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RESEARCH ARTICLE

Modeling sustainable mobility: Impact assessment of policy measures

Johannes Weyer*[1,2], Fabian Adelt[2], Marlon Philipp[2]

Abstract • Sociologically based models of complex systems can help to estimate the impact of policy measures on individuals and explain the resulting system dynamics. Using the example of the Ruhr region and the mobility of the people living there, the article demonstrates the concept of agent-based modeling, which draws on assumptions from analytical sociology and distinguishes between different types of actors. Simulation experiments conducted as part of the InnaMoRuhr project show significant differences in the behavior of these types, especially in their response to policy interventions. Policymakers should take this into account when planning and designing measures aimed at sustainable transformation.

Modellierung nachhaltiger Mobilität:
Eine Abschätzung der Wirkung politischer Maßnahmen

Zusammenfassung • *Soziologisch fundierte Modelle komplexer Systeme können dazu beitragen, die Wirkung politischer Maßnahmen auf einzelne Individuen abzuschätzen und die daraus resultierenden Systemdynamiken zu erklären. Am Beispiel des Ruhrgebiets und der Mobilität der dort lebenden Menschen demonstriert der Beitrag das Konzept einer agentenbasierten Modellierung, die auf Annahmen der analytischen Soziologie rekurriert und insbesondere verschiedene Akteurtypen unterscheidet. Simulationsexperimente, die im Rahmen des Projekts InnaMoRuhr durchgeführt wurden, zeigen erhebliche Unterschiede im Verhalten dieser Typen, insbesondere in ihrer Reaktion auf politische Interventionen. Politik sollte dies bei der Planung und Konzeption von Maßnahmen berücksichtigen, deren Ziel die nachhaltige Transformation ist.*

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Introduction: ABM and policy assessment

Policymakers in areas like transportation, energy, climate, or health, who are planning to introduce new regulations, are usually guided by expectations about the impact of these measures. For example, restrictions during the COVID-19 pandemic should slow down the spread of the virus, and the reductions of public transport prices were aimed at changing modal shift as well as lowering CO_2 emissions.

Frequently, expert advice has been used to assess the potential impact of policy measures in advance and to discuss and evaluate alternative strategies, e.g., in the case of COVID-19 vaccination. Typically, system dynamics models such as SEIRD are used to depict complex interactions between various factors: the numbers of susceptible (S), exposed (E), infectious (I), recovered (R) and dead (D) persons. The online COVID-19 Simulator 'CoSim' (Dings et al. 2022) connects these variables by functions and rates, such as the reproduction rate. This kind of mathematical modeling of system dynamics (SD) allows to adjust various parameters, e.g., the booster willingness, and to assess the impact of those measures by means of simulation experiments (Figure 1). Referring to CoSim, policy makers can assess prospectively, e.g., the effects of reducing the number of quarantine days, thus looking into the future, which can hardly be achieved with other methods.

However, SD models such as CoSim do not – or only partially – consider peoples' individual behavior and its impact on system dynamics. As can be seen in Figure 1, booster willingness is a global variable, applying equally to every person.

Agent-based modeling (ABM) has been established as an alternative approach with some advantages, but disadvantages as well. ABM takes into account the heterogeneity of real people, e.g., in terms of booster willingness, and conceives the 'social elements' of the system as individuals with subjective preferences. It takes a closer look at (i) the individual decision-making process, (ii) the factors that might, or might fail to, influence decision-making, and, finally, (iii) the systemic effects that result from the complex interactions of many people acting in different ways.

ABM allows focusing on typical patterns of agents' behavior, that must be addressed differently by policy measures. For example, lowering prices of public transport will not change mobility patterns of people who are not price sensitive and who are used to taking the car without considering alternatives. SD models might fail to grasp these differences between various agent types. Although ABM is more realistic in this respect, it also has some disadvantages. Due to the huge computer performance needed to calculate each individual decision, simulation experiments can only be conducted with small populations of some 10,000 agents, not with the population of an entire country. Thus, we suggest that combining the benefits of SD (i.e., global population) and ABM (i.e. individual behaviors) might be useful, to better support politicians preparing difficult decisions in the field of transportation, energy, climate, or health policies.

