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Modeling with a municipality: Exploring robust policies to foster climate-neutral mobility

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ABSTRACT

Many European cities are investigating how to transition to climate-neutral transport systems. Due to the transport system's complexity and uncertainty about the future, identifying drivers and choosing effective policies to make the city more sustainable is challenging. Additionally, the chosen policies need to be supported by relevant actors. This study aims to support the municipality of The Hague in generating robust policies supported by and within the municipality. We build on participatory modeling and decision-making under deep uncertainty to create a novel approach to address this goal. In two workshops, the participants formulated goals and objectives, created Causal Loop diagrams, and identified potential interventions. Using a set of possible futures, the interventions were then stress-tested to evaluate their robustness. By explicitly linking, for the first time, participatory modeling and decision-making under deep uncertainty approaches, the participants could understand the system better and deal with uncertainty. Participants gained insight into systemic complexity and methods to deal with it, the inter-relatedness of interventions and their effects, and a shared understanding of the problem and its scope. This study demonstrates the potential of a novel approach to generate supported robust interventions to achieve the goal of a climate-neutral transport system.

1. Introduction

Many European cities are investigating how to transition to climate-neutral transport systems in the next years (European Union, 2022). Owing to the complex nature of the system and uncertainty about the future, identifying drivers to make the city more sustainable and choosing effective policies is challenging. Policies that seem effective in the present may have unintended consequences under different future trends or events that alter the systems' functioning. Transitioning to sustainable mobility has been described as a "very piecemeal, contested, and often fragmented process" (Berger et al., 2014). As such, the transition of the transport system toward climate neutrality is a long-term planning challenge that involves dealing with deep uncertainty (Lyons et al., 2021). To confront the current mobility challenges, new perspectives, knowledge, and approaches are needed (Glaser et al., 2019).

Deep uncertainty emerges when decision-makers lack clarity or agreement on the system, governing actions and their outcomes, which outcomes should be considered, and their relative importance (Lempert et al., 2003). Deep uncertainty is especially evident in decisions made over time in dynamic interaction with the system. In striving for climate-neutral transport systems, the overarching goal may be clear, yet decision-makers face the challenge of dealing with the intricacies inherent in the system. Transport systems are intertwined with other systems, such as energy, land use, and societal dynamics, that amplify the complexity (Lyons, 2004). Moreover, stakeholders engaged with the transition often hold diverse perspectives on the challenges faced and may advocate for different preferred courses of action (Jittrapirom et al., 2021).

Successful policies need support from relevant actors (e.g., decision-makers, civil servants, and local citizens). Engaging stakeholders in the policy-making process through participatory modeling can help to elicit their knowledge, foster social learning, and mobilize support and sustained commitment to transformative initiatives (Voinov et al., 2018; Mingers, 2011; Cockerill et al., 2009). In this context, we define a stakeholder as anyone affected by (*e.g.,* local inhabitants) or able to affect a situation (*e.g.,* decision-makers, public servants). Although many

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stakeholders are important in achieving a climate-neutral transport system, the government is vital as a key stakeholder (Sunitiyoso et al., 2023). While participatory systems modeling is not a novel method, participatory techniques rarely focus on uncertainty or restrict it to variability in input parameters to the model (Voinov et al., 2016).

To address deep uncertainty, the field of decision-making under deep uncertainty (DMDU) provides several approaches that support long-term planning for complex systems under deep uncertainty (Marchau et al., 2019a). However, DMDU studies have been mainly focused on developing analytical approaches, with little explicit regard for shared sense-making and coming to a decision (Führer et al., 2024; Malekpour et al., 2020; Stanton and Roelich, 2021). The literature highlighting and addressing this niche is increasing (*e.g.,* Lempert and Turner, 2021; Bhave et al., 2018; Linnerooth-Bayer, 2021; Bojórquez-Tapia et al., 2021; Johnson, 2021), but still limited.

In this paper, we address the gap in the literature by proposing a novel qualitative participatory modeling approach, building on participatory modeling and decision-making under deep uncertainty approaches, and applying it to a case study in The Hague, the Netherlands. The proposed approach brings together interdisciplinary stakeholders within the municipality to develop robust policies to realize a climate-neutral transport system that the municipality would support. We show participants are well-equipped to envision alternative systems and solutions under uncertain futures. Moreover, we contribute a holistic view of the system with multiple stakeholder perspectives that complement the current research on modeling mobility transitions that tend to focus on single innovations (Hoekstra and Hogeveen, 2017; Jensen et al., 2017; Harrison and Thiel, 2016), or a narrow selection of policies (Köhler et al., 2010; Mercure et al., 2018). By linking these different approaches, which so far have been used separately, the new approach enabled participants to understand the system better, deal with uncertainty, and generate supported robust interventions to achieve their common goal, in this case, the climate-neutral transport system.

This paper is structured in the following manner. We start by introducing relevant theory on participatory modeling under uncertainty and the wicked problem of mobility transitions in Section 2. Then, we describe the methods and the case study in Section 3, followed by the interpretation of results in Section 4. We conclude with a discussion of the process, the outcomes, and implications for future research in Section 5.

2. Participatory modeling under (deep) uncertainty

In this study, we employ participatory modeling under deep uncertainty to untangle the mobility system's complexity and achieve the following: (1) to generate robust interventions for a transition to a climate-neutral mobility system and (2) to mobilize support for those interventions among the participants.

