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Modeling mobility transitions**

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# Participatory Decision-Making under Deep Uncertainty

## Modeling Mobility Transitions

Karoline Führer

# **Participatory Decision-Making under Deep Uncertainty**

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# **Participatory Decision-Making under Deep Uncertainty**

**Modeling Mobility Transitions**

## **Dissertation**

for the purpose of obtaining the degree of doctor  
at Delft University of Technology  
by the authority of the Rector Magnificus Prof. dr. ir. T.H.J.J. van der Hagen;  
Chair of the Board for Doctorates  
to be defended publicly on  
Tuesday, 25 November 2025 at 15:00

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There's no single answer that will solve all of our future problems.  
There's no magic bullet. Instead there are thousands of answers - at least.  
You can be one of them if you choose to be.

– Octavia E. Butler, *A Few Rules For Predicting The Future*



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# SUMMARY

Transitioning to a more sustainable mobility system is a challenging task due to the complexity of the system, the presence of multiple actors with diverging views on the problem, the uncertainty about the system's current state, how the future might unfold and affect the system, and what values to consider. Planning situations with these characteristics are considered wicked problems. We draw on transition modeling, stakeholder engagement, and decision-making under deep uncertainty (DMDU) to support decision-making for the mobility transition.

Dynamic transition models are helpful in understanding and exploring emergent phenomena as a result of the system elements and their relations, as well as the underlying processes. Models can, therefore, aid human reasoning on complex issues. While there have been efforts to model mobility transitions, there is a need for a theory-based model of the whole mobility system that simulates social interactions, endogenous interactions between transport modes, and the emergence of innovations. Further, such a model should be suitable for exploring a wide range of policies.

Modeling with stakeholders and decision-making under deep uncertainty are both approaches that can contribute to coming to decisions for wicked problems. Both offer model-based support for multi-stakeholder decision-making. This shared aim offers a basis for benefiting each other. Participatory modeling focuses on incorporating different perspectives and knowledge, gathering support, and forming shared formalized representations of reality. The participatory process also aims to foster ownership of the problems and necessary actions to resolve them among the participants. A shortcoming of participatory techniques is that they rarely focus on uncertainty or restrict it to variability in input parameters to the model.

Decision-making under deep uncertainty rests on three key ideas: exploratory modeling, adaptive planning, and decision support. Within DMDU, models are intended to be used as exploration tools for generating and examining possible futures instead of being used as prediction tools. DMDU predominantly focuses on the analytics of decision problems and less on stakeholder processes and the creation of transformative agency. Major questions remain on using these analytics effectively to support multi-actor decision-making on deeply uncertain, complex decision problems.

This research aims to design and evaluate a theory-informed approach for participatory decision-making under deep uncertainty for wicked problems. We apply this approach to case studies related to the urban mobility transition in the Netherlands. We contribute to this aim in four parts.

First, we explore the potential for explicitly integrating participation and decision-making under deep uncertainty to address wicked problems in Chapter

2. We analyze how well DMDU typically addresses the ten characteristics of wicked problems and identify three shortcomings: the focus on the analytical techniques, a lack of attention to sense-making and guidance for interpreting analytical artifacts with the various parties to a decision, and no attention to how to come to a decision. These shortcomings indicate a necessity to enable decision-makers to deliberate with each other and with other stakeholders.

Approaches for decision-making under deep uncertainty typically include three general steps: frame, explore, and choose. We use these generic DMDU steps as a guiding framework to identify the benefits of involving stakeholders. In the framing step, engaging stakeholders can provide context-specific knowledge to the researcher. Communicating the relevance of this problem to stakeholders can help to create ownership of the problem and agency. In the exploring step, stakeholder involvement can improve the relevance of the analysis and aid in validating the model and its outcomes. In the choosing step, participatory activities can help to create transparency and trust in the model and trade-offs, as well as create agency to act and implement.

We conclude this part of the research with four challenges in establishing a practice of participatory DMDU: 1) selecting promising projects, 2) designing valuable processes, 3) developing and documenting methods, and 4) evaluating transparently.

Second, Chapter 3 presents a case study focused on the first two DMDU steps: frame and explore. We support the municipality of The Hague in generating robust policies through a novel qualitative approach combining participatory modeling and DMDU. In this study, we develop an innovative approach for participatory modeling under deep uncertainty and illustrate how such an approach can be applied to support the development of a climate-neutral transport system for the city of The Hague.

