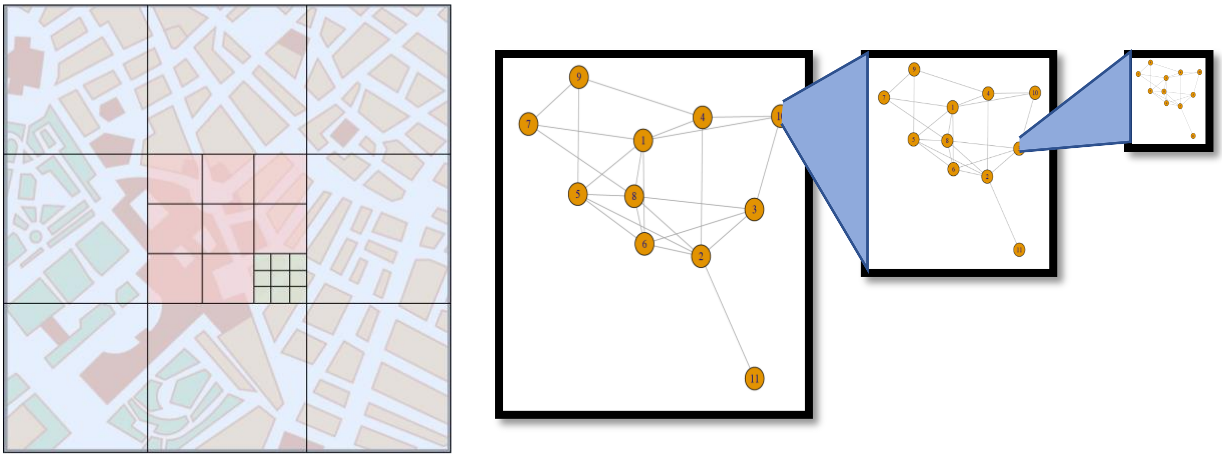

Figure 2: Nested models could be used for more complex regions. An individual agent can be represented by a separate instance of the modeling framework.

Conclusion

The aim of our study is to extend the model of interdependencies between infrastructure systems, businesses, and households by developing an approach to more adequately represent spatially non-uniform areas. This is achieved by outlining the approach of combining models of differing granularities together, thus enabling it to represent non-homogenous areas more accurately.

The major limitation and challenge of our study, is addressing the issue of mapping resources between different levels of granularity in a way that preserves their unique characteristics adequately. Furthermore, optimal levels of granularity need to be established. Finally, a universal approach for selecting the above could be formulated, so that an accurate representation of an urban area can be easily achieved. Then, presentation of the computational framework, and application of the model to a real-world scenario could be attempted.

To address these challenges, we attempt to perform analyses of different mapping functions and approaches to find an optimal solution for the considered systems. Similarly, we focus on devising an adequate depth of this nested approach. Finally, application of the nested approach to a real-world urban area is planned to evaluate the accuracy of the model and its duality with the real-world. Findings of our study could also be applied to other fields where spatial granularity modeling is of significant importance such as to food production supply chain systems modeling [12].

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