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Modelling Cities as a collection of TeraSystems – Computational challenges in Multi-Agent Approach

Mariam Kiran*

School of Electrical Engineering and Computer Science, University of Bradford, Bradford, UK, BD17 1DP

Abstract

Agent-based modeling techniques are ideal for modeling massive complex systems such as insect colonies or biological cellular systems and even cities. However these models themselves are extremely complex to code, test, simulate and analyze. This paper discusses the challenges in using agent-based models to model complete cities as a complex system. In this paper we argue that Cities are actually a collection of various complex models which are themselves massive multiple systems, each of millions of agents, working together to form one system consisting of an order of a billion agents of different types – such as people, communities and technologies interacting together. Because of the agent numbers and complexity challenges, the present day hardware architectures are unable to cope with the simulations and processing of these models. To accommodate these issues, this paper proposes a Tera (to denote the order of millions)-modeling framework, which utilizes current technologies of Cloud computing and Big data processing, for modeling a city, by allowing infinite resources and complex interactions. This paper also lays the case for bringing together research communities for interdisciplinary research to build a complete reliable model of a city.

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Keywords: Interdisciplinary resarch; socio-economic; Cloud computing; big data; agent-based models; city modelling

1. Introduction

A city is an extremely large-scale complex and distributed system that is extremely dynamic in nature and constantly evolving. Complex systems are composed of many interconnected individuals elements, working together

* Corresponding author. Tel.: +44 1274 23 4019; fax: +44 1274 23 4111.
E-mail address: m.kiran@bradford.ac.uk

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to produce an overall behavior of the system. Examples of such systems include ant colonies (composed of individual ants cooperating to exploit the available food sources), human nervous system (composed of tiny neurons sending and receiving signals in the human body) or social structures (humans communicating in networks) as some of the commonly seen complex systems studied. These individual behaviors determine the overall behavior of the system as a whole. Depending on the kind of the system, the individuals will behave in organized or disorganized ways, sometimes producing unpredictable system behavior. This phenomenon is referred to as an emergent behavior, which is a direct consequence of the behavior of the individuals inside the system.

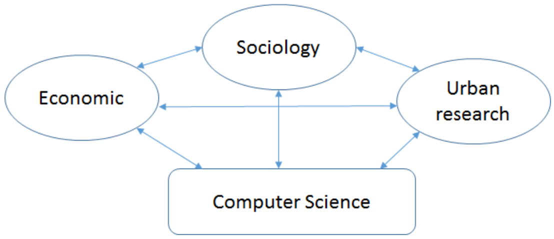
Complex systems need to have mechanisms such as memory for storing information, computation input/output and actions, reward systems assigning credits for the interacting individuals or agent. An agent refers broadly to a bundle of data and behavioral methods, which represents an entity in the computationally constructed world. Agents are designed as problem solvers, having some memory, functions and goals they want to achieve. Being either reactive or proactive influences the decision-making mechanisms of the agents in the models. Final results of unpredictability gives rise to the emergent behavior which often difficult to test in simulation. Various agent-based modeling toolkits have been produced and compared suitable for different scenarios being studied[6].

The agent artificial worlds are computer implementable stochastic models with micro entities interacting with each other and the environment in prescribed ways. This world can thus exist as a 'state', which includes the state of the environment, a population of the micro-entities and the attributes of each of these. These states can combine to produce a history of events. These ordered sequences of states are the representation of the world with the progress of time. This logic has been used to describe agent-based model in various disciplines[1]. Each model is different, based on different perspectives and assumptions of the modelers themselves. A few common issues across them are:

- Variables: Each model is made up of variables and equations as a representation of the real system. If any of the variable changes, it affects the model. For example, exchange rates in currencies or interest rates in an economic model.
- Limits: Every model has limits as to what system it is modeling depending on the modeler's assumptions.
- Different kinds of people and behaviors: Some consumers might be lazy while others spend more than required, on products. There is heterogeneous mixture of individual characteristics.
- Testing: Designing a test suite for testing different assumptions. This involves period testing where variables were the same for periods 1 and 2 but changed in period 3. Most models get rejected due to this[1].
- Rules: Rules are determined for some formulation of the past. These rules should be continually updated using learning methods. These learning methods will be conditional to the agents.
- Behavioral uncertainty and learning in agents: Social economic system analysis largely avoids questions on how economic agents make choices in an evolving world. Holland et al. [2] argued that this is why most modelers turn to game theory to model the strategic learning in games.
- Models are dispersed with parallel interaction among heterogeneous agents. Heterogeneity implies that each individual is different from the other in terms of memory and characteristics.
- Bounded rationationality: agents evolve based on their local interactions forming niches.
- Notion of equilibrium: Most socio-economic models try to work away from the optimum or equilibrium because they are constantly trying to do better and never know whether they have reached an optimum point.

Agent-based model engineering orients towards how the requirements and the system are represented. Use of formal specification methods and different processes to capture internal and external concepts of multi-agent systems has been highly researched[3,4]. Various approaches have been discussed on how the behavior of the system can be represented using semantic approaches such as model checking[5].

Modeling a city will involve modeling financial, transport, social and energy market models to work and interact together. EURACE model is a first ever example of multiple markets of credit, financial and labor markets working together, which was able to demonstrate how changing taxes in one model affected migrations patterns in the labor market and energy crisis of the EU over a period of time[7].



2. Towards Modeling a City of Agents

Fig. 1. City modeling needs a closer multidisciplinary relationship between various disciplines.

Constructing a model of a city is a cumbersome task, involving various disciplines to come together (Figure 1). Computer Science forms the base, which will enable the computational construction of the model to simulate on various architectures. However, to be able to develop correct models, there needs to be a closer communication between all disciplines involved, researchers as well as industries. An early example of a complex city was given by Johnson[8], where the city itself behaves like one individual system but consists of a number of thriving neighborhoods within it. Each neighborhood consists of a collection of people involved in complex networks like the traffic networks. Similar to the ant colonies, the city is a system, which has decentralized control learning from local interactions making the man-made self-organizing system using emergence. A city consists of socio-economic activities and interactions between individual 'decision-makers' such as firms, households, industries and national economies. SimCity (http://www.simcity.com/) is an example of a very popular simulation game that involves building a city from scratch. Players act like mayors of the city and are faced with challenges of setting the correct tax rates and other disasters scenarios.

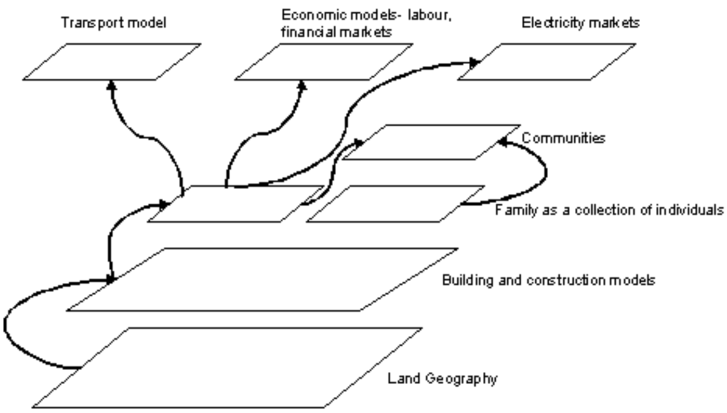


Fig. 2. A Tera Model of a city constitutes of various sub models.

Modeling an individual city involves an intense process of designing, hypothesis formation and realizing the issues being modeled of the real world. Fogel[9] discusses a scientific process involved in forming a model from a real world representation of a city. However the process needs further analysis, (1) Modelers have to identify the macro-issues being represented in the model hypothesis. (2) Identify the mechanisms and agent behavior specific to each model. (3) Identify the macro variables used to study the impacts and uncertainty in the model. (4) Analyze effects of groups and communications among them and impact they have on models; (5) Methodological applications to find efficient solutions for the City model.

