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DOI
10.1016/j.trip.2025.101683

Publication date
2025

Document Version
Final published version

Published in
Transportation Research Interdisciplinary Perspectives

Transportation Research Interdisciplinary Perspectives 34 (2025) 101683

Contents lists available at ScienceDirect

Transportation Research Interdisciplinary Perspectives

journal homepage: www.elsevier.com/locate/trip

Participatory model-based policy exploration for the mobility transition ☆

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ARTICLE INFO

Keywords:
Participatory modeling
Decision-making under deep uncertainty
Mobility transition
Uncertainty
Systems thinking
Urban transport system

ABSTRACT

Decision-making in the context of the mobility transition requires considering complexity, many actors, and uncertainty about the future. So, choosing effective policies to achieve a more sustainable system is challenging. We build on participatory modeling and decision-making under deep uncertainty to create a novel approach to investigate the capabilities of decision-makers to interact with an agent-based model to explore various transport policies. This paper reports the results of two workshops with students exploring the mobility transition for a fictional version of a city in the Netherlands The participants made decisions in the role of either government or transport provider and evaluated the systemic impact of those decisions. We found that the participants were well-equipped to deliberate policy options under deep uncertainty using model simulations depicting a range of possible outcomes under different scenarios, embracing uncertainty in some respects and ignoring it in others. This study demonstrates the potential of participatory model-based exploration for mobility transitions to deliberate policy options under uncertainty using an agent-based model.

1. Introduction

Transitioning a city's mobility system towards more sustainable functioning requires considering complexity, including many actors, and uncertainty about the future and the system itself. Decision-making with the aim to transform the complex mobility system is challenging, as is evidenced by past cases in which policies turned out to be ineffective or had unintended negative consequences (Berger et al., 2014). How technological innovations will change the mobility system, impacting infrastructure, transport modes, and travel patterns is intrinsically uncertain (Lyons et al., 2021). In addition, actors often hold diverging perspectives on the problem and may favor different courses of action (Jittrapirom et al., 2021). These situations in which decision-makers lack clarity or agreement about the system, the possible governing actions and their outcomes, the outcomes should be considered, and the outcomes' importance, are described as deep uncertainty (Lempert et al., 2003). Therefore, transitions do not only require technical solutions, but also collective learning and deliberation.

Through participatory processes, actors can co-learn and deliberate. Learning among actors is a key part of the mobility transition (Glaser et al., 2019). To enrich such processes, models can provide a shared basis for analyzing and understanding complex systems such as the mobility system in transition (Cuppen et al., 2021). Engaging actors in model use allows to include the diverging actor perspectives on the problem and the uncertainty surrounding the consequences of different courses of action. Indeed, engaging actors, such as decision-makers, transport providers, or citizens, in the policy process through participatory modeling may help to elicit their perspectives, foster learning, and potentially mobilize support and commitment to policies (Voinov et al., 2018; Mingers, 2011; Cockerill et al., 2009; de Gooyert et al., 2022). In particular, models in the form of role-playing games are effective in facilitating social learning (Pahl-Wostl and Hare, 2004; Champlin et al., 2022).

Transition modeling has emerged to investigate the complexity of transitions in various domains, including transport (Halbe et al., 2015; Holtz et al., 2015; Köhler et al., 2018; Moallemi and de Haan, 2020). Transitions are typically defined as gradual, continuous processes of structural change within a society or culture (Rotmans et al., 2001), profoundly altering the system's functioning (de Haan, 2010). Dynamic models help to understand and explore phenomena emerging from interactions within the system (Holtz et al., 2015). However, most mobility transition models have a strong focus on technology and mainly investigate the development of a single innovation, such as electric vehicles (Hoekstra and Hogeveen, 2017; Zolfagharian et al., 2020),

☆ This research is part of the project 'On the Move - Transition towards Sustainable Mobility,' funded by NWO, The Netherlands within the program 'Behaviour and Transitions.'

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https://doi.org/10.1016/j.trip.2025.101683
Received 15 April 2025; Received in revised form 4 October 2025; Accepted 12 October 2025
Available online 22 October 2025

hydrogen cars (Köhler et al., 2010), or alternative fuel vehicles in general (Kwon, 2012). Additionally, only a few models explicitly address the uncertainty of transitions (Moallemi and Köhler, 2019). Führer et al. (2024b) developed an agent-based model of the whole mobility system that includes social interactions, endogenous interactions between transport modes, and the emergence of innovations and is suitable for exploring a wide range of policies and uncertainties.

To address deep uncertainty present in the transition process, the field of decision-making under deep uncertainty (DMDU) provides various approaches for supporting long-term planning for complex systems (Marchau et al., 2019a). Typically, DMDU studies focus on analytical tools and approaches but pay little explicit attention to shared sense-making and coming to a decision (Führer et al., 2025; Malekpour et al., 2020; Stanton and Roelich, 2021). Empirical studies on the capabilities of actors to engage with deep uncertainty through participatory activities exist, but their number remains limited (*e.g.,* Lempert and Turner, 2021; Bhave et al., 2018; Linnerooth-Bayer, 2021; Bojórquez-Tapia et al., 2021; Johnson, 2021; Führer et al., 2024a; Akse et al., 2025). These shortcomings indicate a necessity to enable decision-makers to deliberate with each other and with other stakeholders. Therefore, there is a need for activities that engage actors in decision-making under deep uncertainty processes.

Participation and decision-making under deep uncertainty are both approaches to address wicked problems. The lack of consideration of uncertainty in participatory processes and the lack of stakeholder engagement in DMDU studies provide a basis for the two approaches to complement each other. Combining these approaches has the potential to foster deliberation and learning about the mobility transition. Führer et al. (2025) argue that engaging stakeholders in DMDU processes is promising for increasing relevance, ownership, and agency for the participants. Moreover, participants can learn about the system, the problem, and possible courses of action, while researchers can elicit context-specific knowledge and validation from the participants. Therefore, there is a need to study how decision-makers interact with simulation models of mobility transitions, especially models that embrace uncertainty.

