Understanding Emergent Social Phenomena

Methods, Tools, and Applications for Agent-Based Modeling

Extended Abstract

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Introduction

Agent-based modeling is a new branch of computer simulation, especially suited for the modeling of complex social systems. Its main tenet is to model the individual, together with its imperfections (e.g., limited cognitive or computational abilities), its idiosyncrasies, and personal interactions. Thus, the approach builds the model from 'the bottom-up', focusing mostly on micro rules and seeking the understanding of the emergence of macro behavior.

Agent-based models are, as is the case with any scientific model, drastic simplifications of reality. In particular, as the agents of such models often represent human beings, it is easy to feel objections towards such 'caricatures' of humanity. This problem is almost entirely missing from the natural and engineering sciences. Therefore, special care must be taken in preparing these models and in interpreting the results gained. This is why agent-based models normally aim at deepening our understanding of a given system, and providing existence proofs and sufficient conditions for certain phenomena, even though, the method is perfectly capable of developing quantitative predictions. This standpoint is not as uncommon in the social sciences as it is in the natural and engineering sciences. Nonetheless, the understanding gained from agent-based models can be incorporated in research using a different methodology, for example, in the development of a predictive model. Therefore, agent-based models are also viewed by some as a 'stepping stone' for predictive models.

The current trend of applying agent-based models in the social sciences started in the mid-1990s. Being a computational method for researchers in the social sciences who are normally not well-skilled in programming, agent-based modeling also offers significant challenges for practitioners of computer science and information technology. In 1996, when the work summarized in this thesis has started, agent-based modeling and simulation had no standards, no widely adopted methodology, and no well-articulated best-practices. Only a single dedicated toolset existed (Swarm), and even that only in a prototype version. Most agent-based models were written using ad hoc programming techniques and languages. Due to the lack of implementation and publishing standards, these models were 'black boxes', their results were impossible to check or replicate. The last decade has seen an intensive, yet unfinished development of the method, both in understanding the advantages and limitations of the approach and in furthering the (both technical and methodological) toolset of agent-based modeling. The current practice consists of following published guidelines in designing the models and selecting among a set of well-established simulation packages. Applying formalized best practices in implementing the simulation is also becoming common, which helps in publishing a model description that fully specifies the behavior, yet many times more concise than the source code.

In this dissertation I summarize my contributions to the development and application of the agent-based modeling method. I introduce a framework that helps classifying modeling approaches; I present a programming language for agent-based modeling; and I formalize a set of implementation 'best practices'. I also present two applied models using the above results: one in spatial economics and one in econometrics. The former gives an explanation for an empirical regularity found in statistical surveys of US metropolitan areas, while the latter shows the importance of social networks in aggregate choices of groups.

Detailed Summary of the Results

The dissertation is structured in three parts, each of them containing two chapters. In the first part I give an introduction to agent-based modeling and simulation. In the opening chapter I provide an overview of the method, addressing questions related to the methodological-philosophical position of the approach. This is followed by *Chapter 2*, where I define a conceptual framework that helps classifying computational simulations. It yields four implementation strategies ranging from 'equation-based' to 'agent-based' modeling.

Agent-based simulation is often contrasted to traditional, 'equation-based' modeling and simulation. While the latter approach is not properly termed as all computational models are, in fact, 'equation-based'; significant differences exist between these approaches. The proposed conceptual framework highlights these differences and shows that more than these two choices are possible. The framework consists of five conceptual *levels*: the level of consideration (LoC), the level of representation (LoR), the level of dynamics (LoD), the level of information (LoF), and the level of interest (LoI). Specifying these levels in case of a particular modeling problem is at the discretion of the modeler, but equating or differentiating these levels results in different *implementation strategies*. Working with a case study I discuss the possible consequences of these strategies, ranging from an 'equation-based' approach to an 'agent-based' strategy. (See Figure 1.)

	1. step (Krugman)	**2. step (Marionettes)**	**3. step (Autonomous agents)**	**4. step (Bounded rational agents)**
Information (LoF)	Global	Global	Global	Local
Dynamics (LoD)	Market (business) shares	Market (business) shares	Firms	Firms
Representation (LoR)	Market (business) shares	Firms	Firms	Firms

Figure 1. Summary of the 4 studied systems in the case study of *Chapter 2*.

In the second part I summarize my contributions to improve the toolset of agent-based modeling. I present two groups of computational tools to assist modelers in developing agent-based simulations. In *Chapter 3* I present the Multi-Agent Modeling Language (MAML), the first programming language dedicated to the development of agent-based simulations (developed in 1998-99). MAML is a *domain-specific* programming language, in the sense that is it fully dedicated to agent-based simulation. Yet, unlike many other modeling platforms, MAML is unbiased towards the problem domain the particular agent-based model is aimed at. Moreover, it makes no restrictions on the structure of the model or that of the agents. MAML is equally useful, among others, for spatial, cellular automata like models, for network simulations, or for models of agents with complex cognitive capabilities. These latter properties make it *domain-independent* with respect to the problem domain and the model structure.