A *tera* model of a city involves a number of subsystems working independently and with each other to ensure a correct working of the city as one. Each of the sub system (figure 2) is located on basic geography and ecological models which host agents such as people, families and communities living together. These people have jobs represented by economic models allowing them to commute to work, represented by transport models. The day-to-day activities of the people are affected by weather, which are fed in through environment variables, and influences their use of energy that is represented by the electricity market models. Each sub-model needs to design and described from research experts in the domains as a set of agents, the states of each subsystem, input and output variables, which will allow each sub model to be, connected to other sub models. Properties of each subs system can be described as a set of rules and timed events to ensure a correct representation of each sub model in the *tera*system.

The sub model researchers need to work together to identify the global variables that are emerging from the tera model's behaviour for monitoring the city. Some possible examples of overall behaviour include emerging societal norms at lower and global levels of the system, the resilience and vulnerabilities of certain sub systems and the effect it has on other subsystems such as the credit crunch on the labour market, the optimization for design tools for urban planning or supporting new laws.

Creating models of cities can help understand how the various networks evolve and interact with each other, creating more efficient infrastructure. IBM[10] has constructed a list of city functions, their current status and future possibilities. However, computationally creating such a model is a huge challenge. By building each sub model of thousands of agents gives rise to immense data processing which is need to drive the simulations and also to later analyse the data. Certain sub models also do not have reliable data sets to compare results to which risks the credibility of the models created.

Cloud resources are attractive due to the hardware/software resources on-demand which are usually not available to researchers for use to perform scientific applications which require massive amount of data processing particularly in modelling of systems biology or social sciences, applications. For example, authors[13,14,15] have demonstrated using cloud resources for building uncertainty quantifying applications for systems biology applications discussing how to efficiently utilize data/resources. Cloud computing is deemed to replace high capital expenses of infrastructures with lower operational ones, such as to renting cloud resources on demand by the application providers. However, with static resource allocation, a cluster system would be likely to leave 50% of the hardware resources (i.e. CPU, memory, disk) idle, thus baring unnecessary operational expenses without any profit (i.e. negative value flows). Moreover, as clouds scale up, hardware failures of any type are unavoidable. Some researchers have explored how scientific workflows can be used to efficiently manage scientific workflows for resource allocation for cloud models discussing problems of multi-task computation and high demand throughputs. Wittek et al.[12] have argued of an open-source framework to design and execute large-scale social simulations in cloud computing settings and present constraints on the pattern of execution, providing a cost-effective solution for social scientists. However this work focuses on using cloud based HPC only.

3. Identifying Research Challenges in Tera City Modeling

The drive toward Smart City research has given rise to businesses and governments proposing efficient solutions to use sensors and ICT technologies, in order to make intelligent decisions for city functions. Cloud infrastructures and open data have now become easily accessibility by industry and city councils gathering real-time data for decision making. Figure 3 represents the computational architecture of a framework for city agent-based modeling/simulation, with research areas/problems (RA) raised:

RA1: Various research communities need to work together to build their own sub models and identify the variables and agents by which these sub models can work with each other. The model integration can either be done consecutively, where each model simulates along with others or, iteratively, where models finish each of their simulations one after the other. This affects the macro variables emerging.

RA2: Each model contains a number of assumptions about the agents or their behavior when they try to map the real world. These assumptions can affect the results of each of the sub model or because of their integration; affect the results of the emerging global variables. Therefore these need to be documented with the effect each assumption will have on the overall performance of the *tera* model.

