Agent-Based Modelling of Infrastructure Systems

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1. Introduction

Metropolitan areas are complex socio-technical systems whose governance is demanding, even if politicians' only aim is to maintain the current status. However, sustainable transformation of cities and urban infrastructure systems requires more dedication, i.e., to actively promote and manage an open-ended process of change, which involves the change of citizens' minds, habits and daily routines.

Agent-based modelling (ABM) has proved itself as a new method of investigating structures and dynamics of complex systems such as the economy or the climate (Resnick 1995). Social scientists have also adopted this method to study the dynamics of social systems, e.g., in the case of the spread of rumours, infections or innovations (Epstein/Axtell 1996; Ahrweiler 2013; Van Dam et al. 2013; Weyer/Roos 2017). ABM allows researchers to take into consideration the variety and heterogeneity of social actors. Additionally, conducting simulation experiments with artificial social systems enables social scientists to take a look into possible futures of metropolitan regions and to investigate various strategies of policy interventions.

The following article will first present some basic principles and methodologies of ABM by using the example of traffic simulation. Second, we provide an outlook on various simulation frameworks modelling transportation systems, parts of which apply ABM successfully in order to investigate, e.g., policy options to support sustainable transformation.

2. Modelling Complex Systems

Models are abstract representations of real systems (for a discussion of models, cf. also Gönsch/Gurr in this volume). They bridge the gap between theoretical propositions and reality. Models help to translate theoretical concepts, such as the idea of norm-following, into mechanisms that can be formalised as 'comply to norms in most cases'.

A sociological model of a socio-technical system, e.g., a megacity and its transportation infrastructure serving as an example in the following, needs three ingredients:

- *agents*, representing typical real actors, and their rules of decision-making,
- the *context* of action, e.g., the social, technical, political, and institutional structures that serve as boundary conditions for agents' actions,
- and, finally, *rules* of interaction between agents, but also between agents and context. Imagine for example the interaction of bike-riding agents and a traffic light: to what extent do they feel obliged to stop when a traffic light is red?

2.1 Agents

Agents have properties, preferences and strategies, which resemble real actors. Data needed for modelling agents is mostly gathered by means of surveys. This method allows researchers to construct typical agent types, such as eco-friendly or comfort-oriented agents. With modern simulation software one can parametrise each agent differently (referring to age, sex, income, agent type, preferences, routines, car ownership, daily tasks, etc.) so that large populations of heterogeneous agents can be generated for experimentation at the computer screen.

The decision rule in most models of artificial societies is very simple: confronted with various alternatives (e.g., taking the bus, the car or the bike), agents choose the option that benefits them most according to their individual preferences (Konidari/Mavrakis 2007). This concept of subjective expected utility (SEU) is a moderate version of the utility-maximising "homo economicus", including not only situational parameters, but also subjective expectations and preferences, making the model more realistic (Esser 1993; Velasquez/Hester 2013). Hence, given the same situation, the eco-friendly agent may take the bike, while the comfort-oriented one selects the car.

$$\mathrm{SEU}\,(A_i) = \sum\nolimits_{j=1}^{n} p_{ij} * U(O)_j$$

SEU calculation; U(O): utility of an expected result; p: probability of achieving a goal O. (see Konidari/Mavrakis 2007, 6247; quoted from Adelt/Weyer/Hoffmann/Ihrig 2018, 4.17).

Consequently, programmers do not need to implement different rules of decision-making, because one rule applies to all agents but – due to various input parameters – nevertheless produces different outcomes. Even in the case of conflicts of objectives (drive fast, but eco-friendly), this rule produces results which resemble the decision-making of real actors.

2.2 Context

The second ingredient of a simulation model is the landscape in which the agents are moving around. It typically consists of *nodes*, such as residential buildings, working places, shopping malls, crossroads, train stations or bus stops, and *edges* connecting them, e.g., roads, bike tracks or railways for public transport. The shape of this network largely depends on the topic of investigation. Together with available technologies (car, bike, public transport, car sharing, etc.), it constitutes the context and shapes the room for manoeuvre of all agents, providing them with opportunities (bike rental in the vicinity), but also with constraints (bikes forbidden on highways).