A transition is characterized as an ongoing, gradual process of structural change within a society or culture (Rotmans et al., 2001), leading to a profound transformation of the system's functioning (de Haan, 2010). Köhler et al. (2019) describe transitions as multi-dimensional, co-evolutionary processes with many actors with varying characteristics and values. The inherent complexity of socio-technical systems such as the transport system arises from the involvement of multiple actors with potentially conflicting values and perspectives on the system and the present issues. These actors may also have different preferences regarding potential solutions to address the issues. Further, these actors are affiliated and nested within various institutions, each with its own responsibilities and spheres of influence. Consequentially, uncertainty regarding the system and its boundaries, as well as the appropriate scope of the analysis, prevails. On top of that, the future is uncertain. Planning situations with these characteristics have been described as wicked (Rittel and Webber, 1973). The domain of transport has been a focal point for transitions research (Köhler et al., 2019; Holtz, 2011). Mobility transitions, in particular, are not only influenced by policies and economic conditions but also social influences, habits and routines, cultures developed over time, and lock-in situations resulting from earlier decisions (Mehdizadeh et al., 2022).

Modeling is a useful tool for untangling and understanding complex systems such as the transport system. Holtz et al. (2015) highlights three merits of utilizing modeling in the context of transitions. First, models are explicit (Epstein, 2008). In the process of constructing a model, clarity in assumptions, definition of variables, and their relationships are required. These requirements foster transparency and dialogue between stakeholders, making the modeling process a useful tool for participatory processes (Vennix, 1996). Second, models provide a means to explore dynamics within complex systems. Human comprehension and reasoning often fail to appropriately deal with feedback, time delays, and non-linear behavior associated with a complex system (Sterman, 1994). Models can aid in understanding and exploring emergent phenomena resulting from interactions within the system, providing some insights into underlying processes (Holtz et al., 2015). Third, models facilitate systematic experimentation. They provide a means to experiment and explore different policies, assess the consequences of unresolved uncertainties, or evaluate inherent stochasticity. Such experiments would be impossible in the real world as they are prohibitively costly and socially impactful (Kwakkel and Yücel, 2012).

Participatory modeling enables us to incorporate different perspectives and knowledge and gather support. Involving stakeholders in modeling processes aims to formulate shared and formalized representations of reality, offering an established approach to deal with wicked problems (Voinov et al., 2018; Mingers, 2011). The fundamental premise is that engaging stakeholders in modeling facilitates the development of a shared understanding of the problems. The participatory process also fosters ownership of the problems and necessary actions to resolve them among the participants (Franco and Montibeller, 2010; de Gooyert et al., 2022). Participatory modeling functions as a social learning journey for participants, providing a platform to deepen their understanding of the complexity of the system, enhance agreements on causalities (Jittrapirom et al., 2021; Rouwette et al., 2011), and develop an appreciation for the uncertainty inherent in data and methods (Cockerill et al., 2009). Stakeholders can be involved in any component of a participatory modeling process, but it is unlikely that any particular stakeholder is involved in all of them (Voinov et al., 2016).

To generate robust interventions that are effective and not harmful in different futures, we consider deep uncertainty. While there are different levels of uncertainty (Kwakkel et al., 2010), deep uncertainty describes situations in which stakeholders do not know or cannot agree upon the system and its boundaries, the outcomes of interest and their prioritization or desirability, and probabilities for uncertain key variables and parameters (Lempert et al., 2003). A variety of 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). Within DMDU, models are intended to be used as exploration tools for generating and examining possible futures (Marchau et al., 2019b). A central goal of DMDU is to identify robust policies. Robustness is a metric that summarizes how well a policy or intervention performs under a wide range of (uncertain) conditions, and not just in the most likely ones (Lempert and Collins, 2007; McPhail et al., 2018).

Summarizing, the mobility system (1) is complex, wicked, and dynamic, with uncertain futures, and (2) involves various actors who influence the system and have different views on it. Therefore, we combine participatory modeling and decision-making under deep uncertainty to reach our goal.

3. Research design

We applied our combined participatory decision-making under deep uncertainty approach to a case study in The Hague, the Netherlands. This section introduces the context of the case study and the approach followed.

3.1. Case study: The challenge for the municipality of the Hague

The Hague is the third largest city in the Netherlands, with about half a million inhabitants. The Hague is one of 100 cities participating in the EU mission for climate-neutral and smart cities by 2030 (European Union, 2022). As part of this mission, the municipality seeks to reduce emissions in all sectors, including its transport sector. The municipality has identified some potential projects to achieve its ambition, such as an on-demand transport service, an expansion of the zero-emission zones, and an implementation of e-cargo bike hubs. However, it was challenging for the municipality to generate additional ideas and select and prioritize potential projects, as stakeholders have different opinions and preferences. The municipality also wants to consider explicitly the interactions between the mobility system and other systems that the municipality is responsible for, such as the housing sector or spatial development.

As part of the municipality's effort to drive the initiative of climate neutrality by 2030 forward, it organized regular consortium meetings involving stakeholders from different sectors, such as transport operators, user groups, infrastructure companies, and other businesses, to discuss and gather their opinions. The research team came into contact with the municipality and started a co-creation process that explored how a participatory modeling process can support the municipality's decision-making concerning the climate neutrality initiative.

As part of the project, the research team conducted two workshops aimed at enhancing a collective understanding of the city's transport system among the participants. These workshops employed approaches such as modeling and stakeholder engagement. The goal was to leverage these workshops to elicit expert knowledge within the municipality, thus facilitating the co-creation of knowledge, formulating a shared system understanding, and fostering cross-departmental collaborations that will lead to effective interventions that are robust and supported by workshop participants. The process also embraces uncertainty by identifying potential future trends and events and their impacts on possible actions, enabling the robustness of these actions to be evaluated.

3.2. Planning of the workshops

The workshops were planned in close collaboration with our contact persons from the municipality. At the outset of the project, the objectives and desired outcomes of the workshops were discussed and determined. Based on these objectives and desired outcomes, the planning of the activities commenced. After several rounds of discussion, we formulated the agenda for two workshops that lasted three hours. The agenda and activities within each workshop were designed by researchers, with multiple feedback rounds from the municipality contacts.