In this study, we developed a novel workshop process for decision-makers to engage with exploratory modeling to explore various transport policies under various futures using an agent-based model (Führer et al., 2024b). We build on participatory modeling and decision-making under deep uncertainty approaches. This study has three objectives. The first objective is to enable participants to deliberate policies in an uncertain context with each other. This includes model simulations and impacts of policies on the system, but also aspects of the mobility transition that are not part of the model, as well as gaining awareness of the interest of municipalities and providers. The second objective is for participants to learn about and understand key sources of uncertainties that affect the outcomes and, subsequently, their decisions. The third objective is for participants to gain trust in the model.

This paper reports on two separate occasions in which we invited students to participate in a workshop exploring the mobility transition for a fictional version of a city in the Netherlands. The participants made decisions in the role of either government or transport provider and evaluated the systemic impact of those decisions. We found that the participants were well-equipped to deliberate policy options under deep uncertainty using model outputs depicting a range of possible outcomes, embracing uncertainty in some respects and ignoring it in others.

This paper is structured as follows. We first introduce participatory model-based decision-making as well as the wicked problem of mobility transitions in Section 2. Following this, we describe our research design, the model we used, and the case study in Section 3. We conclude by discussing the process, the outcomes, and implications for policy-making and future research in Section 5.

2. Participatory model-based decision-making

In this study, we engage participants in a model-based policy exploration and decision-making process. We use an agent-based mobility transition model to help participants make policy decisions to achieve a more sustainable urban mobility system. The mobility system is complex, wicked, dynamic, and uncertain and involves many actors who influence the system and have different views on it.

Transitions are multi-dimensional, co-evolutionary processes with many actors with varying characteristics and values (Köhler et al., 2019). The involvement of these actors and their potentially conflicting values and perspectives on the system, the problem, and possible solutions make socio-technical systems inherently complex (Thissen, 2013). Further, these actors are affiliated with different institutions, each institution with its own responsibilities and spheres of influence. Planning situations with these kinds of characteristics have been described as wicked problems (Rittel and Webber, 1973). The transport domain has been prominent in transitions research (Köhler et al., 2019; Holtz, 2011). Mobility transitions, especially, are not only influenced by policies and economic conditions but also by social aspects, habits and routines, and lock-ins and lock-outs resulting from earlier decisions (Mehdizadeh et al., 2022).

Modeling is helpful for understanding and analyzing complex systems such as the transport system in transition. Holtz et al. (2015) describes three benefits of using models for transitions. First, models are explicit, meaning that constructing a model requires making assumptions, the definition of variables, and their relationships explicit (Epstein, 2008). Second, models, especially dynamic models, enable exploring dynamics in complex systems. Where human reasoning through mental models fails to properly simulate feedback, time delays, and non-linear behavior in complex systems (Sterman, 1994; Schaffernicht, 2019; Atkins et al., 2002; Brehmer, 1992), dynamic models can help to understand emergent phenomena resulting from interactions within the system. Third, models enable systematic experimentation by providing a means to experiment and explore different policies, assess the consequences of uncertainties, or evaluate inherent stochasticity. Such experiments would be impossible to conduct in the real world due to their cost and social impact (Kwakkel and Yücel, 2012).

Various approaches have emerged to support decision-making under deep uncertainty (DMDU), such as Dynamic Adaptive Planning (Walker et al., 2001), Dynamic Adaptive Policy Pathways (Haasnoot et al., 2013), and Robust Decision Making (Lempert et al., 2003). Using models as exploration tools rather than prediction tools (Marchau et al., 2019b), DMDU aims to identify policies that perform satisfactorily over a wide range of uncertain conditions, and not just in the most likely ones (Lempert and Collins, 2007; McPhail et al., 2018).

A DMDU analysis follows three general steps (frame, explore, and choose), each consisting of several elements (Marchau et al., 2019b; Führer et al., 2025). Different DMDU approaches emphasize different elements without imposing a strict order (Marchau et al., 2019b; Lempert, 2019). We use the elements of the last two DMDU steps as a guiding framework for this study. The first step, frame, is outside the scope of this study, as we use an existing model to explore and choose policies. The second step, explore, includes identifying the outcomes of policies, their importance, and the vulnerabilities given the uncertainties. The third step, choose, includes selecting initial and contingent actions.

Actors can be involved in any component of the modeling process, including using the model and its outputs to make decisions (Voinov et al., 2016). Involving stakeholders in the modeling process allows for incorporating different perspectives and knowledge and creating support, depending on where and how in the modeling process participants are included. Engaging stakeholders in the modeling process can facilitate the development of a shared understanding of the problem and foster ownership over the problem and the necessary actions needed to address it (Franco and Montibeller, 2010; de Gooyert et al., 2022; Rouwette and Franco, 2024). Moreover, participatory modeling can foster social learning among participants by providing a space to deepen their understanding of the complexity of the system, enhance