Similar to agents, every contextual component has properties, partly 'natural' such as the maximum number of cars on a residential road, partly politically definable such as the limit of CO_2 emissions or the amount of city toll at that road. These properties are one of the major 'levers' policy makers can utilise for intervention, e.g., by increasing the city toll for cars with combustion engines or, finally, banning their use.

The same applies to technologies, which have properties, e.g., low pollution of bikes, compared to cars, but even lower speed. These properties can also be changed by means of political intervention, e.g., by applying speed limits for cars, or by the invention of new technologies such as the e-bike, increasing speed and range of the bike.

2.3 Interaction

The final ingredients for an ABM are rules for interactions between agents, but also between agents and context. Agents in transportation systems will typically stay on their lane and maintain distance when approaching another agent. Maybe they also exchange information – referring to scenarios of Car-2-Car communication (Fuchs et al. 2015). Roads may influence agents, e.g., by speed limits or tolls, while agents change the state of a road not only by occupying it for a short period of travel time, but also by wearing it out and by polluting its environment.

Every agent using the transportation system contributes to system dynamics by changing parameters (e.g., the number of cars at a certain road section) and thus indirectly influences other agents, who may decide to switch to public transport if roads are overcrowded. If the current traffic situation is regarded as a relevant parameter, even the comfort-oriented agent, who normally prefers the car, might eventually take this action.

2.4 System Dynamics

A large number of autonomous actions, influenced by the current system state at time t, result in a self-organised process of system dynamics. The emergent effects of this process are hard to predict but constitute system state at time $t+1$. Agent-based modelling is capable of depicting this dynamic interplay of the micro level (agents' actions) and the macro level (system state) – with sometimes surprising results (e.g., traffic congestions), which are not part of the agents' strategies but emerge as a result of their autonomous, uncoordinated actions.

Complex systems often entail non-linear interactions, which can only be investigated by running experiments on the computer and trying to understand the results. For example, lowering prices of public transport does not change agents' behaviour in a linear way. Results reveal some tipping points, which are difficult to interpret, because not all agents change their mind simultaneously. In fact, only certain groups of agents switch at a certain price level.

2.5 Governance

As mentioned before, agent-based models of complex socio-technical systems are a well-suited means for investigating governance issues, e.g., in the case of sustainable transition of the transportation system. According to the respective scenario, various strategies can be tested by means of simulation experiments, e.g., speed limits for cars, rise of fuel prices, road charges, parking management, improvement of bike lanes, bicycle parking garages, reduction of prices for public transport and many more (Philipp/Adelt 2018). Strategies can be distinguished between soft control, using monetary or non-monetary incentives (e.g., tolls), and strong control, relying on bans (e.g., for older combustion engines), but typically are a mixture of various measures.

In terms of programming, intervening in a complex system mostly means to change parameters of technologies or contextual components. Since these parameters are part of agents' utility calculation, an increase or decrease may influence agents' decisions, but not in a deterministic way as former models of direct control may have assumed.

Another option of mobility transition is the introduction of new technologies, such as electric vehicles, and the invention of new mobility practices, such as car sharing or mobility-on-demand. Again, in terms of programming, these new options are included in a way that enables agents to consider them when making their choices, e.g., buying a new car with combustion engine or an electric vehicle.

2.6 A Sociological Perspective

This approach of modelling complex infrastructure systems in many parts resembles the way engineers would do it, e.g., when investigating the causes of congestions (Schreckenberg/Selten 2004). However, from a sociological perspective it is important not to treat human actors as mechanical components, who all behave the same – perfectly rational – way, but as conscious individuals, who act according to subjective preferences. Sometimes, their decisions seem to be irrational (e.g., taking the car for a trip of only one kilometre), but these are everyday practices that have to be considered if one wants to grasp the dynamics of socio-technical systems by analysing the interplay of the micro and the macro level.