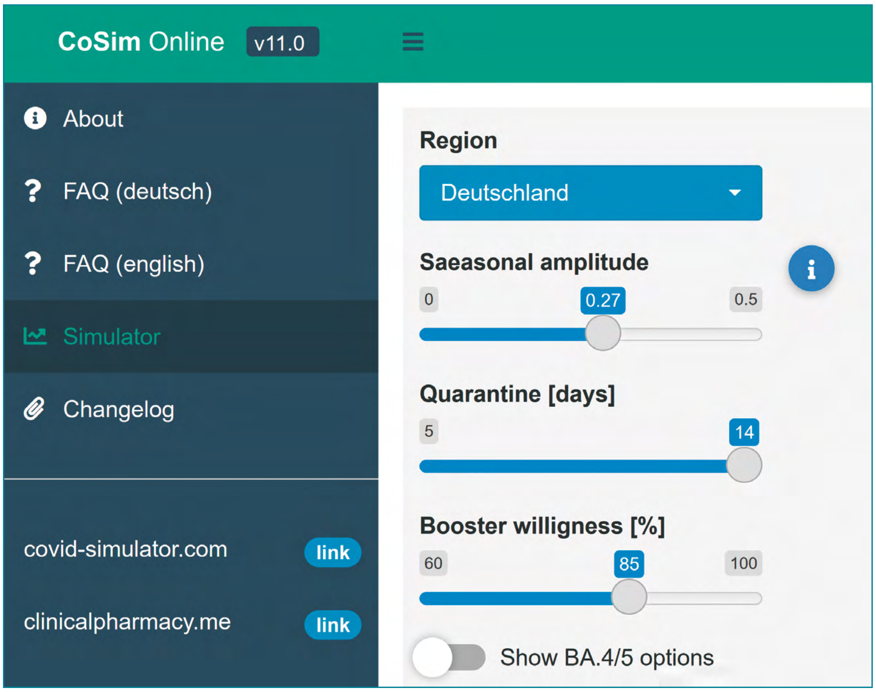

Fig. 1: CoSim COVID-19 Simulator. *Source: https://shiny.covid-simulator.com/covidsim*

Modeling complex socio-technical systems by means of analytical sociology

Agent-based modeling (ABM) has become a frequently used method to experiment with complex socio-technical systems, such as the transportation or the energy system, at the laboratory scale (Gramelsberger 2015; Van Dam et al. 2013). ABM has also been utilized as a tool to provide technology assessment with insights into alternative future pathways (Saam et al. 2019; Weyer and Roos 2017). An overview of various simulation frameworks and a comparison of different approaches to modeling transportation can be found in Weyer et al. (2022).

Some ABM frameworks such as the transportation simulation MATSim use simple decision algorithms, e.g., choosing the transport mode (car, bike, or public transport) that has performed best in the past, measured by time and costs (Horni et al. 2016). Again, this does not reflect the heterogeneity of real people's decisions, who may value time and costs differently.

Rooted in analytical sociology, the simulation framework SimCo (Simulation of the governance of complex systems) has been developed at TU Dortmund University since 2012 to investigate the effects of heterogeneous agents' interactions in infrastructure-based systems. It puts emphasis on the behavior of individuals and their modes of decision-making, which are shaped by subjective expectations (Kroneberg 2014). SimCo allows to explain why people behave differently, e.g., taking the car or the bike, and to simulate the interplay between individual everyday decisions at the micro level and system dynamics at the macro level.