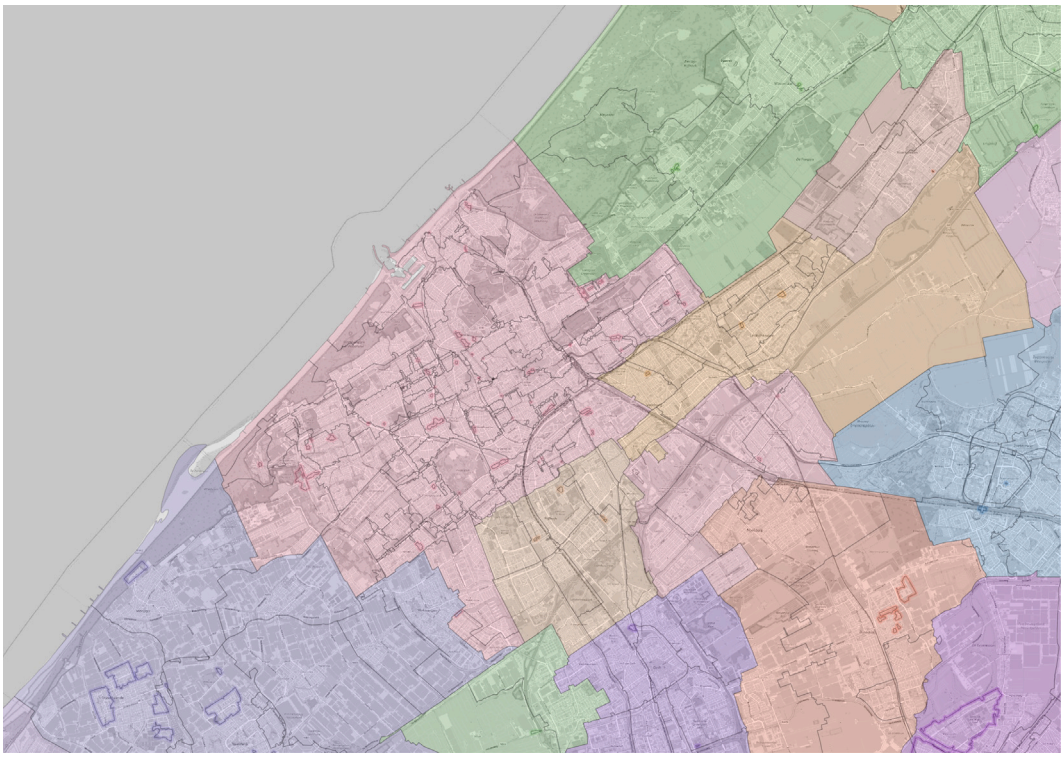

Fig. 1. The city of Den Haas (pink) and surrounding municipalities.
Source: Adapted from OpenStreetMap.

agreements on causalities (Jittrapirom et al., 2021; Rouwette et al., 2011), and recognize the uncertainty inherent in the system, data, and methods (Cockerill et al., 2009).

Insights from transition modeling, decision-making under deep uncertainty, and participatory modeling informed the research design of this study to engage actors in exploratory modeling of the mobility transition.

3. Research design

This section introduces the case study, the model, the workshop steps, and data collection.

3.1. Case study Den Haas

We presented the participants with a fictionalized case study region called *Den Haas*. Den Haas is a city of about 500 000 inhabitants located at the sea. The city has a public transport network consisting of bus, tram, and metro within the city, as well as train connections to other cities. The city is surrounded by smaller municipalities (see Fig. 1).

Den Haas is based on the city of The Hague in the Netherlands. We chose to present it as a fictive city to minimize the impact of any prior knowledge the participants might have.

3.2. The agent-based model

The model used in the workshop is an agent-based mobility transition model (Führer et al., 2024b). This model is based on the Actor-Option framework for modeling transitions (Yücel, 2010). The main building blocks are actors, options, and mechanisms of change. Yücel (2014) provides four main actor roles: users, providers, regulators, and opinion groups. In our model, users are the agents endogenous to the model, while provider and regulator actions are used as inputs in the form of policies. Opinion groups are beyond the scope of this study. Options are ways to fulfill a societal need. For the transport system, the options are the transport modes. Each option possesses a set of attributes that the actors use to inform their decisions. The framework provides various mechanisms of change. For our model, the two main mechanisms are change in option properties through provider and regulator policies and learning among the users.

3.2.1. Model description

The agent-based model we developed can be used to explore the consequences of introducing various combinations of policies and/or innovations. This section provides an overview of the model. A complete model description can be found in Führer et al. (2024b). The model is implemented in Python using the MESA library for agent-based modeling (Masad and Kazil, 2015).

The agents in the model represent the users of the transport system. Each user has a home location, a list of transport modes that are available to it, and a list of habitual trips to perform. The agent population is synthesized using mobility panel survey data (CBS, 2023) for the city of The Hague. In this survey, respondents report the trips they perform. Based on the number of inhabitants per postcode area in the city of The Hague (CBS, 2024), we sample the corresponding number of agents to have 1000 agents in total. The spatial scope for agent locations is the municipal boundary of The Hague. However, the origin and destination locations of the trips can be throughout the Netherlands.

Upon model initialization, the agents are connected in a small-world social network. Then, all agents make their initial mode choice. For this choice, none of the policies are active yet. The model was calibrated to reflect the current modal split of the city of The Hague. The model was then run for 10 time steps, each representing one year. At each time step, a fraction of the users re-evaluate their mode choices. The agents are randomly selected and activated in a random order. Letting only a subset of agents re-evaluate at each time step represents users' habitual behavior not changing every year. Before choosing a mode for each trip, the users first update their available modes. By checking the available modes of their neighbors in the social network, they add new modes.

Table 1
Specification of uncertainties and their ranges.

Uncertainty	Description	Range
k_{social}	Number of initial neighbors when creating the social network	2–8
p_{social}	Probability of rewiring when creating the social network	0.2–0.8
$n_{agents-change}$	Number of agents that re-evaluate their mode choice every time step	50–250
$n_{early-adopters}$	Number of agents that the innovation is added to upon its introduction	10–100

Then, the agents choose a mode for each of their trips through utility maximization. The utility is calculated based on the trip distance and travel time, as well as the mode costs, value of travel time, and comfort.

The system changes through the implementation of provider and regulator policies. These policies change the attributes of the transport modes. If the policy introduces a new transport mode, the mode is added to the list of available modes of a randomly selected subset of agents. These agents represent early adopters who receive information from outside their social network. The rest of the agents learn about the innovation through their social network. Therefore, information spreads among agents with a time delay. The model creates time-series data for the modal split at each time step.

3.2.2. Experimental design

We used the model to explore system behavior under different assumptions. We explicitly considered various uncertainties affecting user choice behavior through Exploratory Modeling (Bankes, 1993; Bankes et al., 2013). Using Exploratory Modeling allows us to systematically test different assumptions to observe various possible outcomes and learn about system behavior.

The Exploratory Modeling and Analysis (EMA) workbench (Kwakkel, 2017) was used to run the experiments and analyze the output data. First, we implemented the model and defined the key parameters, such as option attributes. A combination of values for the uncertain factors is considered a scenario. Next, we specified running the model for ten time steps. Following this, we set up the experiments by identifying the uncertainties, the policies, and the outcome indicators. The four key uncertainties (Table 1) are systematically sampled to represent many possible states of the world. We explored no action and three policies each for the provider and regulator, yielding a total of 16 policy combinations (Table 2). The outcomes of interest are the number of trips performed for each transport mode for each time step. This is then used to calculate a modal split.

Next, we specified 100 scenarios to be used for Exploratory Modeling. To account for the stochasticity in the model, we used five model replications per scenario. Each model replication uses a different random seed. The random seed is used in the random activation order of the agents, the creation of the social network, and the selection of the subset of agents updating their choice.