We apply the approach in a workshop setting with policymakers and civil servants from the municipality who work in urban mobility and related fields. Six visible products result from the workshops: 1) a comprehensive list of objectives to foster a climate-neutral mobility system for the city, 2) KPIs associated with the objectives, 3) Causal Loop Diagrams to help 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 surfaces areas of concern for realizing sustainable mobility, for example, funding, capacity, and public acceptance of the potential interventions.

By explicitly linking participatory modeling and decision-making under deep uncertainty approaches, we observe that the participants can better understand the system and deal with uncertainty. Participants gain insight into systemic complexity and ways of dealing with it, the interrelatedness of interventions and their effects, and a shared understanding of the problem and its scope. The workshop demonstrates participants' abilities to think causally, vary the problem scope, envision diverse uncertain futures, and identify unintended consequences.

This chapter contributes to the practical challenges by providing policy-makers with a systematic approach to address complex challenges, such as the transition to

## SUMMARY

climate-neutral transport systems. The approach facilitates stakeholders in identifying goals and objectives and generating supported, robust interventions. Moreover, stakeholders familiarize themselves with uncertainty and evaluate the identified policies in terms of their robustness, meaning they perform well in a range of uncertain futures. This study demonstrates the potential of a novel approach to generate supported, robust interventions to achieve the goal of a climate-neutral transport system.

Third, we develop an agent-based model that can be used in participatory settings to explore a wide range of policies, presented in Chapter 4. Based on the Actor-Option framework, this model simulates user choices under different policies and uncertainties and how this influences the modal split. In this model, we simulate social interactions by using a small-world social network. Our results show that the parameters used to generate such a network are essential for how the modal shares develop over time. Further, this model allows for interactions between transport modes through competition among the modes. We find that introducing an innovation can have desirable and undesirable impacts on the modal share. The structure of the model allows for any transport mode to be added as a combination of option properties, which opens the possibility for exploring a wide range of hypothetical transport modes that are or will be developed in the future. In this chapter, we present two policies to demonstrate the capabilities of this model. We explore various key uncertainties, mainly impacting the intensity and speed of the diffusion of the innovation. Our analysis reveals the importance of social networks and the number of agents who re-evaluate their choices at each step.

We identify three key insights from the agent-based model. The first insight is that introducing an innovation can reduce the share of modes that are negatively affecting sustainability, but it may also reduce the share of sustainable transport modes. The second insight is that exploring multiple policies at once reveals symbiotic effects of the policies. The third insight is that the key uncertainties regarded in this study have a higher impact if the changes in the modal split are bigger. The uncertainties surrounding the social network have the strongest impact on overall results.

We find that the Actor-Option framework allows us to capture the dynamics among different actors and options at a detailed level. This flexible framework can be tailored toward other mobility studies and, subsequently, policy questions and goals. The model also allows the inclusion of any configuration of technologies as a new transport mode in the analysis. This agent-based model can be used to aid decision-makers by providing insight into simulating transition dynamics and possible future scenarios, also in participatory settings.

Fourth, in Chapter 5, we use the agent-based model to employ participation in the second and third steps of the DMDU analysis: explore and choose. In a role-playing game in which students assume the role of decision-makers, we investigate whether the participants are able to make decisions based on model outputs supplemented with a qualitative discussion on aspects not included in the model. We hold the same workshop twice with two different groups of students, one from the

business faculty of a general research university, the other with students from a technical university.

We find that the participants can use the model and make decisions based on the model outputs, acknowledging the system's complexity. We observe that the participants take on their roles well, perform tasks seriously, and are engaged throughout the workshop. Further, the participants are aware that the model does not represent every aspect of the system and are able to discuss aspects that are not included. However, participants tend to mainly pay attention to the average modal split, indicating that 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. Despite their differing backgrounds, we find no significant difference between the two groups' performance. The similarity in the overall performance of the two groups suggests that this type of workshop can be done with participants of differing backgrounds with no modeling experience.

Through this 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 find that participants understand the what-if thinking behind DMDU approaches, are able to deliberate policies in an uncertain context, and trust the model enough to make decisions. 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. On top of the novel participatory modeling process combining quantitative simulation modeling and qualitative considerations around the model, we contribute a holistic system perspective complementing current research on modeling mobility transitions.

In conclusion, this research contributes a novel approach to address the wicked problem of transitioning to more sustainable mobility. We build on decision-making under deep uncertainty and participatory modeling to enable decision-makers to frame the problem, model the system, generate policies, and deliberate these policies while taking uncertainty into account. By designing, executing, and evaluating DMDU processes involving stakeholders, we make the first steps to establish a practice of participatory DMDU.