MAML was developed for non-professional programmers. Therefore, the main motivations in its design were easing the creation of agent-based simulations, and making the modeling decisions explicit and easy to follow. To this end, MAML offers keywords and language constructs specific to computer simulation and agent-based modeling. With its well-defined modeling constructs MAML has also contributed to the emerging standardization and methodological maturity of the practice of agent-based modeling.

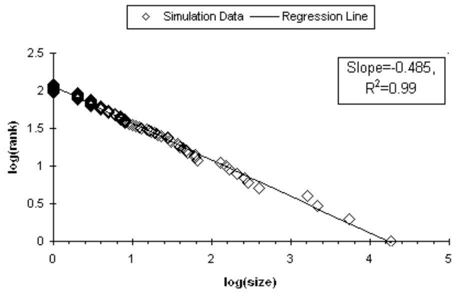
In *Chapter 4* I propose *design patterns*, a software engineering concept, to describe implementation practices common in agent-based simulations. Computational simulations and thus agent-based models are computer programs. Therefore, they involve programming work that modelers, especially students of the social sciences, often do not excel in. This fact contributed significantly to the non-standard, often ad hoc nature of agent-based models at the advent of the method. With time, best practices started to emerge and spread, but in an unordered fashion, mostly in personal communications, following social links. Similar problems were faced earlier by software engineers in professional software development. In response, the concept of *design patterns* was developed to provide a standardized way to describe and communicate application-independent 'best practices' in design and implementation.

Building on this concept, I introduce three patterns that help developing more robust and methodologically correct simulations: the Simple Model, the Model-Agent-Environment, and the Relational Interaction patterns. The first formalizes a solution for simulations with simple event structures, mainly for modelers who are novices to agent-based modeling. The second helps building simulations that are flexible with respect to different interaction topologies, and can effortlessly be checked against various communication structures. Finally, the Relational Interaction pattern furthers the goals of the Model-Agent-Environment pattern and provides an implementation-independent view of the interaction topology that is able to handle multiple, parallel structures easily.

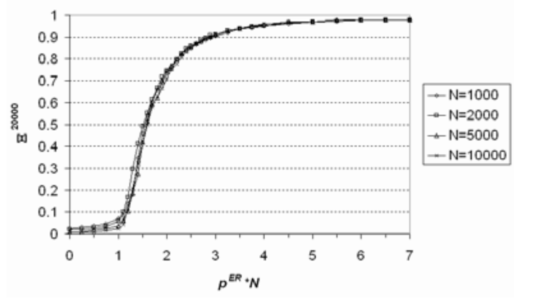
The third part is dedicated to applications of the method and of the tools discussed in the first two parts of the thesis. In *Chapter 5* I present an agent-based model of endogenous city formation where bounded rationality is modeled as limited access to information (i.e., vision). I show that if sufficient heterogeneity is present in this property of the agents, the rank-size distribution of the cities generated by the model replicates the statistical properties found in US survey data.

The rank-size distribution of US metropolitan areas displays an interesting regularity. According to US statistical surveys, the population of a city is inversely proportional to its statistical rank. This empirical regularity has received special attention in the economics and complexity science literature, yet, arguably no plausible explanation has been proposed so far considering individual-level decisions. In this application of the agent-based modeling and simulation method, I build on the case study discussed in *Chapter 2.*

Finally, in *Chapter 6* I introduce another model, one that studies social influence in a setting of repeated discrete choices. Econometric discrete choice analysis is a standard tool in many modeling domains, including transportation demand modeling, the practical motivation for this work. It allows for the computation of individual choice probabilities, given the heterogeneous agents' evaluation of alternatives. However, as Dugundji points out, the method is fundamentally grounded in individual choice, while it seems plausible to assume that social networks influence individuals. [1] Therefore, recent works in the field have focused on incorporating the interdependence of various decision-makers' choices, i.e., social influence.



Rank-size distribution of simulated cities (*Chapter 5*) on a log-log plot, together with the line yielded by linear regression.



Phase transition of aggregated behavior on Erdős-Rényi networks. (*Chapter* 6) The individual points represent the average values over 100 measurements.

Figure 2. Results from the third part (applications) of the dissertation.

In this application I build on the ability of the agent-based method to explicitly model the interaction among the agents. Using this capability, I propose to study social influence in a class of discrete choice models using well-understood generative models of social networks. Furthermore, I present an agent-based version of the given model class, with special focus on the agents' interaction topology and study how this topology effects the system-level, aggregate decision made by the agent population. I show that the phase transition in the underlying network model carries through to the aggregate choice made by the population both in the case of Erdős-Rényi and Watts-Strogatz networks. This finding has a practical importance in discrete choice analysis, as empirical studies may test whether real world networks belong to a given network class, while they may never be able to chart the actual social network. In particular, on small-world networks the system level outcome can be approximated by the, theoretically simpler and easier to handle, fully connected case.

Selected publications on the topic of the dissertation

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