The Importance of Simulation Modeling of Different Systems, with an Emphasis on Agent-Based Modeling

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Abstract: Simulation modeling has become a key instrument for planners and decision makers over the years and its development has increased the accuracy of the resulted data and the efficiency of the simulated model. Agent-Based Modeling is being used in a vast variety of areas, helping in developing new applications, new transport systems, increasing the security of different infrastructures and even helping to manage natural disasters. This modeling technique has a lot of benefits over physically simulating the environment and this accounts for its growing use. This paper presents the importance of simulation modeling, highlights key applications and focuses on tracing the evolution of agent-based modeling in the field of transport.
Keywords: Simulation, Agent-based Modeling, Cybersecurity, Natural Disasters, Transport Planning

INTRODUCTION

Simulation modeling is used to solve real world problems and scenarios with safety and efficiency in mind. Running these simulations gives a very major analysis technique which is straightforward to grasp, verify and communicate. Across many different industries and areas, simulation modeling helps resolving real solutions by providing clear insights while also simplifying complex systems. The present article presents the use of this very important capability and focuses on agent-based modelling in a transport context.

Simulation modeling enables experimentation on a digital simplified representation of a more complex system or infrastructure. Unlike physical modeling, simulation modeling is computer based and by using algorithms, equations and other mathematical functions, simulates and models the real-world counterpart of the infrastructure. Simulation programs help visualize a dynamic environment with the purpose of analysing the data after testing different situations and changes within the system.

The uses of simulations in a business environment are varied. They are commonly employed when conducting different experiments on a simulated version of a real-world system. The ability to visualize the model as it is running the test is what sets simulation modeling apart from other simulation methods such as applied mathematics or linear programming (Bonabeau, 2002). By having the ability to examine processes while the simulation is running and to interact with it in action, those running it gain a better understanding of the system in question.

The alternative to simulation and modeling for certain types of systems is prototyping and testing. Prototyping a product can become very expensive in more complex systems which could significantly delay projects. Simulation modeling offers a practical alternative for running different tests while also stressing the designed model to the limit loads which sometimes is possible only in a virtual environment.

THE CASE FOR MODELING AND SIMULATIONS

Finite element simulation, when used early in the design process, can point a product developer in the right direction which may meet most of his conceptual ideas. Whether developing a brand-new software, improving on an existing one, or attempting to discover the basic explanation for a failure in a product, a simulation might not always provide the answers immediately. However, it can help in making an informed decision and in finding the root of the problems with the product. While simulation modeling can help point engineers and developers towards a more polished product, simulations may also lead to failures if not carefully and objectively evaluated. Creating a useful simulation for a complex system can be very time consuming and should be carefully programmed and looked into. Not adding all the different equations, possibilities and scenarios to a simulation can be very detrimental to the finished data generated by the tested simulation. Oversimplifying a complex system should not be done when precise data is needed. A complex system should be split into smaller ones and be tested within more simulations. The simpler the simulated model, the more precise the data is. After all the different tests, the data should be put back together to find the desired results.

Simulating a concept can also be very important before even starting to build it. The simulated model can show quite clearly how the real-world model should work and how different design flaws can be fixed before starting the development process.

Simulation and modeling are the preferred option in polishing a design and optimizing it. Many sophisticated designs can be compared and contrasted with the help of simulation modeling in a short period of time. One of the main advantages of simulation modeling is best seen when the engineers put their design through extreme loads and conditions that are almost impossible to reproduce in a lab. Simulating conditions in a testing facility is much more difficult than virtually simulating conditions, and in some cases impossible, which increases the accuracy of a test.

For example, in aerospace product development, placing prototypes in wind tunnels allows developers to evaluate the performance of the product in a simulated environment. Seeing the impact a product's environment has on it, such as wind and natural events, is more difficult in a physical lab than in a virtual environment. Simulation modeling helps stakeholders more easily understand the effects on the tested product, ensuring that the product meets specifications in the envisioned operating conditions.

Modeling and simulations help companies become smarter and more efficient in developing products while reducing unnecessary burdens and costs associated with physical prototyping and lab testing. Today, it is not only the products and their behavior under loads that are simulated but also most business and commercial aspects such as supply chains, manufacturing lines and even public transport.

SAFETY AND SECURITY

Running regular simulations of critical infrastructures can also lead to increasing their security and preventing cyberattacks. Testing the security level of a critical infrastructures can also reveal weak points or security breaches which would not be discovered by the infrastructure operators without the simulation of the model.

In recent years, a number of simulation modeling efforts have taken place when it comes to natural disasters. A lot ofdevelopment and effort has been put into this particular domain which is a real concern for a wide variety of stakeholders.