# SAMENVATTING

De transitie naar een duurzamer mobiliteitssysteem is uitdagend vanwege de complexiteit van het systeem, de betrokkenheid van meerdere actoren met uiteenlopende visies op het probleem, en de onzekerheid over de huidige staat van het systeem, hoe de toekomst zich zou kunnen ontploegen en het systeem zou kunnen beïnvloeden, en met welke waarden rekening moet worden gehouden. Plannings-situaties met deze kenmerken worden als wicked problems beschouwd. We maken gebruik van transitie-modellering, stakeholderparticipatie en *decision-making under deep uncertainty* (DMDU) om de besluitvorming voor de mobiliteitstransitie te ondersteunen.

Dynamische transitie-modellen helpen bij het begrijpen en onderzoeken van fenomenen die opkomen als resultaat van de systeemelementen en hun onderlinge relaties. Modellen kunnen daarom helpen bij het menselijk redeneren over complexe kwesties. Hoewel er pogingen zijn gedaan om mobiliteitstransities te modelleren, is er behoefte aan een theoretisch model van het hele mobiliteitssysteem dat sociale interacties, endogene interacties tussen vervoerswijzen en het ontstaan van innovaties simuleert. Bovendien zou een dergelijk model geschikt moeten zijn om een breed spectrum aan beleidsmaatregelen te onderzoeken.

Modelleren met stakeholders en decision-making under deep uncertainty zijn beide methoden die kunnen bijdragen aan het nemen van beslissingen voor 'wicked problems'. Beide bieden modelgebaseerde ondersteuning voor besluitvorming met meerdere stakeholders. Dit gedeelde doel biedt een basis om van elkaar te profiteren. Participatief modelleren richt zich op verschillende perspectieven en kennis, het verzamelen van draagvlak en het vormen van gezamenlijke geformaliseerde representaties van de werkelijkheid. Het participatieve proces is ook gericht op het bevorderen van eigenaarschap van de deelnemers over de problemen en de noodzakelijke acties om deze op te lossen. Een tekortkoming van participatieve technieken is dat ze zich zelden richten op onzekerheid of deze beperken tot variabiliteit in invoerparameters voor het model.

Decision-making under deep uncertainty berust op drie kernideeën: exploratieve modellering, adaptieve planning en beslissingsondersteuning. Binnen DMDU zijn modellen bedoeld als exploratieve hulpmiddelen voor het genereren en onderzoeken van mogelijke toekomstige in plaats van als voorspellingshulpmiddelen. DMDU richt zich voornamelijk op het analyseren van besluitvormingsproblemen en minder op stakeholderprocessen en het creëren van *transformative agency*. Er blijven grote vragen bestaan over hoe deze analyses effectief in te zetten om besluitvorming door meerdere actoren over zeer onzekere, complexe besluitvormingsproblemen te ondersteunen.

Dit onderzoek is gericht op het ontwerpen en evalueren van een op theorie gebaseerde aanpak voor participatieve besluitvorming voor 'wicked problems' onder

grote onzekerheid. We passen deze aanpak toe op casestudies met betrekking tot de stedelijke mobiliteitstransitie in Nederland. We leveren een bijdrage aan dit doel in vier delen.

Ten eerste verkennen we het de potentie voor nadrukkelijke integratie van participatie en DMDU om ‘wicked problems’ aan te pakken in hoofdstuk 2. We analyseren hoe goed DMDU de tien kenmerken van ‘wicked problems’ adresseert en identificeren vervolgens drie tekortkomingen: de focus op de analysetechnieken; een gebrek aan aandacht voor betekenisvorming en begeleiding bij het interpreteren van analytische artefacten met de verschillende partijen bij een beslissing; en geen aandacht voor hoe tot een beslissing gekomen moet worden. Deze tekortkomingen onderstrepen de noodzaak om besluitvormers met elkaar en met andere belanghebbenden te laten overleggen.

DMDU methoden omvatten doorgaans drie algemene stappen: Frame, Explore en Choose. Wij gebruiken deze algemene DMDU-stappen als leidraad om de voordelen van het betrekken van belanghebbenden te identificeren. In de kaderstellende stap (Frame) kan stakeholder engagement de onderzoeker contextspecifieke kennis verschaffen. Het communiceren van de relevantie van dit probleem aan stakeholders kan helpen om eigenaarschap van het probleem en eigenaarschap te creëren. In de verkennende stap (Explore) verbetert stakeholder engagement de relevantie van de analyse; en de validatie en de uitkomsten van het model. In de keuzestap (Choose) helpen participatieve activiteiten om transparantie en vertrouwen in het model te creëren, en stakeholders de kunde en het vertrouwen te geven om te handelen en te implementeren.