We identified potential workshop participants, aiming to gain a wide range of expertise from various teams related to the mobility transition within the municipality. Our contact persons from the municipality chose and invited participants from various departments, such as transport planning, sustainability, smart city, and electric vehicle infrastructure. The participants were selected based on whether their work is related to the mobility transition. The goal was to gather insight from different departments within the municipality. In this way, we aimed to get a system perspective of the city's mobility system and a broad range of possible interventions. Moreover, we also considered the socio-demographic attributes of the potential participants to get a diverse group in terms of socio-demographic attributes, as far as that was possible within the municipality.

In addition to the workshops, we designed a survey to evaluate the process and to get insight into what participants consider the main outcomes and what they learned. We conducted a survey with open-ended questions before and after each workshop.

3.3. Workshop objectives

The overall aim of the workshops communicated to the participants was to support the municipality in accelerating a transition towards climate neutrality in Hague City, focusing on the urban mobility system by involving members of the municipality in a participatory model-building exercise. The objectives of the workshops are as follows:

(A) define and clarify the exact problems, objectives, desirable future states, and barriers to achieving them
(B) elucidate the current understanding of the system (in this case, the transport system) and the relationships with other systems
(C) explore different options (of actions and measures) that contribute toward realizing the objectives and visions
(D) identify different possible futures and uncertainties that can influence actions and preferences on different courses of actions

These objectives guided the design of the workshop steps.

3.4. Design of the workshops

We used DMDU as an overarching framework for the design of the workshops' structure. A DMDU analysis follows three general steps (frame, explore, and choose), each consisting of several elements (Führer et al., 2024). There is no strict order, and different DMDU approaches emphasize different elements (Marchau et al., 2019b; Lempert, 2019). We used the elements of the first two DMDU steps (Framing and Exploring) as a guiding framework for the workshop activities. First, framing the analysis includes formulating the problem, specifying the system and its boundaries, and identifying alternative policies. Second, exploring involves specifying uncertainties or disagreements about external forces or policy changes, outcome indicators, and the relative importance of specific outcomes. The third step, Choosing, is not included in the scope of the project as the selection of options to realize the goal may require consideration of other factors, such as political feasibility or public support, that are beyond the scope of the project. Based on this, the workshops followed six steps:

1. Clarify the goal and scope of the project
2. Define objectives and KPIs
3. Create Causal Loop Diagrams
4. Identify potential interventions
5. Generate possible futures
6. Evaluate the robustness of the interventions

The first step was to clarify the goal and scope of the project. The previously set goal is climate neutrality or net zero emission of all activities within the urban area by 2030. This goal provides specific, measurable, and time-bound outcomes; however, clarification was needed to know what it entails for the mobility system. To clarify the goal, we asked participants to elaborate on what images of the future mobility system the goal of a climate-neutral city suggests to them. We then elicited the relevant scope for this project along the dimensions of space, time, and jurisdiction. We chose these dimensions because they inform the types of interventions that are possible and help to think about who would be responsible. We used nominal group technique for both questions to elicit the outputs (Harvey and Holmes, 2012). This technique has two main steps: participants first generate ideas silently and individually before sharing them with the group in a round-robin fashion.

The second step was to define objectives and key performance indicators (KPIs) that are coherent with and contribute to realizing the set goals. First, the participants were asked to identify specific objectives that can be set to realize the goal. These objectives were required to be tangible and measurable with KPIs. The participants were also asked to specify the stakeholders responsible for reaching these objectives. The aim was for the participants to be explicit about the objectives and actions leading to the set goal.

The third step involved developing a qualitative model in the form of Causal Loop Diagrams (CLDs). Causal Loop Diagramming is a qualitative modeling technique showing the system as causal relations between key variables that are assumed to explain dynamic behavior. Its small number of conventions makes it straightforward to use with a non-technical audience (Lane, 2000). CLDs were employed to visualize complex relationships between variables influencing the utilization of different modes of transport, such as bicycles, public transport, personal cars, and shared cargo bikes. We chose Causal Loop Diagramming over other participatory modeling methods because it allows the creation of a comprehensive overview of the system with directed relationships (as opposed to, e.g., concept mapping) and is qualitative (as opposed to, e.g., Bayesian networks) (Voinov et al., 2018). Additional steps to develop the CLDs into quantitative models were considered by the team but were discarded as more workshops would be required, and the municipality felt quantitative models would have limited benefits at this stage.

We began by identifying all transport modes that the participants believed should be included. Then, a voting session was conducted to determine which modes were most important to the participants. We explained the basic elements of the CLD and created one CLD with the whole group to illustrate the modeling technique before dividing the participants into groups of two to three to create one CLD each. Four modes that received the most votes were assigned to each group to work on. We used the corresponding Group Model Building script to provide step-by-step instructions (Hovmand et al., 2012). Group Model Building (GMB) is a participatory method for involving stakeholders in developing system dynamics models (Vennix, 1996; Andersen et al., 2007). The steps for creating a CLD included first collecting all variables from the group with the nominal group technique to support effective brainstorming. To do this, the participants wrote down variables individually before sharing them round-robin. The facilitators collected them on the wall and asked for clarification where necessary. Second, the variables are connected in the CLD. The central problem variable is the use of the mode that the diagram is created for. When creating the CLD, the variables directly affecting the use were first connected. Then, other variables were connected to create causal chains. In the end, feedback loops were identified and discussed with the participants.

The fourth step was to identify potential interventions that would enable the goals and objectives to be realized. First, the participants wrote down their ideas individually. For each intervention, participants answered the following questions:

- What would be done?
- Which mode will be affected?
- What type of intervention is it? (*e.g.,* infrastructure, financial incentives, rules, new technology, changing values and paradigms, etc.)
- Who would be responsible for implementing the intervention?
- Over what time horizon does it take effect?
- Which objective(s) from the second step does it contribute to?

Then, all interventions were collected on the wall, clustered in a matrix in which the rows represented the mode affected by the intervention, and the columns showed the type of intervention. Clustering the interventions in this way helped to visualize whether there was variety. Participants then voted on the most promising interventions to continue with for the following exercises.