In analyzing natural disasters, there are several research teams that have to work together, intervene and perfectly coordinate their activities in order to safeguard the maximum number of lives possible and minimize damage. For maximum effectiveness, they have to define an organizational structure and adopt a lot of policies in order to improve their performance. The organizational structure and the policies are very important elements that have to be taken into consideration to simulate a real emergency (Grimm, Volker, Railsback, Steven, 2005).

A NON-EXHAUSTIVE PRESENTATION OF REAL – WORLD APPLICATIONS

NATURAL DISASTERS

The management of natural disasters is becoming more and more complex because of the unpredictable nature of certain events which are becoming more frequent and more powerful in the current security environment and under well-known trends, such as climate change. Hence, crisis and emergency situation management encounters important difficulties, while adapting systems to the future state of the environment to meet minimum expectations of functioning, resilience and viability become extremely challenging. The decision makers and the various teams need tools to assist in planning, training and improving responses or system performance.

Simulations are one of the means that can be used by these rescue teams to predict their behavior during a natural disaster. Over the past few decades, natural disasters such as floods, cyclones, earthquakes, volcanic eruptions and droughts have resulted in significant casualties (and very high levels of at-risk population) and affected the lives of millions of people worldwide. These have caused disease as well as large-scale economic losses and displacement. Therefore, simulating and modeling the rescue procedure may help to facilitate the coordination of the team and limit the impact of the event on society. These simulations may improve the efficiency of the rescue teams in the field which leads to reducing losses and damage while also saving lives. 'Multi-agent systems' are among the methods used for modeling and simulating different natural disasters and situations. A MAS can model the behavior of a set of agents/ entities, more or less organized. Agents have a level of autonomy and are immersed in an environment in which and with which they all interact. Modelers and developers can also use MAS to create a computer representation of dynamic events such as natural disasters. Therefore, the application of MAS in a certain area can help managers to experiment and simulate a wide range of possible scenarios for a disaster and assist the rescue team in making decisions. This approach involves the simulation of systems in terms of models and their usefulness. 'Agent-Based Simulation' has many uses in a vast variety of areas such as geography, economics, physics, chemistry, biology and ecology. A great feature of 'Agent Based Simulation' is the ability to capture and represent different dynamic models and scenarios which often consist of multiple entities which have decision-making components programmed inside of them.

Multi-agent-based systems are powerful modeling techniques for simulating interactions in a dynamic complex system and is distinctive from other modeling techniques because of its ability to simulate situations with unpredictable behavior (Andrei & Alexei, 2004). Current technological developments allow us to model systems which include all of the aspects of the natural disaster, its impact on resources, infrastructure, population, the environment, the economy etc. One of the key reasons why people choose 'Agent-Based Simulation' over other alternatives.

ASSESSING NETWORK SECURITY RISK

In today's highly-connected society, computer networks have become an important component in the systems that make up the critical infrastructures of the world. All of the critical infrastructure's components rely heavily on secure computer networks to function correctly. These critical network systems are under a constant threat of cyber-attacks. The most frequentlyattacked infrastructures are the ones in transportation, finance, energy, telecommunications, agriculture and healthcare. One common network attack type targets unauthorized devices and hardware components connected to the network. Such devices are targeted because they are more vulnerable to attack being mostly unmanaged and, thus, more likely to have vulnerabilities (Arokia & Hunmuganathan, 2011).

Moreover, unauthorized devices may already be compromised when entering the network and be used to compromise other devices connected to the same network. For network protection, administrators have to anticipate certain types of cyber-attacks and put in place a defense and safety system in order to stop them or minimize their impact. However, strategies and types of network attacks are very specific to the network environment in which they are executed. In general, there is a high number of different possibilities and scenarios that must be considered when thinking about implementing a capable security system within the network. Testing all of the available scenarios for a real-world system can be very expensive and goes beyond the budget of the company. Thus, the selection and evaluation of effective network defense mechanisms and policies is very difficult and often subjective due to the task being left to the judgement of the administrators and the security department.

Modeling and simulations are often used to remedy this time and budget consuming problem by allowing stakeholders to test in multiple environments different scenarios at a lower cost. Agent-based systems use a computational simulated model of autonomous agents that interact with the surrounding environment and with each other. These types of systems have the system control decentralized and controlled only by the unpredictable behavior of the agents. Agent-based modeling is the preferable simulation technique for the simulation of complex systems with a large number of active objects (such as actors) that are dependent on the order and timing of the events which happen inside of the system. The main advantages of running this type of simulation are the potential for capturing highly complex dynamics and accurate data analysis; the fact that they can be implemented without any changes to the simulated system, as it is an inter-dependent system; and the fact that it is easy to make model changes which are generally local and not global adjustments. There are numerous recent studies which investigate various models appropriate for network intrusion detection and attack prevention.