We sluiten dit deel van het onderzoek af met vier uitdagingen bij het opzetten van participatieve DMDU: 1) de selectie van kansrijke projecten, 2) het ontwerpen van waardevolle processen, 3) de ontwikkeling en documentatie van methoden, en 4) transparante evaluatie.

Ten tweede presenteert hoofdstuk 3 een casestudy gericht op de eerste twee DMDU-stappen: Frame en Explore. We ondersteunen de gemeente Den Haag bij het genereren van robuust beleid door middel van een nieuwe kwalitatieve aanpak die participatieve modellering en DMDU combineert. In deze studie ontwikkelen we een innovatieve aanpak voor participatief modelleren onder grote onzekerheid en illustreren we hoe een dergelijke aanpak kan worden toegepast om de ontwikkeling van een klimaatneutraal transportsysteem voor de stad Den Haag te ondersteunen.

We zetten de aanpak om in een workshopsetting met beleidsmakers en ambtenaren van de gemeente die werken aan stedelijke mobiliteit en gerelateerde domeinen. De workshops hebben zes zichtbare producten opgeleverd: 1) een uitgebreide lijst met doelstellingen ten bate van een klimaatneutraal mobiliteitssysteem voor de stad, 2) KPI's die bij de doelstellingen horen, 3) Causal Loop Diagrams om deelnemers te helpen het transportsysteem te begrijpen, 4) een set interventies om de doelstellingen te realiseren, 5) een brede selectie van toekomstige gebeurtenissen en trends, en tot slot 6) een robuustheidsevaluatie die aandachtspunten voor het realiseren van duurzame mobiliteit blootlegt, zoals bijvoorbeeld financiering, capaciteit en publieke acceptatie van de potentiële interventies.

Door het expliciet koppelen van participatieve modellering en DMDU, zien we dat de deelnemers het systeem beter kunnen begrijpen en beter kunnen omgaan met onzekerheid. Deelnemers krijgen inzicht in de complexiteit van het systeem en manieren om daarmee om te gaan, de samenhang tussen interventies en hun effecten, en een gedeeld begrip van het probleem en de scope ervan. De workshop laat zien dat deelnemers in staat zijn causaal te denken, de scope van het probleem te variëren, zich verschillende onzekere toekomsten voor te stellen en onbedoelde gevolgen te identificeren.

Het onderzoek in dit hoofdstuk draagt bij aan de praktische uitdagingen door beleidsmakers een systematische aanpak te bieden voor complexe uitdagingen, zoals de transitie naar klimaatneutrale transportsystemen. De aanpak faciliteert stakeholders bij het identificeren van doelen en doelstellingen en het genereren van gedragen en robuuste interventies. Bovendien raken sta vertrouwd met onzekerheid en evalueren ze het geïdentificeerde beleid in termen van robuustheid, wat betekent dat ze goed presteren in een reeks onzekere toekomsten. Dit onderzoek toont aan dat een nieuwe aanpak om onderbouwde, robuuste interventies te genereren de potentie heeft bij te dragen aan het doel van een klimaatneutraal transportsysteem.

Ten derde ontwikkelen we een agent-based model dat gebruikt kan worden in participatieve settings om een breed scala aan beleidsmaatregelen te onderzoeken, gepresenteerd in hoofdstuk 4. Gebaseerd op het Actor-Option framework, simuleert dit model gebruikerskeuzes onder verschillende beleidsmaatregelen en onzekerheden en hoe dit de *modal split*, de verdeling van de verplaatsingen over de vervoerswijzen, beïnvloedt. In dit model simuleren we sociale interacties door gebruik te maken van een small-world sociaal netwerk. Onze resultaten tonen aan dat de parameters die worden gebruikt om een dergelijk netwerk te genereren essentieel zijn voor hoe de modal split zich in de loop van de tijd ontwikkelt. Verder simuleert het model competitie tussen de vervoerswijzen. We observeren dat het introduceren van een innovatie zowel gewenste als ongewenste effecten kan hebben op de modal split. De structuur van het model maakt het mogelijk om elke vervoerswijze toe te voegen als een combinatie van vervoersmiddelenkenmerken, wat de mogelijkheid opent om een breed scala aan hypothetische vervoerswijzen te onderzoeken die in de toekomst ontwikkeld zijn of zullen worden. In dit hoofdstuk presenteren we twee beleidsmaatregelen om de mogelijkheden van dit model te demonstreren. We onderzoeken verschillende belangrijke onzekerheden, die vooral de intensiteit en de snelheid van de verspreiding van de innovatie beïnvloeden. Onze analyse onthult het belang van sociale netwerken en het aantal mensen ('agents') die hun keuzes bij elke stap opnieuw evalueren.