In the fifth step, participants were encouraged to think of possible events and trends in the future that can affect the potential interventions identified in the previous step. The outcomes of this step are then used to stress-test the interventions. We used the widely recognized environmental scanning framework STEEP as a guide to get a varied selection. The framework helped to identify potential future events and trends within five categories: social, technological, economic, environmental, and political. Like the previous steps, participants noted their ideas individually before collecting them on the wall.

The sixth step was to evaluate the robustness of interventions using exploratory thinking (Malekpour et al., 2016). Exploratory thinking is an approach that considers alternative perspectives to a planning issue. Participants are asked to think creatively and challenge routine assumptions. Doing so can potentially reveal some blind spots in the business-as-usual-planning (Malekpour et al., 2016). Policies are stress-tested by asking under which conditions a policy will fail to deliver its intended consequences. The goal is to create a shared understanding of the vulnerabilities of different policy candidates (Moallemi and Malekpour, 2018). As a result, some policies might be deemed highly vulnerable and therefore undesirable; some remain viable if their robustness is enhanced through some additional measures (Moallemi and Malekpour, 2018). We modified this approach by first collecting future conditions instead of just asking under which conditions a policy might fail. We did this to generate a wide range of future conditions from which to choose. This exercise was performed in groups of two to three participants. First, participants were asked to describe the consequences of their intervention on the transport system, linking the interventions with the CLD created in the third step. Second, they were asked to select futures from the previous step that may affect the intervention and describe the impact. These impacts might be positive or negative concerning the goal and objectives. The assessments help to determine the necessity for additional actions to safeguard the interventions should these futures occur, making the interventions more robust (*i.e.,* the interventions are effective in any given future).

3.5. Data collection and analysis

We collected data through audio recordings, observation, and a short survey before and after each workshop. This data included the products of the workshop activities, as well as the opinions and insights of the participants. We report the products resulting from the workshop in the next section, classifying them into visible outputs, such as the goal and the model, and the less visible outputs, such as improved communication and shared understanding (*c.f.*, Franco and Rouwette, 2022).

The observation was done by a research team member who was not involved in the facilitation process. Throughout the session, they noted the variety of perspectives, who is participating and who is not, when communication happens, and when participants are open to new ideas. For each workshop step, there were observations specific to that step, such as considerations for decisions or disputed aspects. Before and after each workshop, the participants answered a short survey. Before the workshops, we asked about expectations for collective as well as personal outcomes, as well as concerns they may have. After the workshops, we elicited the key outcomes and insights.

4. Interpretation of results

We conducted two workshops of three hours each, involving nine participants from the municipality. Participants included municipal employees from various departments and various layers of the organization, but they were not all familiar with each other. All participants could contribute equally to the workshops, independent of whether they were involved in the workshop initiation and design phase. The first workshop occurred on May 8, 2023, and the second on June 5, 2023. The workshops were designed and facilitated by the research team. During the workshops, two researchers acted as facilitators and one as an observer. The research team guided the participants through the process but did not contribute to group discussions.

4.1. *Visible products of the workshops*

As a result of the six workshop steps, there are six visible products of the workshops: (1) the overall goal, (2) objectives and KPIs, (3) a Causal Loop Diagram, (4) a list of potential interventions, (5) a selection of possible futures, (6) and the robustness evaluation of four of the interventions.

4.1.1. *Overall goal*

In the first step, we formulated an overarching goal based on the responses from the participants. The goal is *A healthy, clean, safe, inclusive, and climate-neutral transport system that provides diverse selections of sustainable mobility options accessible and affordable to all travelers by 2030*. The scope of this goal was defined along the following dimensions:

Spatial: Neighborhood, city, Rotterdam-The Hague metropolitan area (depending on the measure)

Temporal: pilots and temporary measures as soon as possible, climate neutrality by 2030, national goals by 2050

Juridical: all levels, including national and EU

4.1.2. *Objectives and KPIs*

We defined objectives as measurable targets that contribute toward realizing the goal that was set. A summary of all objectives that participants named in step two of the workshops is the following:

Walking and cycling: Increase the share of walking and cycling trips in the modal split

Public transport and shared mobility: Increase usage of public transport and shared mobility services

Energy use and emission of the transport sector: Transition energy source for transport sector toward sustainable sources

Land use and access to facilities and green space: Adjust land use and transport services to minimize trip distance and maximize accessibility and livability

Private vehicles and associated externalities: Reduce personal vehicle use and associated externalities

Implementation processes and collaborations: Increase the number of successful pilot projects and collaborations with stakeholders

Each objective also has a set of Key Performance Indicators (KPIs). While the objectives are quite comprehensive, it is notable that there were no objectives related to financial or operational aspects of the transport system. The participants identified various stakeholders that they deem responsible for reaching the objectives, primarily the municipality, public transport companies, and the city's residents. Further, they also considered other levels of government, such as the European Union and the national and regional governments. Besides these central stakeholders, others include shared mobility providers, local businesses, other municipalities in the region, housing developers, and large employers.

4.1.3. *Causal Loop Diagrams*

As part of the third step, participants created Causal Loop Diagrams (CLDs) that illustrate how different key variables affect the emissions of a transport mode of their choice. Within the given time, the participants were encouraged to write down as many variables as possible that would influence the emission level of the selected modes. They then had to identify the causal connection between the variables. In the diagram, an arrow with a '+' signifies a positive relationship, meaning that a change in the influencing variable causes a change in the same direction for the influenced variable (*i.e.,* more of variable A leads to more of variable B). Vice versa, a negative relationship is marked through an arrow with a '-.' It means that the change caused by a variable is in the opposite direction (*i.e.,* more of variable A leads to less of variable B). We explained the activity by creating one CLD with the whole group; the result can be found in Fig. 1. Participants were then split into groups. The results from the four small groups can be found in Fig. 2. After the first workshop, the outputs from this exercise were synthesized by the researchers to provide the main insights within one diagram that helps to understand the underlying factors that affect the usage of a transport mode and to identify possible actions and policies that will influence the usage (Fig. 3).