3.2.3. Model output

We ran the model before the workshops as the runtime was too long to run it in the workshop. Therefore, we ran the model for all policy combinations and compiled the resulting graphs in a document that the participants could use in the workshop. For each policy combination, the participants had two graphs to look at: the average modal split over time (see example in Fig. 2) and the number of trips for each mode (see example in Fig. 3).

3.3. Workshop steps

The workshop started with introducing the facilitators, observers, and participants. Then, the goal and objective of the workshop, as well as the case study context, were explained. Following the general introduction, we introduced Agent-Based Modeling and the model the participants would use during the decision-making. We used slides to explain the components and processes in the model and a map to explain the spatial context and the movements of the agents. We explained the model outputs using a business-as-usual scenario and a fictitious policy.

At the end of the explanation, the participants were divided into groups of two. In each group, one participant took on the role of provider and one the role of government. Role descriptions provided information on the objective of their role and the policies they could implement. The government's objective was to transition towards more sustainable mobility by substituting trips with high-emission modes with lower-emission modes while keeping the transport system accessible for everyone. The provider's objective was to be profitable and have a good public image to retain and possibly expand ridership. All groups were provided with the model output graphs for all policy combinations.

The discussion round in pairs involved four main tasks. First, participants chose a policy from a list of pre-defined of policies. Second, they discussed possible results and risks resulting from their chosen policies. Third, they looked at the model outputs for their policy combination and discussed the effects in light of their objectives. Fourth, participants discussed whether there are any future developments this policy might be vulnerable to and how to mitigate these vulnerabilities. Participants were asked to note down their decisions as well as arguments for the decision. This discussion round was performed two times. Participants could choose a new policy or stay with the previous one in the second round.

Following the discussion rounds, the participants presented their results to the plenary group. They were asked to present which policies they think should be investigated further or even implemented, as well as the vulnerabilities they identified. After that, participants were asked to reflect on the usefulness of the model results, their experience of the workshop, and what they learned.

3.4. Data collection

Data was collected through audio recordings, observation, participants' notes, and a short survey before and after the workshop. This data included the opinions and insights of the participants, as well as their behavior during the workshops.

The observation was done by members of the research team who were not involved in the facilitation. Throughout the workshop, observers noted down participants' insights and opinions, what they were discussing with each other, and the questions they posed. During the presentation of each pair's results, the observers noted down their reasoning for the participants' choices as well as their reflections.

During the workshop, participants filled out templates with their decisions and reasoning. Each pair filled out two templates – one for each round. The participants had different colored pens available to them – one for each role to mark a statement as pertaining to their own role and one color specific to their pair to mark statements as consensus.

Before and after the group work, participants answered a short survey. The first survey collected data on their current and past studies, as well as their level of familiarity with mobility and modeling (*very unfamiliar* to *very familiar*). Then, participants were asked to note down some ideas they have for making mobility more sustainable. We asked this question to assess whether the participants had a broad range of ideas. Following this, they were presented with the six mobility policies of the workshop. For each policy, we asked what impact on sustainability they think this policy will have (*very poor* to *very good*) and how certain they are about this impact (*very uncertain* to *very certain*). The second survey was carried out after the group work. Participants were again asked about the impact of the policies and how certain they were about these impacts. By collecting this information in both surveys, we

Table 2
Overview of the policies.

Regulator policies	
Increase parking costs	A fixed parking costs is added to all car trips
Speed limit	More speed limits in the city make all car trips 10% slower
Better bike infrastructure	Better cycling paths and traffic light optimized routes make cycling 5% faster
Provider policies	
Free public transport	The cost of public transport is set to zero
Introduce innovation everywhere	The innovation (shared micro-mobility) is added to a number of early adopters and can be used for all trips
Introduce innovation within the city	The innovation (shared micro-mobility) is added to a number of early adopters and can be used for trips that start and end in the city

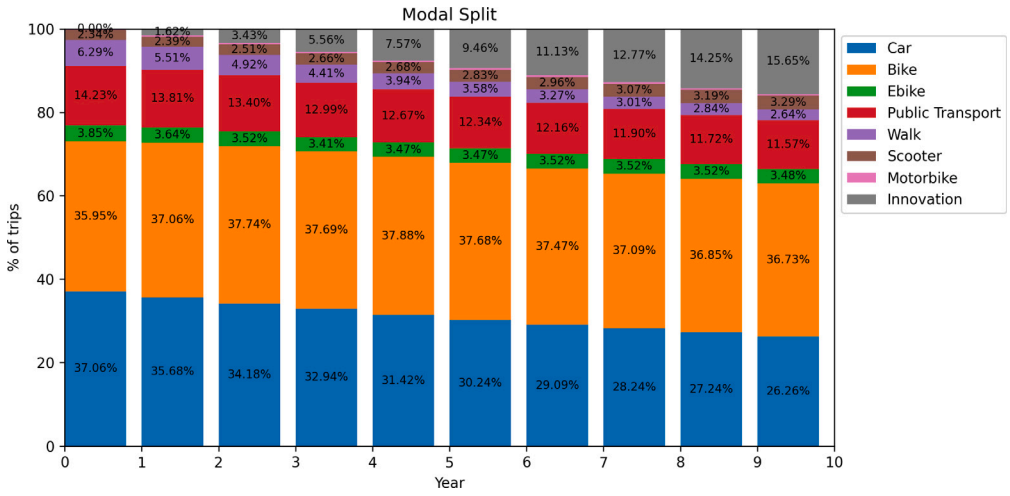

Fig. 2. Modal split over time for the policies 'Shared micromobility within the city' and 'Improved bike infrastructure'.