The concept 'analytical sociology' has been coined by a group of researchers that try to model individual decision-making based on subjective preferences and (perceived) situational constraints (Esser 1993; Hedström and Swedberg 1996). Their goal is to understand the subjective reasoning of individuals and to explain chosen actions systematically as the result of a bounded-rational decision-making process, which can be reproduced by a mathematical algorithm. This algorithm includes situational factors ('Is there a bus station close to my home?') and preferences ('How much do I value traveling fast, cheap, environmentally friendly etc.?'), but also habits and routines ('Am I used to look for public transport opportunities, or do I automatically use my car?').

All three components of the decision-making algorithm are shaped by subjective perceptions, not only in the case of (subjective) preferences and (subjective) habits, but also in the case of (subjectively perceived) situational constraints ('Maybe, there is a bus station, but I have never noticed it.').

This decision algorithm, however, applies to all individuals similarly: Faced with various alternatives, e.g., taking the car or the bike, agents compare the utility (SEU) of each available option A (Figure 2), according to individual preferences (U) and probabilities (p) of achieving a goal by means of various action alternatives, and then typically choose the option that benefits them most (Konidari and Mavrakis 2007; Velasquez and Hester 2013).

$$SEU(A_i) = \sum_{j=1}^{n} p_{ij} \cdot U(O)_j$$

Fig. 2: SEU Calculation: U(O) = Utility of an expected result; p = probability of achieving a goal O. *Source: Konidari and Mavrakis 2007, p. 6247*

Table 1 illustrates this mathematical procedure referring to two fictitious people, who have different preferences (U): person A likes to travel fast, but does not care about costs, while person B is a money-saver, who is not interested in traveling fast. Probabilities (p) are the same for both persons here, but obviously could be adjusted due to different personal, residential or other situations, e.g., if fuel prices rise sharply, or cycle tracks are not available.

	Fast travel	Cheap travel	Utility
Person A			
Preferences (U)	10	4	
Car (p)	0.8	0.3	**9.2**
Bike (p)	0.3	0.8	6.2
Person B			
Preferences (U)	3	8	
Car (p)	0.8	0.3	4.8
Bike (p)	0.3	0.8	**7.3**

Tab. 1: Transport mode choice of two fictitious people (U values ranging from 1 to 10, p values from 0.0 to 1.0). *Source: authors' own compilation*

However, even this simple example shows that mode choice, based on mathematically calculated subjective utility, is very different: Person A takes the car (utility 9.2), while person B takes the bike (7.3). Parameters would have to be adjusted heavily to achieve behavioral change.

Hence, analytical sociology may contribute to making ABM more realistic, combining the idea of a general decision-making algorithm, that can be implemented into software, and the individuality of real people who decide autonomously based on subjective preferences, (subjectively) perceived situational constraints, and, finally, individual habits and routines that emerge as results of daily practices.

Based on the idea of individual decision-making, ABM allows to design complex systems by means of interactions of a large number of interdependent agents. Each agent in a transportation system changes the state of the system through their actions, e.g., choice of transport mode or route, and thus contributes to system dynamics. And each agent is vice versa influenced by the dynamic state of the system, e.g., traffic jam. This dynamic interplay of agents and system can hardly be investigated by theoretical reasoning. Experimental methods such as computer simulation provide researchers with the opportunity to observe self-organized processes of system dynamics and their emergent effects, which are hard to predict – and sometimes even surprising. Complex socio-technical systems often entail non-linear interactions, which can be investigated by running experiments on the computer and trying to interpret the results.

The simulation framework SimCo

The simulation framework SimCo has been developed to sustain and to push forward governance research, which mostly had been based on qualitative case studies. Focusing on governance and policy issues, SimCo does not pay much attention to physical dimensions of complex socio-technical systems such as the width of cycle tracks, but puts emphasis on the social dimensions of mobility or energy systems, i.e., the mobility or energy behavior of artificial agents who are designed to resemble real people's behavior. Therefore, the physical structure of the system is depicted as an abstract network, consisting of nodes and edges, which are freely parameterizable in their respective dimensions. As a general-purpose framework, SimCo allows conceptualizing edges as roads or cycle tracks and nodes as working places, residential places, or shopping malls.