The key message from the diagram is that the usage of a transport mode is initiated by travel demand and can be affected by influencing variables (e.g., cost, availability of the mode and alternatives, parking facilities, and frequency of the service). These factors can increase or decrease the usage of a mode. The usage can be further influenced by reinforcing variables (*e.g.*, ownership, perceived safety, space, convenience, and habit). Reinforcing variables are part of a loop that links back to the variable and further exacerbates the effect in the initial direction of change (*i.e.*, increase leads to further increase, decrease leads to further decrease). Using these modes will generate emissions, which substitution with a greener mode with lower emissions can reduce. For example, according to the participants, the usage of bikes is directly influenced by whether a bike path is available. This is a positive relationship; the assumption is that more bike paths lead to more bike use. A reinforcing variable in this case is, for example, bike ownership; a high bike ownership can lead to more bike usage, and a high bike usage can lead to a further increase in bike ownership. Knowing these variables and their relationship can help identify interventions to influence the usage and ownership of a transport mode. However, compared with existing transport System Dynamics models (Wiman et al., 2022), the variables describing the changes in demand, such as developments in the population, job market, or general attractiveness of the city, were omitted. Further, it is notable that no negative loops were identified, meaning that limiting factors were not taken into account.

4.1.4. *Interventions*

In step four of the workshops, the participants generated a set of 25 interventions with great diversity regarding the mode affected and the type of intervention (Table 1). Interestingly, the interventions identified during the workshops were entirely different from the potential future projects of the municipality's climate-neutral mission. From the list of interventions, participants then chose four interventions to investigate further.

4.1.5. *Future events and trends*

The fifth outcome is a wide selection of possible future events and trends that can influence the project (Table 2). Common themes include AI and data, pandemics, and a shift in social awareness. In the elicited futures, negative futures are mainly shocks, whereas positive futures are mainly trends. Many of the futures can be considered quite likely; less likely futures are mainly shocks. The time scale of the events or trends is roughly the same as the goal (2030), some of them possibly longer.

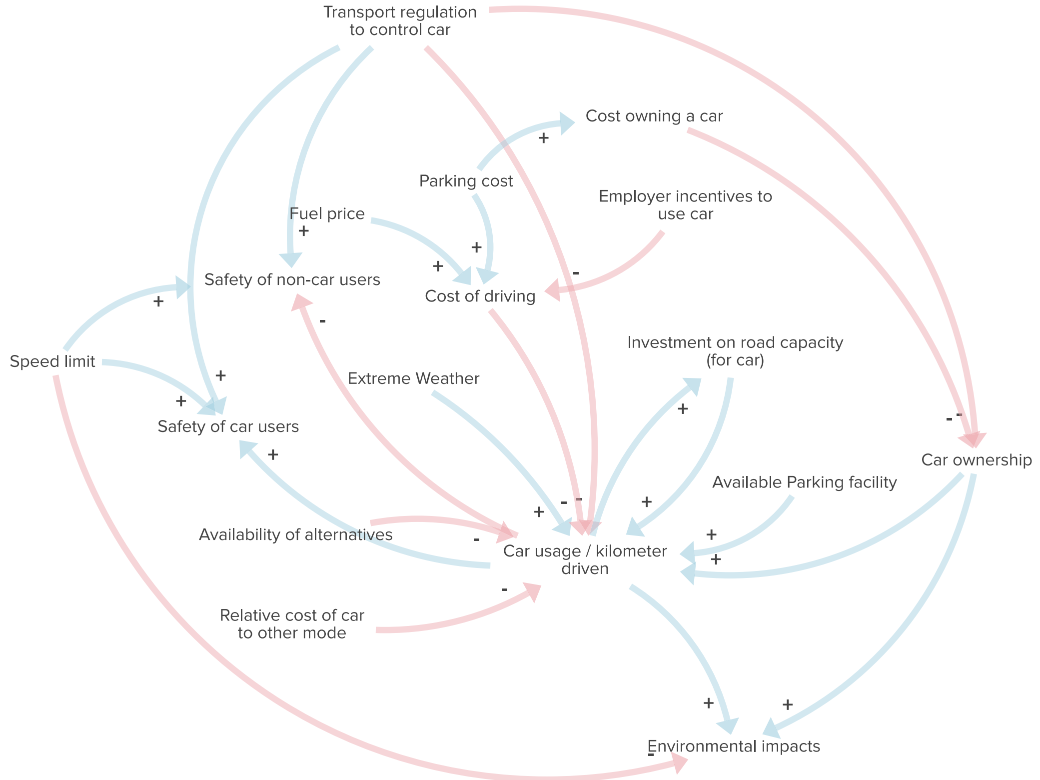
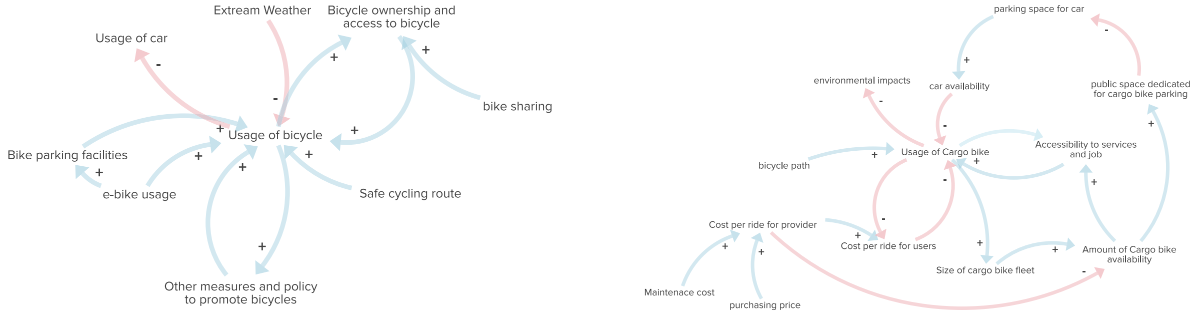
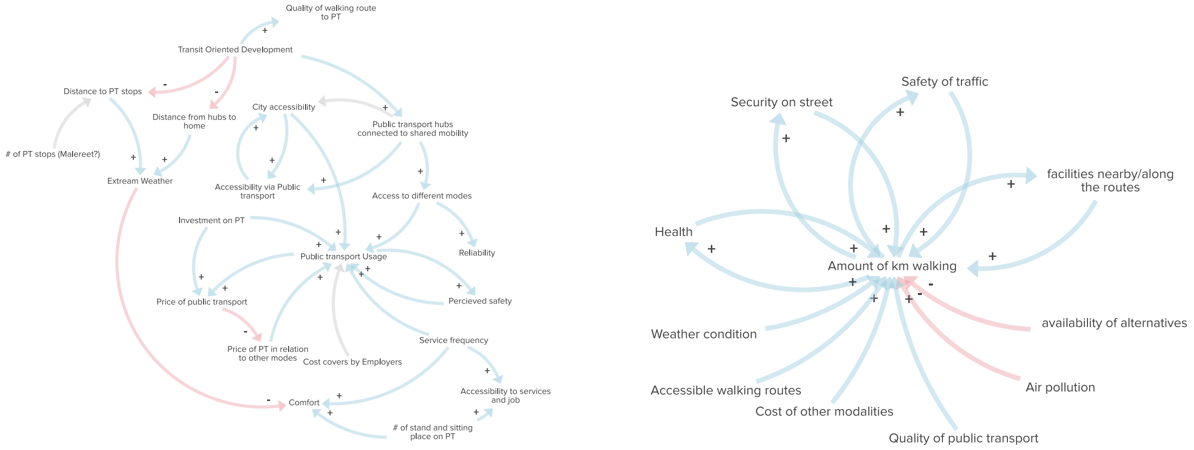


