

Abstract

Society consists of interconnected individuals, groups, and institutions, giving rise to complex phenomena like social norms, epidemics, and crowd flow. Network science offers a powerful framework to model these dynamics by capturing heterogeneity and interactions through nodes and edges. In this work, we explore epidemics and crowd flow through the lens of network science, examining both its strengths and limitations.

The first objective of this work is to explore the network representation for population dynamics and built spaces. From population dynamics, we mainly deal with epidemic models. But network epidemic models are found to be useful in other scenarios like opinion propagation, traffic congestion, and computer virus spreading. The built space model is intended for crowd flow modelling. So the second objective is to develop simulation models for epidemics and crowd flow based on these network models. While simulating a process, one major task is to calibrate the simulation parameters. Thus, we set our third objective to explore the simulation parameters. Sensitivity analyses and parameter estimation methods are studied from the network perspective. While studying epidemics and crowd flow or any network processes, one of the major applications is to control them, often using the allocation of resources. For our fourth objective, we explore resource allocation strategies. For epidemics, we consider testing kit allocation, and for crowd flow, the application is a facility layout planning problem. Studies often point out that network models are less scalable and require more computational resources. So for our final objective, we chose scalability studies for these applications.

We start with modelling epidemics on a network. The population under consideration is modelled as a contact network, and diseases spread through the network from individual to individual. The third chapter introduces two simulation methodologies for modeling epidemics using a contact network. We experiment with different types of network models and conduct exhaustive sensitivity analyses by varying epidemic parameters. To capture the dynamic nature of epidemics, we have computed the effective reproduction number. We then explore graph coarsening methods as a part of our scalability objective.

After the foundational epidemic modelling study, we focus on parameter estimation. Existing epidemic parameter estimation methods mostly follow Bayesian approaches and non-network methodologies. We employ graph neural networks along with network epidemiological models for parameter estimation. To improve the scalability of the approach, we explore graph reduction methods. We approach the parameter estimation method from the perspectives of classification and inference. We do experiments with different types of network models, and the performances are compared against existing approaches.

In the next chapter, we explore two strategies for testing kit allocation using multi-armed bandits. For epidemics, sequential allocation policies can incorporate findings from everyday data and can improve the allocation strategies. Bandit-based allocation does exactly that. The first strategy does prevalence computation using an empirical Bayesian approach, allocation using Thompson sampling and Gittins index, and integrates pooled testing to maximize the kit usage. The second strategy incorporates network models and makes use of graph neural networks to compute prevalence. Both methods are compared against selected benchmarks and proved to be efficient.

For the final chapter, we consider facility layout planning for an airport check-in area. For service systems like airports, crowd flow is a major decision factor. We develop a network representation model for facility layouts and propose a novel network-based simulator for crowd flow dynamics. A simulation-optimization framework is developed with this simulator and a genetic algorithm optimizer. Experiments are conducted using a real airport layout. Results prove the efficacy of the proposed methods.

We have explored the advantages of network approaches in epidemics and crowd flow modelling, and studied applications such as testing kit allocation and facility layout planning. These approaches are found to capture more granular details of the system. However, scalability remains the most critical factor that must be prioritised when planning for real-world scenarios. Overall, the findings highlight the potential of network-based methods to enhance both understanding and decision-making in complex spatial and epidemiological systems, provided that scalability challenges are adequately addressed.