We identificeren drie inzichten uit het agent-based model. Het eerste inzicht is dat de introductie van een innovatie het aandeel van vervoerswijzen die de duurzaamheid negatief beïnvloeden kan verminderen, maar ook het aandeel van duurzame vervoerswijzen kan verminderen. Het tweede inzicht is dat het onderzoeken van meerdere beleidsmaatregelen tegelijk symbiotische effecten van de beleidsmaatregelen aan het licht brengt. Het derde inzicht is dat de belangrijkste onzekerheden in deze studie een grotere impact hebben als de veranderingen in de

modal split ook groter zijn. De onzekerheden rond het sociale netwerk hebben de grootste invloed op de algemene resultaten.

We concluderen dat het Actor-Option framework ons in staat stelt om de dynamiek tussen verschillende actoren en opties op een gedetailleerd niveau vast te leggen. Dit flexibele framework kan worden aangepast aan andere mobiliteitsstudies en vervolgens aan beleidsvragen en -doelen. Het model laat ook toe om elke configuratie van technologieën als een nieuwe transportmodus op te nemen in de analyse. Dit agent-based model kan worden gebruikt om beleidsmakers te helpen door inzicht te verschaffen in het simuleren van transitiedynamiek en mogelijke toekomstscenario's, ook in participatieve settings.

Ten vierde, in hoofdstuk 5, gebruiken we het agent-based model in een participatieve setting, met focus op de tweede en derde stap van de DMDU-analyse: Explore en Choose. In een rollenspel waarin studenten de rol van beslissers aan nemen, onderzoeken we of de deelnemers in staat zijn om beslissingen te nemen op basis van modeloutputs aangevuld met een kwalitatieve discussie over aspecten die niet in het model zijn inbegrepen. We voeren dezelfde workshop twee keer uit met twee verschillende groepen studenten, een van de business faculteit van een algemene onderzoeksuniversiteit, de andere met studenten van een technische universiteit.

We stellen vast dat de deelnemers het model kunnen gebruiken en beslissingen kunnen nemen op basis van de output van het model, waarbij ze de complexiteit van het systeem erkennen. We zien dat de deelnemers hun rollen goed oppakken, hun taken serieus uitvoeren en gedurende de hele workshop geëngageerd zijn. Verder zijn de deelnemers zich ervan bewust dat het model niet elk aspect van het systeem weergeeft en zijn ze in staat om aspecten te bespreken die niet in het model zijn opgenomen. De deelnemers hebben echter de neiging om vooral aandacht te besteden aan de gemiddelde modal split, wat aangeeft dat de outputs die aan de deelnemers worden gepresenteerd en de interface waarmee deze outputs worden gepresenteerd zorgvuldig moeten worden gekozen om te voorkomen dat ze de onzekerheid negeren. Ondanks hun verschillende achtergronden vinden we geen significant verschil tussen de prestaties van de twee groepen. De overeenkomst in de algemene prestaties van de twee groepen suggereert dat dit type workshop kan worden uitgevoerd met deelnemers met verschillende achtergronden zonder modellerervaring.

Door deze nieuwe aanpak van participatieve besluitvorming onder grote onzekerheid laten we zien dat een activiteit met rollenspel- en spelelementen veelbelovend is om modelgebaseerde besluitvorming te onderzoeken met deelnemers met verschillende achtergronden. We observeren dat deelnemers het what-if denken achter DMDU-benaderingen begrijpen, in staat zijn om beleid af te wegen in een onzekere context en het model voldoende vertrouwen om beslissingen te nemen. De deelnemers hielden ook rekening met aspecten buiten het bereik van het model om kwetsbaarheden te bespreken, zoals exogene invloeden of toekomstige gebeurtenissen. Bovenop het nieuwe participatieve modelleerproces dat kwantitatieve simulatiemodellering en kwalitatieve overwegingen rond het model combineert, dragen we een holistisch systeem perspectief bij dat het huidige onderzoek

## SAMENVATTING

naar het modelleren van mobiliteitstransities aanvult.