Fig. 1. Causal Loop Diagram on car use created by the whole group.



(a) Bicycle (b) Cargo-bike



(c) Public transport (d) Walking

Fig. 2. Causal Loop Diagrams created in the small groups.

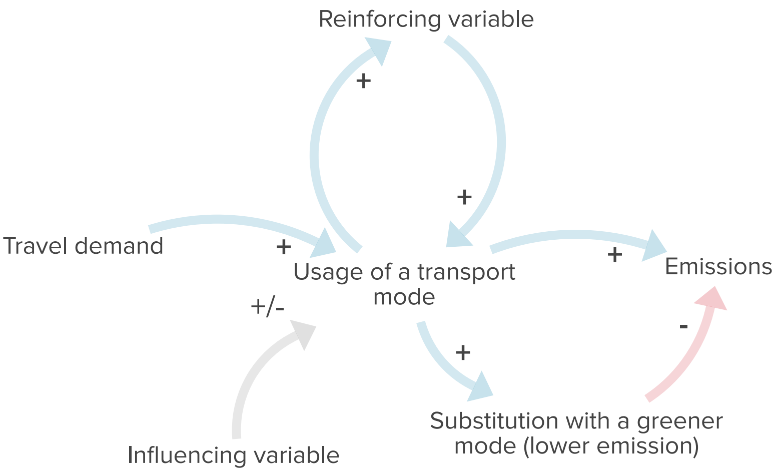


Fig. 3. Causal Loop Diagram summarizing the key insight.

Table 1
Interventions for each transport mode.

Public transport
Only electric public transport is allowed in the city center in combination with stops/parking for the last mile
Free public transport
More space for bikes in trams and trains
Easier planning of public transport and shared mobility trips (Mobility as a service), provide one integrated trip planner for all PT and shared mobility
Walk, bike, and cargo-bike
Core facilities (work/health/social/education) are max. 10-15 min. walking or cycling away
Improve biking infrastructure to make The Hague a bike-friendly city
Increase the amount of safe, spacious, and accessible bike paths; every street should have a better cycling space than car space; bikes should get priority at stoplights
Convenient, safe, and green routes to schools
Advertise and normalize walking and bike use on a national level; car use should be the new smoking
Every street has a shared cargo-bike
Gasoline car
Making owning a big car much more expensive than owning a small car
Introduce more car-free zones (pedestrian- and bike-focused areas), ban all cars from the city center (except for emergency vehicles and transport for older people)
Abolish unjustified private car ownership, no more new cars in the city
Decrease the amount of parking spaces and the amount of parking permits in The Hague
Increase parking costs in the whole city (owner's permit should increase by 200% and only one car is allowed per household, visiting permits should be reduced)
Reduce speed for cars
Replace parking (car) places with greenery and bike parking when construction starts in a street
Offer residents and local businesses to easily swap parking spots for bike spots, spots for shared micro-mobility, green spaces, or terraces
Close streets for cars to make more safe routes for 'slow traffic'
(Experiment with) car-free days (exception: first response vehicles, buses, etc.)
'Cars as guests' as the norm on all inner-city streets Substitute car trips of employees of companies at all business areas
Electric car
Every street has a shared electric car
Automatic limit speed of electric vehicles (city center, Scheveningen area, around schools)

Table 2
Potential futures identified with the help of the STEEP framework.