Sociological theory of action as well as sociological macro-micro-macro models thus are essential ingredients to make artificial societies a realistic image of real societies, e.g., in metropolitan areas (Hedström/Swedberg 1996; Ostrom 2010; Esser 1993).

3. Traffic Simulation

During the last decades, various traffic simulation tools have been developed. Not all of them are ABM-based, and only a few refer to sociological concepts of action. Only in recent years have some of those frameworks started to include decision-making of social actors.

3.1 Nagel-Schreckenberg Model (NaSch)

In the 1990s, Kai Nagel, Michael Schreckenberg, and others developed a traffic simulation model, grounded in cellular automata concepts (Nagel/Schreckenberg 1992). This model can be regarded as the forerunner of all subsequent models. In their approach, a single-lane highway consists of cells, each occupied by a maximum of one car, which increases or reduces its speed according to the state of the cell ahead. The resulting traffic flow, created by all cars-on-cells, reveals various fluctuations (such as congestions) which can also be observed in real traffic systems.[1] Although Nagel and Schreckenberg frequently refer to the "individual (though statistical) behaviour of the driver" (1992, 2229), they mainly emphasise the technical performance of the car (conducted by a human driver) in terms of acceleration or deceleration.

OLSIM

Later, the NaSch model has been extended to two-lane highways in order to investigate the issue of lane change (Knospe et al. 2002).[2] Moreover, it was used to model the network of highways in North Rhine-Westphalia, a densely populated state of Germany with frequently congested roads (Selten et al. 2004; Schreckenberg et al. 2005).

In 2002 the government of North Rhine-Westphalia decided to establish the online traffic information service *autobahn.NRW*, based on the online simulation OLSIM, which used real-time data from 4,000 detection devices to calculate and to forecast traffic – again in real time (Schreckenberg et al. 2005; Weber et al. 2006). Plans to extend this service to secondary roads and to establish a comprehensive traffic information system called "Ruhrpilot", however, were facing the growing competition by commercial, but freely available services such as Google Maps, which entered the German market in 2011. The service *www.verkehr.nrw* still exists but meanwhile uses data from TomTom (Konrad/Weyer/Cepera/Adelt 2020).

3.2 Multi-Agent Transport Simulation (MATSim)

In contrast to Michael Schreckenberg's OLSIM, which is grounded in the cellular automata concept, Kai Nagel switched to agent-based modelling (ABM) and, together with other colleagues, in the late 1990s invented the general idea of MATSim, which was completed in 2004 (Nagel 2004; Nagel/Axhausen 2016). The Swiss city of Zurich was the first example that demonstrated the value of traffic demand modelling based on individual plans instead of origin-destination matrices, as in the case of other traffic planning tools. MATSim (www.matsim.org) is open source and today is used worldwide as a simulation and planning tool (Horni et al. 2016).

1 A simple traffic simulation which resembles the NaSch model can be found in NetLogo (Wilensky 1997).

2 The research team of Reinhard Selten also investigated route choice behaviour and the impact of information on route choice but did not use the NaSch model, but instead performed laboratory experiments with students (Selten et al. 2007).

MATSim is a microscopic traffic simulation based on modelling the behaviour of large numbers of individuals and their daily plans, which are fixed in advance but can be improved if other plans are available (Horni et al. 2016, 3; 7; 37ff.). The traffic flow model is queue-based: links (e.g., roads) between nodes (e.g., crossroads) serve as waiting queues, where cars wait until they can step forward (Horni et al. 2016, 6–7). MATSim abstains from modelling physical movement of road users, as car-following models do.