Concluderend kan worden gesteld dat dit onderzoek een nieuwe aanpak biedt voor het probleem van de transitie naar duurzamere mobiliteit. We bouwen op DMDU en participatieve modellering om beleidsmakers in staat te stellen het probleem te kaderen, het systeem te modelleren, beleid te genereren en dit beleid af te wegen, rekening houdend met onzekerheid. Door het ontwerpen, uitvoeren en evalueren van DMDU-processen waarbij belanghebbenden betrokken zijn, zetten we de eerste stappen naar participatieve DMDU.



# ZUSAMMENFASSUNG

Der Übergang zu einem nachhaltigeren Mobilitätssystem ist eine anspruchsvolle Herausforderung aufgrund der Komplexität des Systems, des Zusammenspiels mehrerer Akteur:innen mit unterschiedlichen Sichtweisen auf das Problem, der Unsicherheit in Bezug auf den aktuellen Zustand des Systems, die mögliche Entwicklung und die Auswirkungen der Zukunft auf das System sowie die zu berücksichtigenden Wertvorstellungen. Planungssituationen mit diesen Merkmalen werden als ‘wicked problems’ bezeichnet. Wir nutzen das Modellieren von Transformationsprozessen, Stakeholderbeteiligung, und *decision-making under deep uncertainty (DMDU)*, um die Entscheidungsfindung für die Mobilitätswende zu unterstützen.

Dynamische Modelle sozio-technischer Transformationen sind hilfreich, um aufkommende Phänomene zu verstehen und zu erforschen, die sich aus den Systemelementen und ihren Beziehungen ergeben. Modelle können daher die menschliche Denkfähigkeit in komplexen Fragen unterstützen. Es gibt Ansätze zur Modellierung von Mobilitätswenden, aber es besteht Bedarf an einem theoriebasierten Modell des gesamten Mobilitätssystems, das soziale Interaktionen, endogene Interaktionen zwischen Verkehrsmitteln und das Entstehen von Innovationen simuliert. Darüber hinaus sollte ein solches Modell geeignet sein, ein breites Spektrum an politischen Maßnahmen zu untersuchen.

Das Modellieren mit Stakeholdern sowie DMDU sind Ansätze, die dazu beitragen können, Entscheidungen für ‘wicked problems’ zu treffen. Beide bieten modellgestützte Hilfe für die Entscheidungsfindung unter Einbeziehung mehrerer Stakeholder. Dieses gemeinsame Ziel bietet eine Grundlage, um gegenseitig voneinander zu profitieren. Bei der partizipativen Modellierung liegt der Schwerpunkt auf der Einbeziehung verschiedener Perspektiven und Wissen, dem Einholen von Unterstützung und der Entwicklung gemeinsamer formalisierter Darstellungen der Realität. Der partizipative Prozess zielt außerdem darauf ab, die Verantwortung der Teilnehmenden für die Probleme und die notwendigen Maßnahmen zu deren Lösung zu stärken. Ein Mangel partizipativer Techniken ist, dass sie sich selten auf Unsicherheiten konzentrieren oder diese auf die Schwankungen der Eingangsparameter des Modells beschränken.

Decision-making under deep uncertainty beruht auf drei Kernideen: explorative Modellierung, adaptive Planung und Entscheidungsunterstützung. Im Rahmen von DMDU werden Modelle als Explorationswerkzeuge zur Erzeugung und Untersuchung möglicher Zukunftsszenarien und nicht als Prognosewerkzeuge verwendet. DMDU konzentriert sich in erster Linie auf die Analyse von Entscheidungsproblemen und weniger auf die Prozesse der Interessengruppen und die Bildung transformativer Agency. Es bleiben wichtige Fragen offen, wie

diese Analysen zur Unterstützung der Entscheidungsfindung mehrerer Akteure in unsicheren und komplexen Situationen effektiv genutzt werden können.

Diese Forschung zielt darauf ab, einen theoriebasierten Ansatz für partizipative Entscheidungsfindung unter großer Unsicherheit für 'wicked problems' zu entwickeln und zu evaluieren. Wir wenden diesen Ansatz auf Fallstudien zur urbanen Mobilitätswende in den Niederlanden an. Wir verfolgen dieses Ziel in vier Teilen.