Social
Deurbanization (migration of population away from the city)
Peak car (young generation no longer feels the need for private cars)
Increased in population (100,000 more inhabitants by 2040)
Mass migration driven by extreme climate change
Individualized society (decrease in social cohesion and community)
Sharing society (increase in values, habit, and acceptance to share resources)
Increase of norm to own big cars (SUV)
Elimination of private vehicles in city
Awareness of climate change becomes more prevalent
Technological
Wide use of drones for logistics
Wide use of self-driving vehicles
Discovery of new technology or types of resources that revolutionize the energy system
Wide use of energy sharing and optimizing system
High electricity demand leads to congestion on the electric network
Wide use of AI in the mobility sector
Limited use of AI in the mobility sector
High use of data and information to support decision-making
Environmental
Intensive and frequent flooding
Outbreaks of bird flu or other pandemics
Rising sea level
Climate change and extreme weather
Higher prevalence of viral diseases due to warm climate and high density of bio-industry
Economic
Real costs of transport are being considered instead of economic cost
Cost for public transport use or biking are paid fully by the employer
Higher poverty rate
Localization in product consumption leads to reductions in imports
Shortage of raw material leads to more circularity
Public transport becomes more unreliable because of privatization and investment shortage
End of Dutch fishing industry
Political
Increase in acceptance and support for climate-related restriction interventions
Rise of populism
Shift to the radical right
Phasing out of internal combustion engines and all new cars to be electric in 2030
Complete stop of emissions on a national level (car suddenly not allowed anymore)

4.1.6. Robustness evaluation

The sixth outcome is the robustness evaluation of the selected four interventions. In this step, the participants first described the consequences of implementing the selected four interventions on the transport system. Then, they chose four to five futures from the list of potential futures (Table 2) and described their expected impacts on the interventions identified in the previous step. In this way, the participants uncovered vulnerabilities of interventions and also explicitly examined the underlying assumptions they may have about each of the interventions. A vulnerability could, for example, lead to

Table 3
Robustness evaluation for the intervention ‘Free public transport’.

Future trends and events	Impacts on the intervention
More inhabitants in the city	Not enough capacity in public transport Investments needed More income and profitability and, therefore, more certainty More people means the investment goes up
Climate change (Heat and extreme weather, sea rise)	Public transport more desirable in hot and cold weather than bike/scooter/walk Fewer cars, fewer emissions, less climate change More acceptance due to the knowledge of climate change
Public transport becomes privatized, less reliable, and more expensive	Unreliable, especially in rural areas People will use it less, especially the disabled inhabitants It must be prevented!
Shift to public right	No funding for public transport, intervention stops
Increasing data use in the future	Privatization can be desirable in combination with data Payment in the form of data Combination public transport and energy infrastructure for other electric modes

the intervention failing to deliver its intended outcome or that the interventions cannot be implemented at all. Common themes in the robustness analysis across the different interventions were funding, capacity, and public acceptance.

For example, one of the interventions regarded in more detail was “Free public transport outside of rush hours and the whole day for lower-income citizens”. The potential consequences that this group identified are the following:

- Large increase in the use of public transport
- Ridership is more distributed over the day
- Less use of cars but also bikes and walking
- High costs (unclear where the money will come from)
- Certainty of the costs
- Lowering the income gap

The futures chosen by the participants and their impact can be found in Table 3.

4.2. Less visible products of the workshops

In addition to the visible outputs from the workshops, we gathered insights on the individual and group processes through observations, a reflection at the end of the workshops, and self-reported data in a short survey.

Throughout the workshop, the participants seemed motivated and engaged with the process. They were attentive to the instructions and could follow them to fulfill the tasks according to our expectations. Even when presented with a technique that was novel to all participants, such as the Causal Loop Diagrams, the participants were able to generate variables, contribute to creating a Causal Loop Diagram in the group, and shortly after creating their diagrams in small groups with limited guidance from the facilitators. To ensure equal contributions from all participants, we designed the workshop activities so that everyone would contribute, for example, collecting ideas on post-its first and asking for answers in a round-robin fashion.

The workshops contributed to the participants’ learning at different levels. At the project level, they learned facts related to the project from each other, such as the current mobility policy, the responsibilities different stakeholders have, and the current tasks of different municipality departments related to the project. Participants reported a shared understanding of the problem and the goal. At the methodology level, the participants learned new tools to deal with system complexity, such as the Causal Loop Diagrams, Systems Thinking, and the robustness evaluation process for policies and measures. At the system level, they reported learning about the interdependencies and complexity of the transport system. The participants reported that the workshop enhanced their system knowledge by illuminating the importance of the whole picture, the interconnectedness, and the factors that influence mobility choices. On the other hand, some of the relations with other systems still seemed unclear. One participant reported that *“we did not get to map out everything so were not able to reach the bottom”*.

The participants noticed limited disagreement during the workshops and that there might be a *“discrepancy between what they want based on their expertise and the political feasibility”*. Participants think the knowledge to reach the objectives already exists, but many hurdles, such as power, values, and norms, are not addressed yet. A surprising insight for one participant was widening the thinking of the municipality: *“reframing of mobility as a journey and experience, which I do on a personal level (how do I like to travel?) but had not talked about in a municipal setting (what would all the co-benefits be if mobility was more than getting from A to B?)”*. The participants agreed on the importance of interdisciplinarity and that systems thinking and embracing uncertainty are required in the municipality. They indicated a willingness to change and embrace new methods in their work. Participants further indicated a need for deeper collaboration within and beyond the municipality.

5. Discussion and conclusion

In this study, we developed an innovative approach for participatory modeling under deep uncertainty and illustrated how such an approach can be applied to support the development of a climate-neutral transport system for the city of Hague. This study demonstrates the potential of the approach to generate interventions and evaluate their robustness in the highly uncertain context of climate-neutral mobility. Our focus with this study lies on step 1, ‘Frame’ and step 2, ‘Explore’ of DMDU (Marchau et al., 2019b; Führer et al., 2024), when there is still room for more and different solutions (d’Hont and Slinger, 2022).

We applied the approach in a workshop setting with policymakers and civil servants from the Hague municipality who work in transport and related fields. Six visible products resulted from the workshops: (1) a comprehensive list of objectives to foster a climate-neutral transport system for the city, (2) KPIs associated with the objectives, (3) Causal Loop Diagrams that helped participants understand the transport system, (4) a set of interventions to realize the objectives, (5) a wide selection of future events and trends, and finally, (6) a robustness evaluation that surfaced areas of concern for realizing sustainable mobility, for example, funding, capacity, and public acceptance of the potential interventions.