MATSim has been designed to investigate (daily) traffic demand – as the aggregate result of various agents' daily plans, which are fixed and can only be changed the next day. Typically, MATSim scenarios depict real cities or regions and take available data, such as census data, traffic counting, OpenStreetMaps (OSM) data and others, to calibrate the model.

MATSim is rooted in computational physics and in complex adaptive systems (CAS), but it lacks a sociological foundation of action and interaction. Agents' preferences are modelled, but only considering time or budget restrictions, which is much less than a sociological concept of agency would do. Additionally, agents stubbornly follow their prefabricated plans and do not change behaviour during the day, e.g., due to situational restrictions such as congestions or road closure.

NEMO

The project "Neue EmscherMobilität" (NEMO, 2017–2020; http://www.nemo-ruhr.de; no longer exists) has used MATSim as a tool for modelling mobility in the Ruhr region. NEMO was the impetus for including sociological concepts of agency and governance into MATSim.[3] Similar to SimCo (see 3.4 below), the authors aim to include individual preferences in its behavioural models and to implement various scenarios and visions that entail intervention strategies, e.g., promoting bicycle traffic (Ziemke et al. 2019; Kaddoura et al. 2020). Furthermore, MATSim is now able to integrate multiple transport modes, but still not multimodal transport chains.

In the course of project NEMO, MATSim was used to investigate the impact of several measures, such as the closure of residential roads, the conversion of roads into bicycle tracks, but also new options like car-, bike- and ride-sharing, depending on the respective scenario to be analysed. These scenarios had been called "Healthy and Sustainable City", "Smart City" or "Deurbanisation". Experiments proved that most of the measures applied served to change users' behaviour, resulting in a measurable improvement of environmental indicators and/or quality of life (Ziemke et al. 2019; Kaddoura et al. 2020).

3.3 Various Frameworks

SUMO

Simulation of Urban Mobility (SUMO; sumo.dlr.de) is a traffic simulator, which has been developed by the German Aerospace Center (DLR) since 2000. SUMO is a "microscopic, space-continuous and time-discrete car-following model" (Krajzewicz 2010) consider-

3 Personal communication with J. Alexander Schmidt (5. November 2019).

ing mainly the physical movements of vehicles, e.g., in the case of lane changing (Krauß 1998; Krajzewicz et al. 2012).

Researchers from TU Dortmund University managed to integrate social behaviour and especially individual route choice into an extended SUMO-S (Adelt/Weyer/Fink 2014). Additionally, they considered "frame selection" (Kroneberg 2014) – a concept that takes into account routines and habits instead of assuming all actions being based on (subjective) rational calculation. However, Adelt, Weyer and Fink dropped SUMO-S, mostly because the efforts needed to create new scenarios for a microscopic traffic simulation were too high. In order to investigate more general questions of governance, they developed SimCo from scratch – a more abstract simulation framework rooted in sociological theory of action (see 3.4 below). Even the developers admit that "the usage of SUMO [is] a little bit uncomfortable in comparison to other simulation packages" (https://sumo.dlr.de/docs/SUMO_at_a_Glance.html#software_design_criteria).

IVV VENUS, VISUM and VISSIM

Compared to SUMO and MATSim, the purpose of which is mostly academic, other traffic simulation frameworks are more directed towards the practical use of traffic planning. For example, IVV VENUS (www.ivv-aachen.de/produkte/softwareprodukte/detailseiten/venus.html) is a macroscopic model using various structural data for modelling traffic demand and calculating the impact of, e.g., building new highways or new cycle tracks. IVV VENUS is trip-based, meaning that typical trips (from home to work, etc.) are primary constituents for modelling the macroscopic view.