Erstens untersuchen wir das Potenzial für die explizite Integration von Partizipation und DMDU, um 'wicked problems' anzugehen (Kapitel 2). Wir analysieren, wie gut DMDU typischerweise die zehn Merkmale von 'wicked problems' bewältigt, und stellen drei Schwachstellen fest: den Fokus auf die Analysetechniken, einen Mangel an Aufmerksamkeit für die Sinnbildung und die Interpretation der analytischen Artefakte durch die verschiedenen Entscheidungsparteien, und die nicht vorhandene Aufmerksamkeit für die Art und Weise, wie man zu einer Entscheidung kommt. Diese Mängel weisen auf die Notwendigkeit hin, die Entscheidungsträger:innen zu befähigen, sich untereinander und mit anderen Beteiligten zu beraten.

DMDU-Ansätze umfassen in der Regel drei allgemeine Schritte: Frame, Explore und Choose. Wir verwenden diese allgemeinen DMDU-Schritte als Leitfaden, um die Vorteile der Einbeziehung von Stakeholdern zu ermitteln. In der Rahmenseitungsphase (Frame) kann die Einbeziehung von Stakeholdern die Forschenden mit kontextspezifischem Wissen versorgen. Die Vermittlung der Relevanz dieses Problems an die Beteiligten kann dazu beitragen, dass sie sich das Problem zu eigen machen und selbst handeln. In der Erkundungsphase (Explore) kann die Einbeziehung von Stakeholdern die Relevanz der Analyse verbessern und bei der Validierung des Modells und seiner Ergebnisse helfen. In der Phase der Entscheidungsfindung (Choose) können partizipative Aktivitäten dazu beitragen, Transparenz und Vertrauen in das Modell und die Kompromisse zu schaffen sowie Handlungsfähigkeit und Umsetzungsbereitschaft zu erzeugen.

Wir schließen diesen Teil der Forschung mit vier Herausforderungen bei der Einführung einer partizipativen DMDU-Praxis ab: 1) Auswahl vielversprechender Projekte, 2) Gestaltung sinnvoller Prozesse, 3) Entwicklung und Dokumentation von Methoden und 4) transparente Evaluierung.

Zweitens wird eine Fallstudie vorgestellt (Kapitel 3), die sich auf die ersten beiden DMDU-Schritte konzentriert: Frame und Explore. Wir unterstützen die Stadt Den Haag bei der Entwicklung robuster politischer Maßnahmen durch einen neuen qualitativen Ansatz, der partizipative Modellierung und DMDU kombiniert. In dieser Studie entwickeln wir einen innovativen Ansatz für die partizipative Modellierung unter großer Unsicherheit und veranschaulichen, wie ein solcher Ansatz angewendet werden kann, um die Entwicklung eines klimaneutralen Verkehrssystems für die Stadt Den Haag zu unterstützen.

Wir verwenden den Ansatz in einem Workshop-Setting mit politischen Entscheidungsträger:innen und Mitarbeitenden der Stadtverwaltung, die im Bereich der städtischen Mobilität und verwandten Bereichen tätig sind. Sechs sichtbare Produkte resultieren aus den Workshops: 1) eine umfassende Liste von Zielen zur Förderung eines klimaneutralen Mobilitätssystems für die Stadt, 2) mit

den Zielen verbundene KPIs, 3) Causal Loop Diagrams, die den Teilnehmenden helfen, das Verkehrssystem zu verstehen, 4) eine Reihe von Interventionen zur Verwirklichung der Ziele, 5) eine große Auswahl an zukünftigen Ereignissen und Trends und schließlich, 6) eine Robustheitsbewertung, die Bereiche aufzeigt, die für die Verwirklichung einer nachhaltigen Mobilität bedenklich sind, z. B. Finanzierung, Kapazität und öffentliche Akzeptanz der potenziellen Interventionen.

Durch die explizite Verknüpfung von partizipativer Modellierung und DMDU-Ansätzen beobachten wir, dass die Teilnehmenden das System besser verstehen und mit Unsicherheiten umgehen können. Die Teilnehmenden gewinnen einen Einblick in die systemische Komplexität und den Umgang mit den Zusammenhängen zwischen den Interventionen und ihren Auswirkungen, sowie ein gemeinsames Verständnis des Problems und seiner Tragweite. Der Workshop zeigt, dass die Teilnehmenden in der Lage sind, kausal zu denken, den Umfang des Problems zu variieren, sich verschiedene ungewisse Zukünfte vorzustellen und unbeabsichtigte Konsequenzen zu erkennen.