TRANSPORT PLANNING

Modern transportation systems are made up of large and complex interactions that are based on the unpredictable behavior of travelers as they interact among themselves and with the dynamic environment and the behavior of traffic which is always different, making the schedule very hard to follow. Agent-based systems and simulations provide an appropriate method to model such a complex situation. In this kind of system, agents independently perform their duties while interacting with other agents and the surrounding environment (Auld et al., 2016). In order to understand the behavior of a single entity, the entities are seen as great means of developing and upgrading complex systems where these very complex systems are broken down to the level of agents being driven by their activities and routes. The advent of agent-based transport models brought with it the ability for transport planners to model and simulate the travelling behavior and be able to test decisions before implementing them in order to find the best solutions for the travelers while keeping the costs down.

Agent-based models in transport planning are defined as models providing a microscopic representation of route decisions of individuals as they move from one place to another. These models simulate the behavior of agents as they interact with one another and the environment and their impact on the transportation system.

Transport planning went through major changes in the 1950's with the development of the '4 step transport model'. This type of transportation model is still relevant to this very day. The '4 step transport model' provides transport planners with a realistic traffic flow representation, which is used afterwards to recommend changes to the infrastructure such as new public transport routes, new stations, road expansions etc. (Chen & Cheng, 2010). However, the complexity of programming such a simulation and the objectives of transport planning have changed over time and, with it, the need to better understand travel behavior at a microscopic scale and keep into consideration how these changes can impact the environment, things which were not taken into consideration this much in the past (Abdulsattar et al., 2019). This change includes the shift in focus from expanding the road infrastructure to upgrading the public transport and focus more on travel demand management, especially by introducing new alternative transport modes and implementing new technologies.

AN IN-DEPTH ANALYSIS OF SIMULATIONS IN TRANSPORT PLANNING

There has been a substantial increase in models that can answer questions such as: how to promote cooperation in road networks to achieve maximum performance for already existing transport networks, how to reduce vehicle emissions, how to meet growing demand while effectively and efficiently exploiting the existing transport infrastructure, how to evaluate the effects of raising road pricing policies, how to adapt the road infrastructure to the ongoing increase in demand and many more questions which are being asked by the road administration authorities. These questions point to the need of trying to simulate the real behavior of travelers, their trip attributes and how they interact with the transport system. The old 4-step model does not capture and simulate how most of the travelers really behave due to its nature of modeling the data. That data includes space, time and travelers. Moreover, aggregate data does not accurately represent the behavior of the travelers, making the data from the simulation very different from a real-world scenario. This type of model causes a loss of vital information that makes it less sensitive to changes in trip attributes or time dependencies among other important information needed to accurately answer the questions asked above.

A better option compared to the classic 4-step model is the agent-based model which provides a suitable platform for meeting all of the needs. At its core, agent-based models have the conceptual definition of what an agent really is. Agents are singular independent entities capable of making decisions autonomously and of interacting with the others and with the surrounding environment. They are governed by a set of programmed behaviors which can be called rules that define how they interact, these rules being created from real-world behaviors, making two agents faced with the same situation take a different decision due to their unscripted decision making. A second aspect of an agent-based model that makes it capable to simulate real-world situations is its flexibility and modularity (Adnan et al., 2015).

After learning the generic aspects and benefits of agent-based modeling, implementing it for a real-world scenario needs to be made by dividing it into three basic components: 'The physical environment', 'The agents' and 'The strategies of the agents'.

1. 'The physical environment': This makes up the scenario data for the agent-based model and consists of the transport network, transport supply, land use data etc. These items never change and are usually set initially as boundary conditions.

2. 'The agents': These usually are vehicles or travelers.

3. 'The strategies of the agents': These are the rules which guide the various interactions in the built environment. Based on these different rules and boundaries, agents can be given activity schedules, types of activities, locations of activities, routes of travel between these activity locations and more. These strategies form different modules and can be always adapted and changed depending on the object of study.

These components are simulated with the use of what is called the 'Mobility Simulator'. This simulator models the physical transport system which, working on the set rules, boundaries and the strategies of agents, uses them to compute and simulate what happens to the agents as they move in the physical environment, writing down the needed data (Heath, Hill & Ciarallo, 2009).

A popular approach of applying agent-based modeling into transport planning is through completing activity-based demand modeling. Agent-based modeling in transport planning could be used to combine activity-based models with traffic flow assignment in order to build a more complete and more realistic model representing the travel behavior. This simulation enables a better understanding of the effect of the decisions of the different travelers when interacting with the other agents and the transport network as they travel in the network to carry out their daily routes and activities. Activity-based models capture the travel patterns from an objective point of view as the various activities of the agents occur in the travel network.

Activity-based models should not be confused with agent-based models. An activity-based model is a travel demand modeling approach based on predicting travelers' activities where the daily activities are being carried out and location, time and transportation mode can also be predicted. In this case, a population synthesis is carried out in order to model this simulation, collecting schedules of different people containing their travel patterns and activities.