According to analytical sociology, SimCo tries to explain system dynamics as the emergent result of the interactions of heterogeneous agents, making autonomous decisions. SimCo has been used for various experiments on risk management and system transformation, mostly in road transportation (Philipp and Adelt 2018; Weyer et al. 2019). Several what-if scenarios have been investigated analyzing the effects of external interventions on individual behavior, especially on mode and route choice (Adelt and Hoffmann 2017). Conducting experiments with simulation frameworks such as SimCo helps to better understand the real-time dynamics of complex socio-technical systems and to explain, e.g., why (various) people react (differently) to political measures intended to promote sustainable transformation (Weyer 2019).

By experimenting with various scenarios, e.g., of future mobility, experimenters can analyze the probability of success of different policies, such as banning cars with combustion engine

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(strong measure) or lowering prices for public transport (soft measure). ABM can be used as a method for assessing policy measures and their – sometimes unintended – effects, and also for predicting which policy strategies might have the biggest impact, e.g., in terms of sustainable transformation, and which would probably fail to achieve their goals.

Simulation of mobility in the Ruhr district

The Ruhr district with about five million inhabitants is one of the largest metropolitan areas in Germany, albeit with a rather atypical structure. Compared to Berlin, Hamburg, or Munich, there is no single center; instead the Ruhr district has a polycentric structure with a few big cities and several medium-sized or small towns. Like other metropolitan areas, the Ruhr district must cope with the challenge of sustainable transformation, especially in transportation, which is lagging behind other sectors.

InnaMoRuhr

In the InnaMoRuhr project (Concept of an integrated, sustainable mobility for the University Alliance Ruhr), three big universities collaborate in developing and implementing concepts for future transportation. The overall purpose of the project is to find out which policy measures or interventions may contribute to changing the mobility behavior of people studying and working at these three universities. One key element is the development of an agent-based model of the Ruhr district that can be used to test various scenarios, e.g., of promoting new modes of transport, such as bicycle traffic or car sharing, or even intermodal transportation, such as by bike to the station, by train to university.

As a first step, a survey has been conducted to collect data about typical mobility practices, but also about demands for future mobility: Participants were the students and employees of the three Ruhr universities. These data have been used to construct four scenarios, which were discussed and evaluated by members of all three universities at five scenario workshops. In parallel, the Ruhr model was technically implemented, partly relying on the NEMO model developed by other researchers, using the simulation framework MATSim to model and analyze urban transportation in the Ruhr district (Kaddoura et al. 2020; Ziemke et al. 2019). NEMO already depicts, e.g., the network of roads and tracks, the distribution of residential quarters, and the daily mobility behavior of people. However, since MATSim puts emphasis mostly on physical dimensions of transportation, such as travel time and costs, several sociological components had to be integrated, such as bounded-rational decision-making and, above all, the various agent types implemented in SimCo. The final step are real-world experiments to test those scenarios in practice that have proven promising in the scenario workshops as well as in simulation experiments.

Actor types

One major result of the survey (N = 10,782) was data about individual preferences (U values) and specific probabilities (p values) of achieving various goals with different modes of transport. As Table 2 shows, respondents were asked to indicate their travelling preferences (U values) in terms of dimensions like 'fast', 'cheap', or 'safe' by adjusting a slider in an online questionnaire (values ranging from 0 to 10). Numbers in column 'mean' show that respondents value speed (7.8) and reliability (8.1) highest and comfort (4.7) lowest.