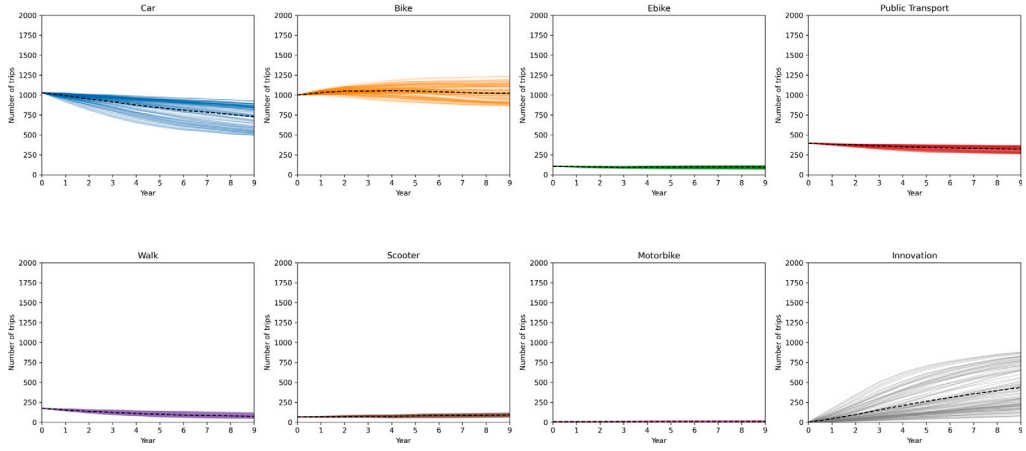

Fig. 3. Number of trips over time for the policy combination of 'Shared micromobility within the city' and 'Improved bike infrastructure', each line represents one scenario.

could assess whether their view on the policies changed. The second survey concluded with a reflection on the workshop by asking about policies that were not covered but should have been, satisfaction with the results and interactions of the workshop, and key insights.

4. Results

We held the same workshop twice with two different groups of students. Group A were students from the business faculty of a general research university. Group B were students from a technical university. The motivation for running the workshop with two different groups was to see the role of experience in modeling. We expected that the students from the technical university would have more experience, which would alter the results of the workshops.

In this section, we report on the findings from each data source: the survey before the workshop, the decisions documented by the participants, the observation, and the survey after the workshop.

4.1. Survey before the workshop

The survey before the workshop provides us insight into the background and expertise of the participants. The students of Group A were

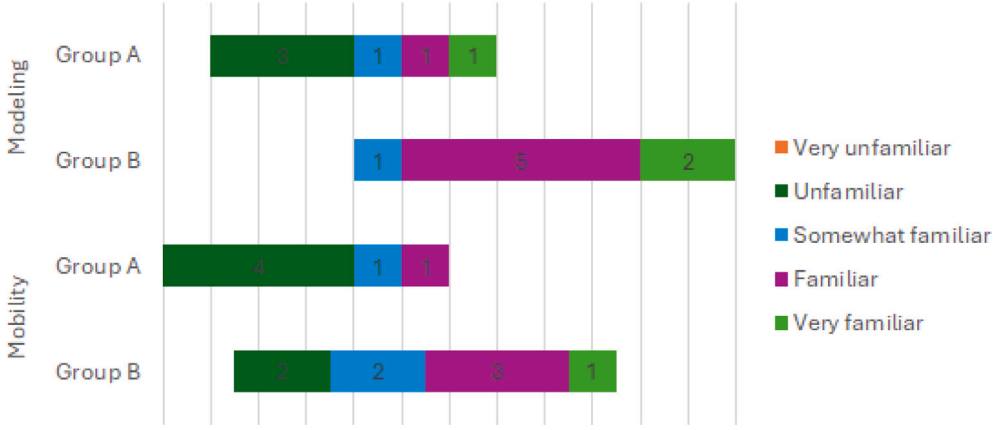

Fig. 4. Participants' familiarity with modeling and mobility.

from several different study programs related to business, economics, and finance at both the Bachelor's and Master's levels. One member of the research team filled in to replace a no-show. This group of participants was paid for their participation since it was customary at the decision-making lab where this workshop was held. The students of Group B were all first- and second-year students in the master's program, Engineering and Policy Analysis, with varying engineering backgrounds. This group was not paid, as the workshop's contents relate to one of their courses.

To assess the participants' familiarity with modeling and mobility, we used a Likert scale with five levels: very unfamiliar, unfamiliar, somewhat familiar, familiar, and very familiar. Fig. 4 illustrates the participants' self-reported familiarity levels. The two groups differed in both categories. Half the participants in Group A reported being unfamiliar with modeling. For Group B, all participants stated that they were at least somewhat familiar with modeling, with most of them saying that they were familiar.

Regarding mobility, more than half of Group A stated that they were unfamiliar with the topic. The participants of Group B reported varying levels of familiarity, from unfamiliar to very familiar. To summarize, overall, Group B reported a much higher level of familiarity with modeling. The level of familiarity with mobility is more balanced between the two groups, with Group B also showing a slightly higher level.

To assess whether the participants have a broad range of policy ideas, we asked them about their ideas for more sustainable transport. The answers included policies for almost all transport modes, most notably improving public transport and cycling infrastructure. Other ideas included improved routing based on analyzing mobility patterns, reducing travel distances through city planning, and mobility hubs.

4.2. Decision documentation

In both workshops, each policy, other than the option of no action, was chosen at least once. Only one participant chose no action from the government. The provider policy that was most often chosen was innovation within the city. The government option most often chosen was better bike infrastructure, closely followed by increased parking costs.

Following the chosen policy, participants stated why they chose their policies, including expected outcomes and risks. This was mostly stated for each role; a few pairs added consensus statements as well. For both groups, the reasoning for a choice most often stated was an expected increase in trips made with modes other than the car. Other than that, participants in both groups reported choosing a policy based on its merits, as stated in the description, or through a process of elimination. A participant from Group B stated: *'I chose this policy because it sounds more reasonable than other options. The speed limit has already been tested and is not effective. The third policy is too expensive.'*

The risk most stated by both groups was regarding the costs of implementing a policy, especially because it could mean less funds for other policies. Group A identified the risk of damage and high costs for implementing shared micromobility ('possible problems with how people care about the shared bikes, they may destroy them faster, servicing costs and recovery might be high'). A risk that was mentioned multiple times by Group B is crowding and net congestion as a result of several policies.

Next, the participants looked at the model outputs and were asked to describe the effect of the policy and whether it aligned with their objectives. Most groups described the change in the number of trips for several modes. The modes that were reported the most are car, innovation, public transport, and walking. All groups then related these changes to the objectives of their role. Two groups also reported unexpected results: *'It mainly has an impact on innovation and car, we would expect more impact on other alternatives (e.g. public transport)', and 'unexpected is that, compared to the previous run, the effect is less than we hoped for: less decrease in car use, more decrease in public transport, walking decrease quite similar'*. Some groups also identified more risks or expectations.

Finally, participants were asked whether they could identify any future events that their chosen policy might be vulnerable to and how that might be mitigated. The main themes running through the answers are funding, demand, public discourse, cost, and safety. Overall, these vulnerabilities are close to current issues discussed in media and literature. Most groups were able to come up with mitigation ideas for these issues.