In order to build a multi-agent simulation for an agent-based model requires the creation of a transport network, implementing agents in this network and programming rules for them on how to behave in the transport system based on a real-world scenario and activity schedule. While this may look simple, many modules that make up this system are complex in their interactions. Although these models can be programmed from scratch or through beginner-friendly platforms such as Netlogo, there are some limitations when applying these platforms to large-scale complex networks. As the agent-based modeling field has developed over time, there were a lot of developments in simulation software which have the ability to simulate large networks for traffic conditions, traffic flow etc. Examples of software usually used include AIMSUN which is focused entirely on reproducing traffic conditions in an urban environment and Sumo used for a multi-modal simulation of road surface traffic. Moreover, there was a large increase in the development of activity-based demand simulators such as ALBATROSS and FEATHERS. These programs could not integrate the different aspects of transport modeling together, nor give a good agent-based model structure. The usual approach is to combine these different models together in a 'loose' fashion. The very first fully integrated large-scale agent-based model simulation was TRANSIMS which was then followed by other frameworks heavily improving on it. These frameworks include MATSIM, SIMMOBILITY and POLARIS.

Transportation Analysis and Simulation System, also known as TRANSIMS, is a project made by the Los Alamos National Institute and is used for disaggregate modeling and analysis of trave behavior of large-scale transport systems. TRANSIMS has been used to create different transport scenarios for a lot of large cities such as Portland and in countries such as Switzerland (Simon, Esser & Nagel, 1999).

Multi-Agent Transport Simulation, also called MATSIM, is a very similar software to TRANSIMS and was built to solve some of the challenges and problems found when using TRANSIMS, one of which being the lack of open access.

MATSIM is a mesoscopic traffic flow simulator used for dynamic traffic assignment and provides a fully integrated agent-based model representing the flow of traffic by tracing the travelers' daily schedules and activities resulted from their decisions.

SIMMOBILITY is 'the first agent-based integration of a fully econometric activity-based demand model system with a simulation based dynamic traffic assignment system'. This software provides a multi-scale simulation framework which covers interactions of land-use, transportation and communication between millions of individual agents.

POLARIS, also named Planning and Operations Language for Agent-based Regional Integrated Simulation, is aiming to solve the issues which TRANSIMS and MATSIM exhibit. It integrates different models together and provides a plug and play system for legacy software in its software.

Moreover, there are newer programs developed to extend existing frameworks such as EQASIMand BEAM, which have both extended the MATSIM framework. Most of these frameworks are in constant development and improvement but the issues outlined in the following paragraph significantly slow down the development.

THE LIMITATIONS OF AGENT-BASED MODELING

The limitations of agent-based modeling have not been understood clearly because of the complex phenomena that comes with modeling human behavior (Manzo & Matthews, 2014). The first limitation would be input data. The input data used in an agent-based simulation framework is fundamental to the results, making the understanding of the error and the manner in which it affects the model very important. The collection of the data is one-way, so errors can be introduced into the model. While it would be a near perfect scenario to model all of the aspects of human behavior and the transport system, the data required to accomplish this model is not publicly available and can be very costly to obtain. This leaves the choice of selecting the data and choosing only the data available to the public, data being a statistical representation of reality. The second limitation of agent-based modeling is the cost of computation. The system dynamics of an agent-based model is dependent on a close to real-world representation of a complex environment. This means that there needs to be a large number of agents whose behaviors are simulated. Multi-agent simulations of agents' behavior provide a good framework for implementing various models. Important details to implement like: land use, route choice, mode of transportation choice, destination choice, schedules etc. All of these details raise the complexity of the model which also needs some runs for a proper calibration. The larger the scale and complexity of the model and also the more complex the questions, the more computing power and resources are required, affecting the performance of the model. A MATSIM simulation run for Paris, capturing 10% of the population, can take up to 5 hours to complete on a modern system (Ḧorl, Balac & Axhausen, 2019). This weakness in agent-based modeling makes the old '4-step model' still relevant and used to this day. A third problem which agent-based models have is validation. Validation of a simulation is essential as it shows how well the model can reproduce the real-world scenario which is being simulated. Different validation techniques are used in agent-based modeling such as face validation which is based on experience and verification-checking with real-life traffic data. Additionally, analysts explore how the outcome data compares when different input data is being put into the model.

CONCLUSIONS

This article aimes to show the benefits of Agent-Based Modeling and its evolution through the years. Agent-Based Modeling has and is still solving a lot of real-world problems in a large variety of areas which affect millions of people. Being compared to other types of simulations and calculations, Agent-Based Modeling has proven its efficiency in a lot of areas such as Natural Disasters, Cybersecurity and Transport Planning (all described in the article) while being cost-effective, accurate and diverse when using it. It is also very popular in designing products, applications or even when planning on adding new features to an already existing program.

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