In addition to the visible workshop products, softer learning effects occur when people participate in such a workshop and then return to their regular work environment. For example, we observed the participants built a shared understanding of a complex system (*i.e.,* the transport system). Supporting participants to prevent them from falling back into their old way of thinking requires a deep level of learning (see also Pahl-Wostl et al., 2007; Bandura and McClelland, 1977; Reed et al., 2010; Akkermans, 1995). We hypothesize that this kind of participatory workshop fosters soft learning effects, helps build actor coalitions (see Vreugdenhil, 2010), and can even help facilitate a paradigm shift, but further research on this is required.

What insights did we gather from applying this innovative approach? Participants found value in the systematic structure of the approach and how the process supported the generation and exchange of ideas. They particularly appreciated the systems perspective gained through the process (particularly the formulation of CLDs), which seems to be a promising and integrative decision-making approach within the municipal organization. Additionally, the process also enabled the participants to explore the robustness of possible interventions and think about how to enhance the robustness in the future.

Despite initial concerns, participants were able to gain systems perspectives and address the uncertainty in the process effectively. The workshop demonstrated participants' abilities to think causally, vary the problem scope, envision uncertain futures, and identify unintended consequences. Notably, the causal loop diagrams, the interventions generated, and their evaluation are the key outcomes according to participants.

There are two notable limitations of this study. The first limitation is the limited diversity of the participants, who are municipal employees tasked with planning and policy-making for transport and mobility-related problems. Although these participants work in different departments related to mobility, it can be observed that the group may have high homogeneity in their values and approach to the subject. The participants were determined to foster sustainability by sacrificing other objectives. For example, solutions that could be controversial, such as replacing parking spaces with greenery, were raised without much contestation among the group members and were adopted without explicit consideration for the systemic effects on accessibility (particularly for vulnerable groups, such as mobility-impaired citizens and wheelchair users). Including a wider group of participants may widen the perspectives on the problem and the scope. Potential additional participants are, for example, citizens, transport providers, or stakeholders who may not be as sustainability-focused as the current participants.

Due to the homogeneity of the group, there were limited conflicting viewpoints during the workshops, all of which were readily resolved through discussions among the participants. When applying this approach to other cases, it is possible that some conflicts may emerge for facilitators to navigate. Rouwette and Franco (2024) provide strategies to manage emotion and conflict: establish communication norms to create a safe environment, foster thinking regarding shared goals, and invite participants to reflect on their reactions if a situation gets very emotional.

The second limitation is the contextualization of the approach and its results to the case. We designed, applied, and evaluated an approach for participatory modeling for decision-making under deep uncertainty in a single case study. As such, the resulting identified interventions cannot be directly generalized to other cases. Even if those cities are similar in size, inhabitants, or structure, they will differ in other aspects. However, future research can examine the generalizability of the process developed in this study by applying the process to support policy-making in other cities that strive to be climate-neutral.

Another avenue for future research is a deeper investigation of the Causal Loop Diagrams and interventions. The Causal Loop Diagrams are a constructionist representation of how the participant group viewed the system and its problem, and they helped to identify policy interventions and assess these qualitatively. The facilitators guided the group while remaining neutral on content. While the Causal Loop Diagrams reveal the relationships among system variables, they only uncover the existence and direction of such relationships. To address the intensity of connections, methods such as Interpretive Structural Modeling (Duleba et al., 2013; Sorooshian et al., 2023) could be useful when choosing interventions for implementation.

The resulting policy interventions require further exploration and evaluation regarding efficacy, desirability, or approval within the municipality and by the public. We hypothesize that quantitative modeling, in combination with participatory approaches, can explore policy robustness even further. Moreover, additional work is needed to investigate the potential of participatory activities closer to the actual implementation of policies, especially when the aim is to democratize the decision-making (Mayer et al., 2004).

To ensure the successful implementation of interventions, collaboration and coordination between different municipal departments and external stakeholders is essential. Further research could examine factors that contributed to the success of similar interventions implemented in other cities and analyze how they could be applied in the context of The Hague. When it comes to choosing interventions for implementation, understanding how they integrate into existing systems and policies will facilitate the implementation process.

After implementation, evaluating the implementation and impact of the policies requires a comprehensive framework, including key performance indicators to measure success and data collection methods. The key performance indicators developed in the workshops can be a starting point for this. Based on this evaluation, periodic reviews and adjustments can ensure the effectiveness of the interventions over time.

This study contributes to the practical challenges by providing policy-makers with a systematic approach to address complex challenges, such as the transition to climate-neutral transport systems. Its scientific contribution lies in addressing the two knowledge gaps in DMDU and participatory modeling. DMDU methods are highly analytical and rarely participatory; their applications often involve a limited group of experts, which can limit the perspectives and inclusiveness of the results. On the other hand, the participatory modeling processes rarely embrace uncertainty. The approach purported in this study addressed both by developing a protocol for participatory modeling under deep uncertainty for climate-neutral mobility. The resulting approach can be applied to support cities with ambitions to transition towards more sustainability. The approach facilitates stakeholders in identifying goals, objectives, and possible interventions. Moreover, stakeholders familiarize themselves with uncertainty and evaluate the identified policies in terms of their robustness, meaning they perform well under a range of uncertain futures. In conclusion, this study contributes to collecting viewpoints on transitioning from a fossil-fuel-dependent mobility system to a climate-neutral one. We see a role for participation in this space and demonstrate how well municipal employees are capable of imagining a broad range of uncertain futures and assessing policy robustness. We believe that participatory processes can help mobilize support for actions towards climate neutrality.

CRediT authorship contribution statement

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

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

The data that has been used is confidential.

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