This similarly applies to other commercial products such as VISUM (www.ptvgroup.com/de/loesungenprodukte/ptv-visum), which creates a macroscopic image and "predict[s] the effects of proposed changes in configuration of the transport network" (Jacyna et al. 2017), e.g., due to changing demand. The complementary traffic planning tool VISSIM (www.ptvgroup.com/de/loesungen/produkte/ptv-vissim) depicts the microscopic situation and provides realistic, virtual images of the traffic flow and the interaction of various transport modes, e.g., pedestrians and cars at a bus stop. VISSIM includes behavioural models of pedestrians and other transport users, but agents' behaviour and interactions are regarded from a technical point of view (Fellendorf/Vortisch 2010). This benefits traffic planners in their efforts of optimising transportation infrastructure, e.g., making bus stops safer or better suited for multimodal transport. However, decision-making of individual agents in terms of sociology is not considered here either.

Commercial Services

Finally, commercial services such as TomTom, Apple Maps, Google Maps, Here and others provide real-time services for the purpose of route guidance (Konrad et al. 2020). This differs from the long-term perspective of planning tools. However, these services also deliver valuable data, which can be used to improve the quality of other simulation frameworks.

3.4 Simulation of the Governance of Complex Systems (SimCo)

The simulation framework SimCo has been developed at TU Dortmund University, starting in 2012. Its main motivation has been to sustain and push forward governance research, which mostly had been case study-based and had been caught in a "governance trap" (Grande 2012; our translation). According to Edgar Grande, this was due to lacking knowledge of social mechanisms that make up social systems and allow external forces to intervene.

Focusing on governance issues, SimCo from the very beginning does not pay much attention to physical details, such as length and size of bus stops, but puts emphasis mainly on social mechanisms that shape and guide individual behaviour (Adelt et al. 2018). Therefore, the network, depicting a metropolitan transportation system, consists of nodes and edges, the dimensions of which are freely programmable. This allows for conceiving them as roads, cycle tracks or tracks for public transport (edges), as working places, residential areas or shopping malls (nodes). As a general-purpose framework, SimCo intends to explain system dynamics as a result of the interaction of heterogeneous agents making autonomous decisions – and vice versa: explain agents' behaviour as a result of individual preferences and situational constraints. SimCo thus is one of the first attempts to translate a sociological macro-micro-macro model systematically into an agent-based model (Esser 1993).

SimCo has been used for various experiments on risk management and system transformation, mostly in road transportation (Philipp/Adelt 2018; Weyer/Adelt/Hoffmann 2019; Weyer et al. 2020). Several what-if scenarios have been investigated analysing the effects of external interventions on individual behaviour of various agent types, above all on mode and route choice. One major result of these experiments is: political interventions, e.g., to minimise risks (congestions or emissions) or to change the system towards sustainability, work best if the governance mode of soft control is applied, working with incentives and not with strong measures such as bans (as in the case of strong control; Weyer/Adelt/Hoffmann/Konrad/Cepera 2020). Additionally, this sociological approach has also been used to model the energy system and its sustainable transformation (Hidalgo-Rodríguez et al. 2017; Hoffmann/Adelt/Weyer 2020).

4. Governing Transitions of Metropolitan Areas

All models presented here intend to contribute to a better understanding of the dynamics of metropolitan infrastructure systems, such as transportation or energy. In their self-perception, all approaches serve as analytical instruments and, finally, as planning tools, trying to better understand possible pathways towards a sustainable future, e.g., by implementing policy scenarios such as ride-sharing or multimodal transport.

However, the concepts differ with regard to their emphasis on physical infrastructure (e.g., VISUM and IVV VENUS), on physical movement of transportation units (e.g., NaSch, SUMO), on traffic demand (e.g., VISUM, MATSim) and on user behaviour (e.g., MATSim, SimCo).

Furthermore, traffic planning tools such as VISUM are not agent-based but use structural data for computation of (macroscopic) traffic demand, whereas SUMO, MATSim and SimCo are agent-based to better understand the non-linear dynamics of complex socio-technical systems by taking into account individual decisions of agents at the micro level.

However, as MATSim's interfaces for planning tools show, both worlds can be integrated and thus might profit from each other in order to better understand the sustainable transformation of metropolitan areas.

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