Additionally, these data were used to create five distinct actor types by means of cluster analysis in the statistics program SPSS (Weyer 2022). Actors were clustered according to similarities in U values within-group and dissimilarities between-groups. As can be seen in Table 2, numbers differ remarkably between those five clusters. For example, actor type #4 ('comfort-oriented') rates comfort (+2.8) and safety (+1.4) much higher, and prices (–3.1) and environmental concerns (–2.1) much lower than the average (column 'mean'). Conversely, actor type #5 ('environmentally conscious and price sensitive') rates prices

Dimension	Type 1	Type 2	Type 3	Type 4	Type 5	Mean
Fast	**–1.6**	**–0.8**	**1.0**	0.8	0.8	**7.8**
Cheap	**–0.6**	0.5	0.9	**–3.1**	**1.4**	6.3
Environmentally friendly	**1.7**	**0.9**	**–2.2**	**–2.1**	**2.1**	5.9
Comfortable	**–1.6**	0.8	0.3	**2.8**	**–2.2**	**4.7**
Safe	**1.7**	0.2	**–0.6**	**1.4**	**–2.7**	6.2
Reliable	0.5	**–1.9**	0.8	0.5	0.5	**8.1**
N =	2,081	2,522	2,808	1,598	1,747	10,782
Share	19.3 %	23.4 %	26.0 %	14.8 %	16.2 %	
Description of actor groups	(1) Risk averse and environmentally conscious; (2) Indifferent; (3) Pragmatic; (4) Comfort-oriented; (5) Environmentally conscious and price sensitive					

Tab. 2: Actor types, clustered by six dimensions of preferences (U values); high numbers (deviations from mean) are marked green, low numbers red.

Source: Weyer 2022, p. 20

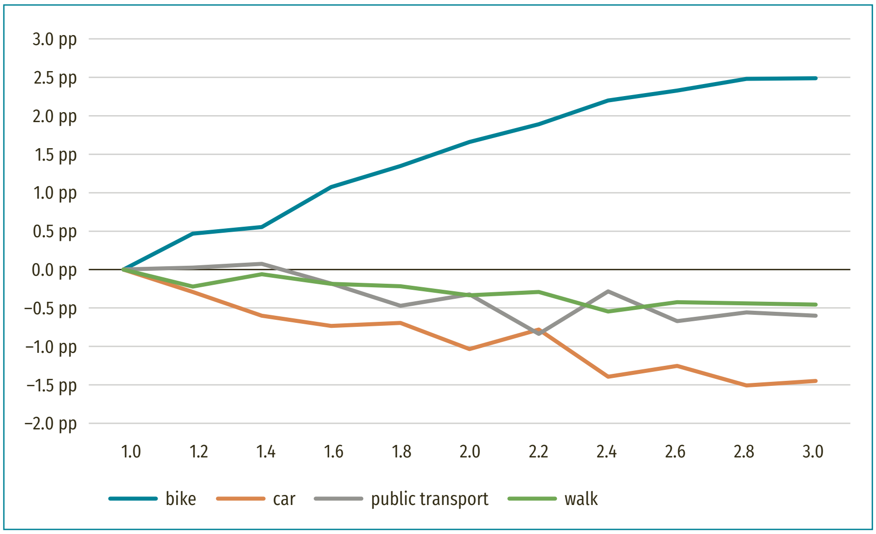

Fig. 3: Results of simulation experiments with raising bike comfort, depicting changes in mode choice compared to base scenario in percentage points (y-axis) related to depth of interventions (x-axis).
Source: Philipp et al. 2023

(+1.4) and environmental concerns (+2.1) much higher, but disregards comfort (–2.2) and safety (–2.7).

These actor types have been implemented as agent types in the MATSim-SimCo Ruhr model and experiments have been conducted to test three scenarios: (1) a mobility budget that allows people to gain experiences with alternative modes of transport; (2) a car sharing service that fills gaps in public transport between university and railway stations; (3) and a bicycle station that makes traveling by bike more convenient and safer. The following sections will present only the latter scenario.