4.3. Observations

During the workshop of Group A, the participants did not ask many questions. The main questions that arose were clarifying questions about the nature of the innovation. Conversely, Group B asked many questions, mainly about the model and scope. Participants of Group B asked about reasons for dynamics in the model, agent behavior, limits to their choices, and which kind of trips are included in the model.

When reporting on their choices, Group A focused a lot on business models, revenue, and funding when discussing the policies. The participants were optimistic about introducing innovations into the system and highlighted the importance of public–private partnerships for the innovations to succeed. Group B was concerned about the political impact of the policies and how different policies could complement each other. In their reporting, many participants clarified which effects were expected or unexpected. One pair deliberately chose to explore what they expected to be the worst option to see what would happen.

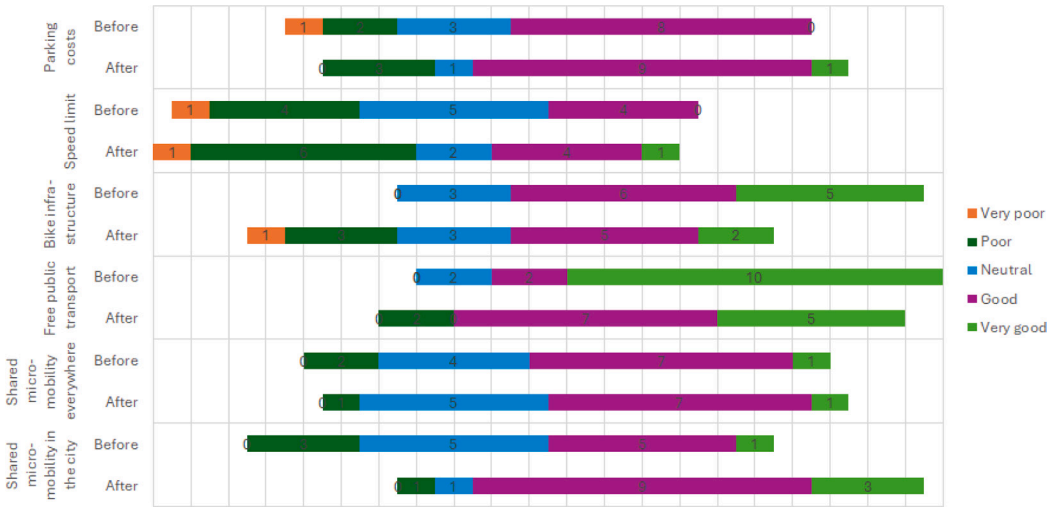

Fig. 5. Survey answers before and after the workshop for each policy regarding the sustainability effect.

During the reflection round, participants from Group A discussed the limitation of not including costs in the model as they regarded this as the most deciding factor. When asked about the usefulness of the model results, participants stated that they mainly regarded the modal split over time and less the plots for individual modes. They interpreted line plots with a smaller range as more certain outcomes and a wide range as more uncertain. Participants from Group B stated that they would appreciate more detail on how users shift from one mode to another, the cost-effectiveness of policies, and more demographic information. This group also discussed how their own bias and preferences influence their decisions. The participants stated that the model results were helpful to them.

4.4. Survey after the workshop

The survey after the workshop covered four topics: a change in the participants' judgment of policies, ideas for further policies, satisfaction with the results and interactions of the workshop, and participants' key insights.

First, we asked the participants to judge the policies used in the workshop. In both the survey before the workshop and after, the participants answered for each policy the effect on sustainability they expect (Fig. 5) and how certain they are about this effect (Fig. 6). Due to the small size of the group, statistical tests were not considered for these results. From the visual analysis, we can see that the two policies *Better bike infrastructure* and *Shared micro-mobility in the city* have the biggest changes. Better bike infrastructure is perceived to be less sustainable after the workshop than before. Shared micro-mobility in the city is perceived to be more sustainable than before. When it comes to how certain the participants think this sustainability effect is, all policies except *Free public transport* are perceived as slightly more certain.

To further investigate the changes in the survey answers, Figs. 7 and 8 show the changes in the answers. '−1' indicates a change to one category lower in the Likert-scale. From this, we can see that while there were no significant changes overall visible in the aggregated survey answers for the policies, the participants changed their answers between the two surveys.

Second, we asked the participants if there were any policies that had not been covered but should have been. Multiple participants answered that they were satisfied with the policies already covered or had no further policies to add. Many answers included financial incentives, such as discounts for specific user groups, subsidies, or bike leasing schemes. Other suggested policies were shared taxis, car parking near the train station, banning older cars from the city, and policies targeting businesses.

Third, participants reported their satisfaction with the workshop results and interactions during the workshop. All participants stated that they were satisfied with the workshop's results, and some emphasized that they found it interesting. Regarding the interactions during the workshop, all but one participant reported that they were satisfied. The unsatisfied participants stated that interaction in bigger groups would have brought more discussion or ideas to the table. Other participants noted that the workshop was engaging, educational, and fun.

Fourth, participants reported on their key insights. Collaboration between the provider and government was a central concern among participants. Furthermore, participants learned about how transport modes are connected to each other and the impact of policies, such as the potential of micro-mobility or infrastructure improvements. Participants reported that they could work well with the model results and looked at the problem from a new perspective. One participant noted that thinking about vulnerabilities should be more common.

4.5. Interpretation of results

We interpret the results in relation to the three workshop objectives: understanding uncertainty, deliberating policies, and trusting the model. For each objective, we lay out the results pertaining to the objective and discuss to what extent the objective has been met.

The first objective was to enable participants to deliberate policies in an uncertain context. Participants were actively discussing policies and their impact throughout the workshops. Relating the outcomes back to their objectives and reporting results as unexpected shows an understanding of the model and its outcomes. In relation to this objective, we also aimed for participants to discuss aspects of the mobility transition not captured in the model. Participants were able to have this discussion, which resulted in risks and vulnerabilities. Furthermore, we also expected participants to gain awareness of the interests of municipalities and providers. Many participants discussed the importance of public–private partnerships and also reported this as a key insight multiple times. For these reasons, we conclude that participants in this setting could deliberate policies in an uncertain context.

