Meta-modeling of an Agent-Based Social Network Model

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Abstract

Understanding the characteristics of social networks is one of the primary goals in computational social science as they constitute scaffolds for various emergent social phenomena from disease spreading to political movements. Here we focus on studying a generalization of the weighted social network model, one of the most fundamental agent-based models for describing the formation of social ties and networks. This generalized weighted social network (GWSN) model incorporates triadic closure, homophilic interactions, and various link termination mechanisms, which have been studied separately in previous works. Accordingly, the GWSN model has an increased number of input parameters, and the model behavior gets excessively complex, making it challenging to clarify the model behavior. We have executed massive simulations with a supercomputer and used the results as the training data for deep neural networks to conduct regression analysis to predict the generated networks' properties from the input parameters. The obtained regression model was also used for global sensitivity analysis to identify which parameters are influential or insignificant. This methodology is applicable to a large class of agent-based models, thus opening the way for more realistic quantitative agent-based modeling.

Introduction

When analyzing the structural patterns of real social networks, the artificial networks generated by models have served as references for comparison and given us more profound insights into their properties (Kertész et al., 2021). Here we wish to classify the models of social networks into two categories: static models and dynamic models. The static models constitute a family of models in which the network links are randomly generated with certain constraints. The class of models includes the Erdös-Rényi model, the configuration model, the exponential random graph model, and the stochastic block models (Newman, 2018; Barabási and Pósfai, 2016; Menczer et al., 2020). Since these models often have analytical tractability, we can infer the model parameters for a real social network analytically; thus, these models are useful as null models. For instance, one can judge whether an observed quantity is significantly different from the expected null-model value or not, thus serving as hypothesis testing.

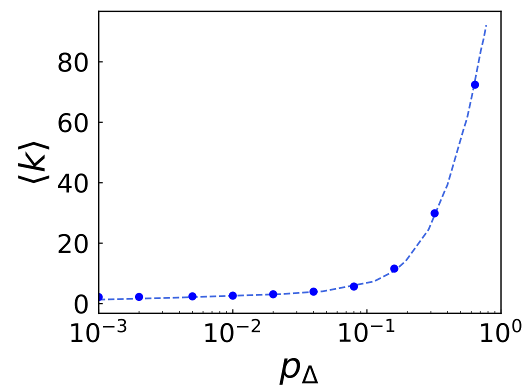

Figure 1: Average degree $\langle k \rangle$ of the GWSN model as a function of the probability of triadic closures p_Δ. The points are obtained from the simulations, while the curve indicates the prediction from the regression model, indicating that the metamodel reproduces the simulation model well. Other network quantities, including clustering coefficient and assortativity, also show good agreements. Details are in Murase et al. (2021).

On the other hand, dynamic models or agent-based models describe how the network evolves as a function of time. One of the primary objectives of the dynamic models is to find the mechanisms that lead to specific structures observed in empirical networks. Here the models are defined by the rules on how nodes and links are created or deleted to incorporate the perceived mechanisms of the evolutionary processes of social networks. This class includes Barabási-Albert scale-free network model and its generalizations, as well as Kumpula et al.'s weighted social network (WSN) model (Kumpula et al., 2007). The latter will be the focus of the present paper. These models allow us to get insight into how and why the observed networks have been generated and, more importantly, predict the possible evolution of real networks.

While the static models are often analytically solvable, the analytical tractability of dynamic models is limited to some basic cases. These basic models are usually designed to be as simple as possible to identify the most critical mechanisms, yet they should not be considered for quantitative comparison and prediction. When models are extended to incorporate aspects of reality, understanding their behavior becomes a formidable task since the parameter space is high-dimensional and non-trivial relationships between the parameters may occur. This makes choosing appropriate parameters or understanding the model behaviors practically impossible.

Indeed, a couple of extensions to the WSN model have been proposed to consider more realistic aspects (Murase et al., 2014, 2015, 2019), each of which leads to non-trivial and non-linear consequences. While these additional mechanisms were studied independently in previous works, these mechanisms coexist in real-world social networks, which, if incorporated within one model, pose a challenge because they often interact in non-trivial ways.

In this work, we overcome this difficulty with the high-performance computing (HPC) approach and the development of metamodels to investigate the parameter space of an agent-based model of social networks. We performed a massive number of simulations and used these simulation results as training data for a neural network model to either infer or analyze the properties of the generated networks. Such a regression model is called a metamodel or surrogate model as it is a model of a simulation model (Wang and Shan, 2006). Metamodels are developed as approximations of the expensive simulation process to improve the overall computation efficiency. They are found to be a valuable tool to support activities in modern engineering design, especially design optimization. Once a good metamodel is obtained, it is helpful for various purposes, including parameter tuning, understanding of the model behavior, and sensitivity analysis. The metamodel is effective, especially when the simulations are computationally demanding, which is the case for agent-based models with many parameters. To the best of our knowledge, this study is the first attempt to apply the metamodeling approach to an agent-based model of social networks.

First, we conducted about 25 million independent Monte Carlo simulations whose input parameters were randomly sampled from the 10-dimensional parameter space. Each simulation typically finishes in 10 minutes, while some require longer computation times significantly. Using these simulation results as training data, we conducted regression analysis using deep neural networks to learn the simulation model's input-output relationship. Here the input is the input parameters of the agent-based model, such as the probability of forming a tie via triadic closure, and the output is the network quantities such as average degrees and clustering coefficients. Figure 1 shows an example of the regression model, showing how the average degree changes as the probability of triadic closure p_Δ changes. The points are obtained from the simulation, while the dashed curve is obtained by the regression model. As shown in the figure, the regression reproduces the simulations pretty well. Although the parameters other than p_Δ are fixed to certain values in this figure, the regression model works for different parameter values as well.

Once the metamodel is constructed, the computation of the network quantities is pretty fast, which can be used for a wide range of purposes. Here, we conducted a sensitivity analysis, a statistical method to evaluate how the uncertainty in the output of a model or system can be divided and attributed to the uncertainty in its inputs. It tells which input parameters are essential and which are not. We adopt the variance-based sensitivity analysis proposed in Saltelli et al. (2010) among the various methods. Figure 2 shows the sensitivity indices for each input parameter. It shows that p_Δ is the most critical parameters that affect the average degree significantly.

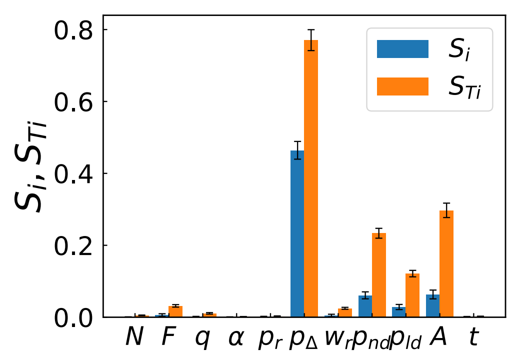

Figure 2: Variance-based sensitivity analysis of GWSN model. Sensitivity indices for each input parameter are shown.

The metamodeling approach demonstrated in this study should be useful to a wide range of agent-based models. We believe that this work opens the way to more quantitative and predictive agent-based simulations of human behaviors, leading to practical applications. This study's details, including the model definition, other numerical results, and methods, are published in Murase et al. (2021).

Acknowledgments

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