Design of experiments

The basic NEMO model entails the whole Ruhr population, scaled down at one percent, resulting in 50,000 agents who behave according to the logic of MATSim, which is *not* based on analytical sociology. For our study, this global population of the Ruhr district was complemented by a university-specific population, representing twenty percent of about 130,000 members of three universities at Duisburg-Essen, Bochum and Dortmund. These 25,683 university agents were split up in the five agent types mentioned above, with additional variation in age, sex, profession, place of residence etc. They also behave according to the general logic of MATSim, but decision-making is based on subjective preferences and bounded rationality, referring to SimCo.

The original NEMO agents thus serve as a kind of 'background noise', affecting, e.g., the occupancy of roads, or public transport units used by both subsets of agents. However, the interventions within the scenarios only affect the university population – the main object of our study.

Experiments were conducted to test the willingness to change behavior, which is rather high, according to survey data: Faced with the option to take the bike to the station and the train to university (at a scale of 1 = no to 5 = yes), 73.7 percent of respondents were willing to make use of this option (sum of 4 and 5). However, the differences between agent types are remarkable: Comfort-oriented people rate this option much lower (3.32), and environmentally conscious and price sensitive people much higher (4.46) than the average (4.00).

To test the scenario 'bicycle station', comfort of cycling has been defined as the crucial parameter, the change of which might affect peoples' behavior, especially their willingness to take the bike for short or medium trips. Discussions in the scenario workshops revealed that many people like cycling but hesitate to use their own bike – especially expensive electric bikes – since safe storage at work or at the train station cannot be guaranteed.

Hence, experiments were conducted, increasing the parameter 'bike comfort' (p value, resulting from the survey) by using a factor from 1.0 (base value) to 3.0 (very high) in increments of 0.2. Since changing mobility patterns typically requires a combination of various policy measures, the costs of using cars for commuting were raised likewise (steps of 0.1) in a separate series of experiments, adjusting the parameter 'car costs' by using a factor from 1.0 (base value indicating low costs) to 0.0 (very expensive).

Finally, both measures have been combined, investigating the impact of simultaneously increasing bike comfort, e.g., by means of a bicycle station, and car costs, e.g. by introducing parking fees (Philipp et al. 2023).

Every single experiment depicts one typical day, starting in the morning and ending in the evening, including the daily mobility patterns of both the NEMO and the university population. According to MATSim's programming logic, the final daily plan is the result of 500 iterations, in which each agent adapts and optimizes its daily routine by trying various mobility options. This procedure has been executed with eleven parameter values per experiment (see x-axis of Figure 3).

Results of experiments

Figure 3 shows the results of simulation experiments with increased bike comfort using a factor from 1.0 (base value) to 3.0 (high comfort); changes in transport mode choice, indicated in percentage points (pp) compared to the baseline scenario are depicted (on the y-axis). Obviously, the intervention works, since transport mode choice shifts to bike (+2.5 percentage points at comfort level 3.0) at the expense of the other three modes. The reduction of car use (–1.4 pp) is highest compared to the baseline scenario.

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In combination with a stepwise increase of (perceived) car costs, these numbers are even slightly higher: Bike usage rises by 3.6 pp, while car usage drops by 2.1 pp.

However, numbers differ when agent types are considered (Figure 4). Results are rather surprising, since it is not the two groups of environmentally concerned people (+1.9 and +1.1 pp for bike at intervention level 3.0 – filled columns), but mainly the groups of indifferent (+3.0 pp) and pragmatists (+4.1 pp) that contribute most to change by refraining from car use (–2.0 and –2.8 pp at level 3.0 – striped columns). At first glance, this seems to be counterintuitive, but if one considers that environmentally concerned people already are used to taking the bike, even if the weather is bad and storage is complicated or risky, then results are reasonable.

Hence, two agent types of environmentally concerned people (#1 and #5) reveal almost no change and only a minor trend of renouncing car use. This is partly because car ownership is much lower in those two groups: 63.6 and 58.5 percent, compared to an average of 71.7 percent and a maximum of 87.6 percent in the group of comfort-oriented (Weyer 2022, p. 23).

