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MULTI–SCALE HOSPITAL EVACUATION SIMULATION TO IMPROVE HEALTHCARE RESILIENCE

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ABSTRACT

In disasters, a big challenge of the healthcare systems is the evacuation and mobility of patients. Hospital evacuation simulation considering patients with different mobility characteristics, needs, and interactions, demands a microscopic modeling approach, like Agent-Based Modeling (ABM). However, as the system increases in size, the models become highly complex and intractable. Large-scale complex ABMs can be reduced by reformulating the micro-scale model of agents by a meso-scale model of population densities and partial differential equations, or a macro-scale model of population stocks and ordinary differential equations. In this study, crowd dynamics considering people with different physical and mobility characteristics is modeled on three different scales: microscopic (ABM), mesoscopic (fluid dynamics model), and macroscopic (system dynamics model). Similar to the well-known Predator-Prey model, the results of this study show the extent to which macroscopic and mesoscopic models can produce system-level behaviors emerging from agents' interactions in ABMs.

1 MOTIVATION AND IMPACT

The healthcare system is an essential subsystem of communities which ensures the health and well-being of the members of communities. Hence, the resilience of the healthcare system plays an essential role in the resilience of the whole community. In disasters, patient mobility is a major challenge for the healthcare systems to overcome. This is where the scientific society enters with modeling and simulation techniques to help decision-makers. Evacuation simulation is a potentially helpful tool for emergency responders and policy makers to evaluate different patient mobility strategies and evacuation plans. Evacuation simulation can be classified into three main families: (1) macroscopic models that only consider population size with an estimated exit rate, like the stock-and flow or System Dynamics Models (SDM); (2) mesoscopic models that consider crowds as spatiotemporal densities, e.g. fluid-dynamic models (FDM); and (3) microscopic models, like agent-based models (ABM), that predict the crowd dynamics by considering individual behaviors and interactions. Each of these modeling approaches has specific advantages and limitations. In general, macroscopic and mesoscopic models fail to incorporate social behaviors of individuals in decision-making processes while microscopic models possess the advantage of having the capability of implementing unique behaviors and interactions of heterogeneous individuals by which diverse and unexpected macroscopic responses can be observed, but they are difficult to implement due to complexities in defining exhaustive rules for human behaviors and decision-making processes.

As for spatiotemporal models with multiple types of interacting agents, we can reduce the complexity of models by reformulating the micro-level agents with meso-level population densities and partial differential equations, or macro-level population stocks and ordinary differential equations. While model reduction reduces model complexity, it compromises the ability to predict emergent system-level behaviors that cannot be predicted by simply studying the agent-level behaviors. Accordingly, the goal of this research effort is to study the extent to which macroscopic and mesoscopic models can produce system-level behaviors emerging from agents' interactions in ABM in the context of the movement of crowds with different mobility characteristics and needs, as in patient evacuation. The results of this study provide a spectrum of models for decision makers to evaluate evacuation policies, and insight for modelers about expected behavior of evacuation models on different scales. As for case study, the evacuation of the Johns Hopkins Hospital's Emergency Department will be modeled.

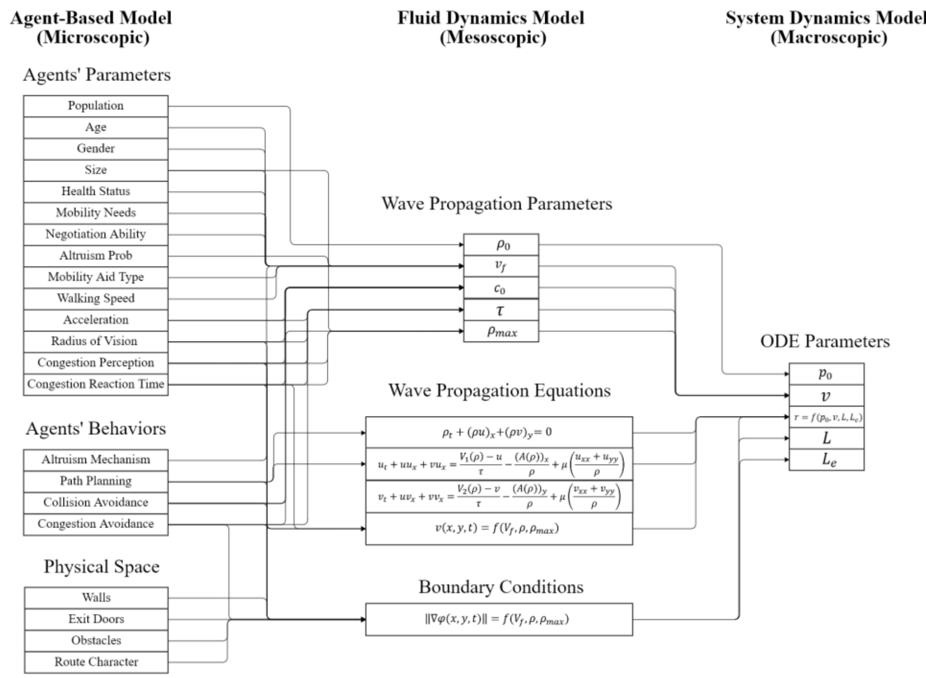

Figure 1: How the ABM reduces to FDM and SDM.

2 MULTI-SCALE MODELS

Microscopic: As for the ABM, agents are classified according to a system of non-ICU patient classification based on mobility needs. Each class of patients can have specific interactions with the environment, other patients, and staff. The agents use shortest path algorithms for path planning and avoid collision and congestions based on a set of rules developed by the author.

Mesoscopic: There is a specific family of mesoscopic models for the simulation of crowd movements using concepts from fluid dynamics and wave propagation. These models adapt the equations from mass conservation and momentum conservation laws in the form of 1D and 2D partial differential equations. A few competent fluid dynamics models can be found in the literature for crowd simulation. In this study, the Payne-Whitham (PW) Model is used (Payne 1971; Whitham 1974), and a method is developed and used to model a meso-level interaction among multiple crowd density waves.

Macroscopic: The SDM is developed by reducing the ABM. Based on the ABM, an equation is developed which gives total exit rate of each class of patients based on room characteristics and population. This equation is used in the SDM as the flow rate parameter where each section of a hospital (room or corridor) is modeled as a stock, consisting of a set of second-level stocks for different types of patients.

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