The second objective was for participants to understand key sources of uncertainties that affect the outcomes and their decisions. During the workshops, the participants did not discuss the uncertain parameters used in the model in particular. Participants interpreted wider ranges as more uncertain, which shows they understand uncertainty in the model outputs but ultimately preferred to regard the average modal split over time. When it came to thinking of future trends or events that might impact their policy, they were able to generate many ideas.

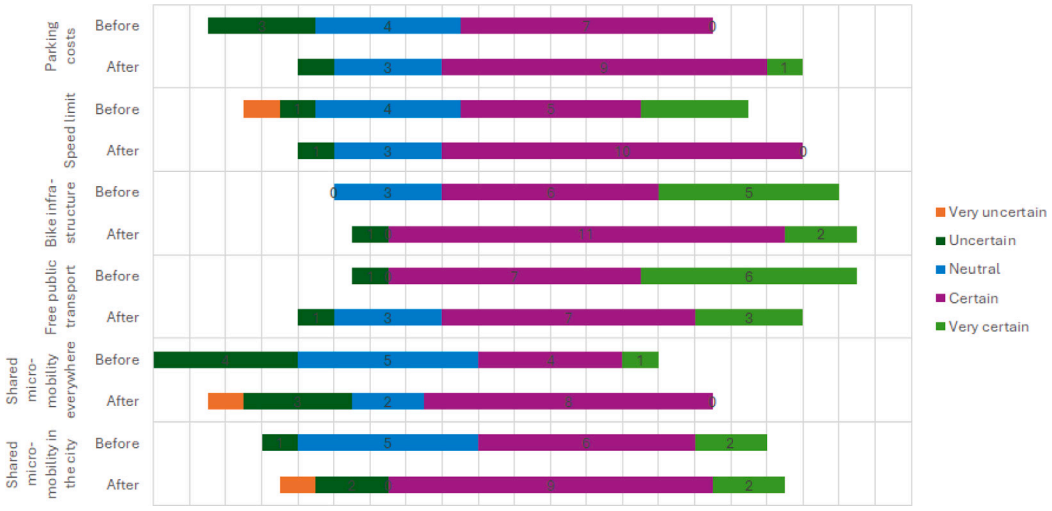

Fig. 6. Survey answers before and after the workshop for each policy regarding the certainty of the sustainability effect.

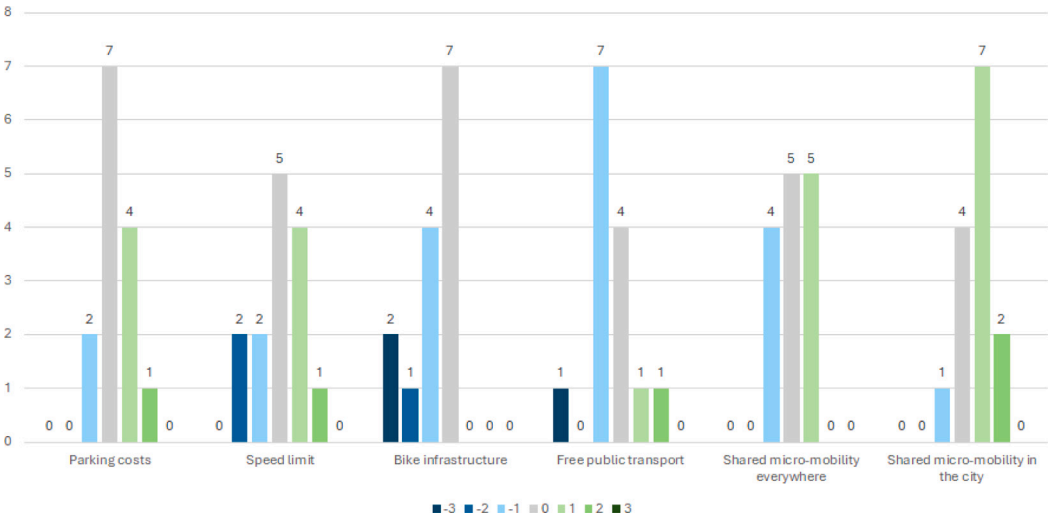

Fig. 7. Change in the survey answers before and after the workshop for each policy regarding the sustainability effect.

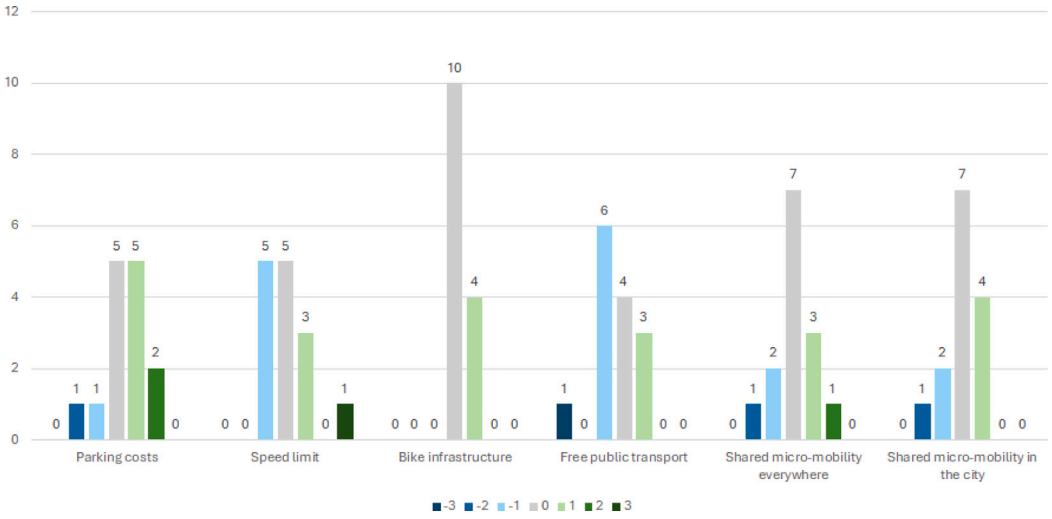

Fig. 8. Change in the survey answers before and after the workshop for each policy regarding the certainty of the sustainability effect.

However, most vulnerabilities were close to current issues. Therefore, we infer that participants understood the what-if thinking inherent to many DMDU methods but did not regard specific uncertainties or think very far out of the box.