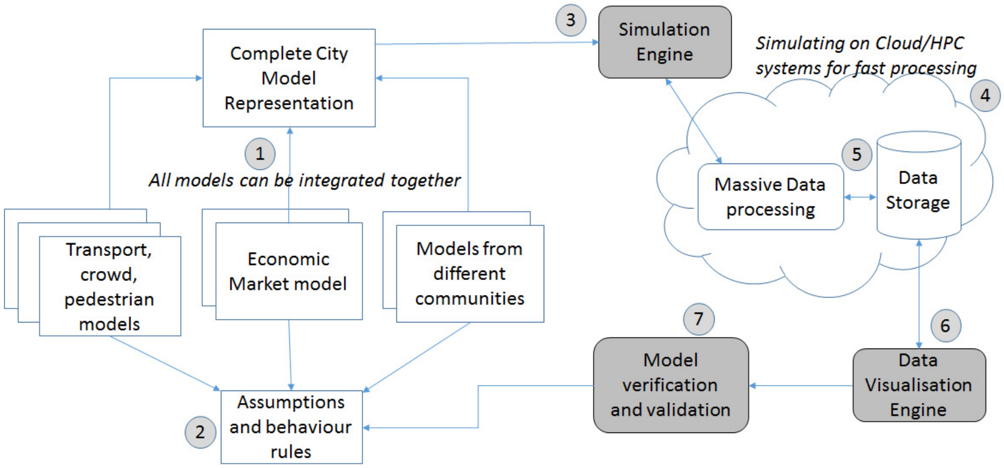


Fig. 3. Proposed Framework for Tera Modeling for a City.

RA3: Need for a common language to define each of the sub models is necessary. The simulation engine will take this as an input and compile the complete city model as one. Various modeling languages have defined their own schemas to describe and document models[6]. A model definition language should be able to define how models are integrated and merged as one.

RA4: The resulting model will have an order of millions of agents representing various individuals and performing various functions in each sub model. Therefore there is a need for fast processing and data processing. Past modeling techniques, which involve large-scale system, modeling have used high performance computing grids and GPU cards to quickly process large complex equations for multi-massive variables to produce emergent solutions to predict how systems behave[11]. However these techniques are hindered by number of architectural issues, which limits the power of agent-based modeling techniques for producing larger systems due to memory available, system architecture and processing time. Porting agent-based simulations on Clouds for high performance computing, allows researchers access to unlimited virtual resources and data storage for their models. However this still raises a number of Cloud computational research issues still under development, such as (1) Performance concerns for processing and scalability during simulations. (2) Enormous amounts of data being produced/processed to study simulations (3) Secure access to shared models/data for research community.

RA5: The massive amounts of data processing will require massive amounts of data storage as well which may either be consistently read/written to a database or just dumped for analysis later. Access to data storage raises concerns among various communities not having access to the necessary hardware to enable this. Adoption of the MapReduce computing model and the open source Hadoop system for large scale distributed data processing, and a variety of ad hoc mash up techniques that weave together Web applications will be able to cater to this research area. However, these are just first steps towards managing complex tasks and data dependencies in the Cloud, as there are more challenging issues such as large parameter space exploration, data distribution and optimization.

RA6: After the simulation data has been produced, an additional data visualization engine using various machine-learning techniques is needed to analyze the data. These issues are tackled as Big Data problems in order to perform analysis on massive amounts of data being produced.

RA7: The overall model of the city is based on a number of sub models integrated together. Due to the emergence of macro variables the model needs to be verified and validated to analyze whether it is a correct and reliable representation of the city to be able to perform analysis on. Software testing of emergence is a complex problem because of the underlying emergent and sometimes random phenomenon exhibited in these models. If the model is not reliable, a further analysis can rectify the assumptions in the sub models, to identify the reasons of the overall city model errors and failures.

4. Conclusions

Cloud computing is gaining tremendous momentum in both academia and industry, more and more people are migrating their data and applications into the Cloud. A system of the city can prove useful especially after the recent advances in open and big data markets. It will also enable localized case studies to be conducted on the model. However the research challenges discussed above prove that further work needs to be done to utilize the true potential of Cloud and virtual processing for building massive models.

Tools that support extreme-tera scale system modeling and analytics, where data and models can be shared can bring various expertise together to build reliable city models and open further research issues of analyzing dependability and performance of simulating complex systems in terms of quality of service on the clouds, further tools and techniques to make more informed decisions on the computational side. And on the social-economic research side we can ask questions like why certain norms emerge in society, why some companies perform better, does the correct timing and policy hold the key to success, and others which require a complete understanding how cities work.

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