Agent type #4 of comfort-oriented people is hardly affected by increasing bike comfort, but agent types #2 (indifferent) and #3 (pragmatic) might be interesting target groups for policy measures fostering a transformation of the transportation system. Instead of addressing people who are already environmentally concerned and willing to travel climate friendly, politics should take a closer look at people that are indifferent or pragmatic but still – in contrast to comfort-oriented people – responsive to changing situational constraints, e.g., new opportunities (bicycle station) or restrictions (parking fees).

Numbers are slightly different, if two measures – raising bike comfort and car costs simultaneously – are combined. Bike use is even 2.0 percentage points higher among agent type #3 (pragmatic) at intervention level 3.0, at the expense of car use in this group (–1.7 pp). Again, comfort-oriented people (agent type #4) react differently: Car use goes up by 1.4 percentage points at intervention level 3.0, where cycling is convenient and car driving is extremely expensive – at first glance a counterintuitive effect as well.

This points at two findings: Many comfort-oriented people are willing to pay a high price to maintain their familiar habits. And second – still to be validated in more detail – temptation to use the car may rise, if streets are empty and congestions are rare, because many people have switched to bikes. This is a typical non-linear effect that can only be investigated by means of computer simulation.

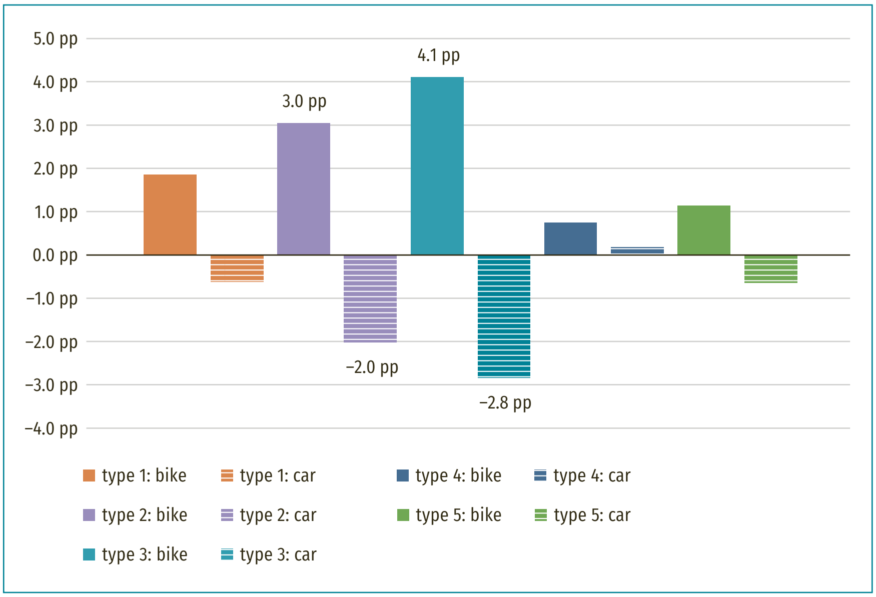

Fig. 4: Changes in transport mode choice compared to base scenario in percentage points (y-axis) of five agent types (x-axis) by raising bike comfort at level 3.0 (filled column: bike, striped column: car).
Source: Philipp et al. 2023

Conclusion

Combining analytical sociology and agent-based models helps to better understand the variety of individual actions, the resulting system dynamics, and, finally, the different willingness of people to react to external interventions. Agent-based models, rooted in sociology, create a more realistic picture than other models, since they grasp everyday practices of people, who behave according to subjective preferences and make bounded-rational decisions.

Simulation experiments help to assess the impact of political interventions. Results of experiments with the MATSim-SimCo Ruhr model show that different agent types react very differently to measures intended to make transportation more climate friendly. Additionally, they help to identify those groups that may contribute most to sustainable transformation. Surprisingly, these are neither environmentally friendly actors, used to riding the bike, nor comfort-oriented actors, used to commuting by car, but two groups of rather indifferent or pragmatic people that are willing to change behavior.

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