The third objective was for participants to trust the model and its outcomes. The participants reported that, overall, they found the model results helpful for decision-making. Some participants stated that they would have preferred more information, such as how users shift from one mode to another, cost-effectiveness, and more demographic information. So, we infer that the participants trusted the model enough to make decisions in this context. Sharing more details about the model, how it works, and the outcomes would have increased trust further.

5. Discussion and conclusion

In this study, we developed a novel approach to enable decision-makers to interact with an agent-based model to explore various transport policies. We applied the approach in two workshops. The first objective was for participants to understand uncertainty and its impact by understanding key sources of uncertainties that affect the outcomes and, subsequently, their decisions. The second objective was to enable participants to deliberate policies in an uncertain context. This included model outcomes and impacts of policies on the system, but also aspects of the mobility transition that are not part of the model, as well as gaining awareness of the interest of municipalities and providers. The third objective was for participants to gain trust in the model. In this section, we reflect on the insights provided by the workshops, discuss the limitations and further research, and conclude with the contribution of this study.

5.1. Insights for participatory DMDU

The workshops provided us with three main insights: on to the participants' interaction with the model, on the participants' engagement with uncertainty, and the applicability to other groups.

The first insight relates to the interaction of participants with the model. The participants could use the model and make decisions based on the model simulations. We observed the participants actively discussing policies and their impact and relating the resulting model outputs back to their objectives, which demonstrates their understanding of the system, model, and policies. The participants did not fall into the pitfall of linear thinking but instead acknowledged the system's complexity, feedback effects and non-linearity. Moreover, the participants took on their respective roles well and performed the tasks seriously with relatively few cues. They were engaged throughout the workshop and interacted well with the tool showing the model outputs.

The second insight relates to the participants' capability to engage with uncertainty. The long runtime of the agent-based model makes participatory exploratory modeling and analysis challenging. We circumvented that by running all policy combinations beforehand and presenting the results in a document. The participants were aware that the model did not represent every aspect of the system and were able to discuss aspects that were not included. The participants were given two types of model outputs: one more simplistic figure showing average modal split across scenarios and one more detailed figure depicting the individual scenarios. We observed that participants tended to favor figures depicting the average modal split. Therefore, the outputs that are presented to the participants and the interface through which these outputs are presented need to be carefully chosen to prevent them from ignoring uncertainty.

The third insight relates to the applicability to other groups. Despite their differing backgrounds, we found no significant difference between the two groups' performance. The group with a more technical background asked more specific questions about the model and how it works. The group with a business background asked more finance and business-related questions. This difference indicates that participants will discuss what they are most familiar with. The similarity in the overall performance of the two groups suggests that this type of workshop is appropriate for educated participants of different disciplinary expertise with or without modeling experience. Therefore, we conclude that involving policymakers in a workshop including uncertainty is promising.

5.2. Limitations and further research

We identify two main avenues for further research, one related to the further development of the workshop design and the other related to the application to policy-makers. From the limitations of the current workshop design, we identify a need for more policy possibilities and to foster more creativity. When translating the workshop insights from students to decision-makers, challenges arise from the context in which decision-makers operate.

The first limitation of the current workshop design is the selection of policies. Each role has a limited number of policies, and participants can only choose one policy at a time. In addition, the participants can only choose policies at one point in time, and there is no possibility of adapting over time. Further development of the model and its interface could provide the possibility of choosing multiple policies and intervening at different points in time. Moreover, instead of each policy being either active or inactive, policies could have varying strengths (*e.g.,* different speeds for the speed limit).

The second limitation of the current workshop design is a limited diversity of ideas. Participants stuck to familiar ideas and discussed topics they knew most about. Future research should focus on the selection of participants and workshop design. Bringing together participants of different backgrounds together in heterogeneous groups can introduce new ideas and facilitate conversation across disciplines. During future workshops, we recommend tweaking the workshop design in a way that stimulates creativity.

The first challenge when translating this workshop to decision-makers is the organizational complexity. In the current role-playing game, we assume a single decision-maker representing the municipality and provider, respectively. In reality, decision-makers are embedded in an organization with a plurality of opinions, power dynamics, and bureaucratic structures. A way to include this organizational complexity is to have small groups discuss the policies for the provider and the government.

The second challenge arising from the translation to decision-makers is the difference in risk perception and accountability. While students may generate ideas without real-world constraints and feel free to choose policies, decision-makers must consider legal, financial, and political risks. These higher stakes need to be considered when applying this workshop design to case studies concerning decision-makers. Future workshops could include more consideration of risks and their mitigation.

The third challenge related to the translation to the real world is the context-dependence. Participatory processes are shaped by governance structures, political cultures, and planning traditions. In the Netherlands, there is a strong tradition of consensus-finding in planning compared to countries with more hierarchical institutional contexts (Koppenjan and de Jong, 2018). Local policy makers are frequently requested to join different science-policy workshops as stakeholders of their policy field (van Berkel and Verburg, 2012) and are open to experimenting with innovative approaches (Führer et al., 2024a). These attributes may not hold in contexts with lower trust, more adversarial politics, or different planning cultures. Therefore, considering the institutional and cultural context is important when designing and assessing participatory model-based planning approaches.

5.3. Concluding remarks

This study contributes a novel approach to participatory decision-making under deep uncertainty. We demonstrate that an activity

with role-playing and gaming elements is a promising approach to exploring model-based decision-making with participants of varying backgrounds. We found that participants understood the what-if thinking behind DMDU approaches, were able to deliberate policies in an uncertain context, and trusted the model enough to make decisions in an uncertain context. In addition to interacting with the model, the participants took aspects outside the model's scope into account to discuss vulnerabilities, such as exogenous influences or future events. We contribute an approach for participatory DMDU for the wicked problem of mobility transitions by combining quantitative simulation modeling and qualitative considerations around the model. We specifically explored the role of decision-makers, investigating their capability to interact with exploratory modeling outputs.

CRediT authorship contribution statement

Karoline Führer: Writing – review & editing, Writing – original draft, Supervision, Software, Methodology, Formal analysis, Conceptualization. **Floortje M. d'Hont:** Writing – review & editing, Supervision, Methodology, Formal analysis, Conceptualization. **Etiënne A.J.A. Rouwette:** Writing – review & editing, Supervision, Methodology, Formal analysis, Conceptualization. **Jan H. Kwakkel:** Writing – review & editing, Supervision, Software, Methodology.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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