Dieses Kapitel leistet einen Beitrag zur Überwindung der praktischen Herausforderungen, indem es den politischen Entscheidungsträger:innen einen systematischen Ansatz zur Bewältigung komplexer Herausforderungen wie der Verkehrswende bietet. Der Ansatz erleichtert es den Akteuren, Ziele zu identifizieren und tragfähige, robuste Interventionen zu entwickeln. Darüber hinaus machen sich die Beteiligten mit der Unsicherheit vertraut und bewerten die ermittelten Maßnahmen im Hinblick auf ihre Robustheit in einer Reihe von unsicheren Zukünften. Diese Studie zeigt das Potenzial eines neuartigen Ansatzes zur Entwicklung von unterstützten, robusten Interventionen, um das Ziel eines klimaneutralen Verkehrssystems zu erreichen.

Drittens entwickeln wir ein agentenbasiertes Modell (agent-based model), das in einem partizipativen Rahmen verwendet werden kann, um eine breite Auswahl an Strategien zu untersuchen (Kapitel 4). Auf der Grundlage des Actor-Option-Frameworks simuliert dieses Modell die Entscheidungen der Nutzenden unter verschiedenen politischen Maßnahmen und Unsicherheiten und wie diese Entscheidungen den Modal Split beeinflussen. In diesem Modell simulieren wir soziale Interaktionen mit Hilfe eines sozialen Netzwerks. Unsere Ergebnisse zeigen, dass die Parameter, die zur Generierung eines solchen Netzwerks verwendet werden, entscheidend dafür sind, wie sich die Modal Shares im Laufe der Zeit entwickeln. Außerdem ermöglicht dieses Modell Interaktionen zwischen den Verkehrsmitteln durch Wettbewerb zwischen ihnen. Wir stellen fest, dass die Einführung einer Innovation erwünschte und unerwünschte Auswirkungen auf den Modal Split haben kann. Die Struktur des Modells erlaubt es, jedes Verkehrsmittel als eine Kombination von Merkmalen hinzuzufügen, was die Möglichkeit eröffnet, eine breite Palette von hypothetischen Verkehrsmitteln zu untersuchen, die in der Zukunft entwickelt werden. In diesem Kapitel stellen wir zwei politische Maßnahmen vor, um die Möglichkeiten dieses Modells zu demonstrieren. Wir untersuchen verschiedene zentrale Unsicherheiten, die sich hauptsächlich auf die Intensität und Geschwindigkeit der Verbreitung der Innovation auswirken. Unsere Analyse zeigt die Bedeutung von sozialen Netzwerken und die Anzahl der Nutzenden, die ihre Ent-

scheidungen bei jedem Schritt neu bewerten.

Aus dem agentenbasierten Modell lassen sich drei wichtige Erkenntnisse ableiten. Die erste Erkenntnis ist, dass die Einführung einer Innovation den Anteil der Verkehrsmittel, die sich negativ auf die Nachhaltigkeit auswirken, verringern kann, aber auch den Anteil der nachhaltigen Verkehrsmittel reduzieren kann. Die zweite Erkenntnis ist, dass die gleichzeitige Untersuchung mehrerer politischer Maßnahmen symbiotische Auswirkungen der Maßnahmen offenbart. Die dritte Erkenntnis ist, dass die wichtigsten Unsicherheiten, die in dieser Studie betrachtet werden, einen größeren Einfluss haben, wenn die Veränderungen des Modal Split größer sind. Die Unsicherheiten im Zusammenhang mit dem sozialen Netzwerk haben den stärksten Einfluss auf die Gesamtergebnisse.

Wir stellen fest, dass das Actor-Option- Framework uns erlaubt, die Dynamik zwischen verschiedenen Akteuren und Optionen auf einer detaillierten Ebene zu erfassen. Dieses flexible Framework kann auf andere Mobilitätsstudien und somit auch andere politische Maßnahmen und Ziele zugeschnitten werden. Das Modell erlaubt es auch, jede beliebige Konfiguration von Technologien als neues Verkehrsmittel in die Analyse einzubeziehen. Dieses agentenbasierte Modell kann zur Unterstützung von Entscheidungsträger:innen eingesetzt werden, indem es Einblicke in die Simulation von Übergangsdynamiken und möglichen Zukunftsszenarien bietet - auch in partizipativen Settings.

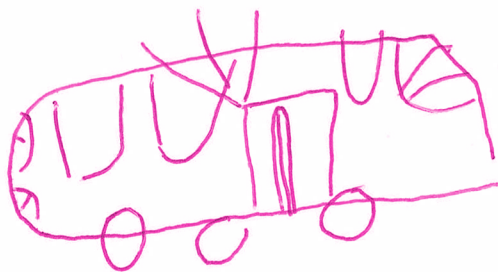
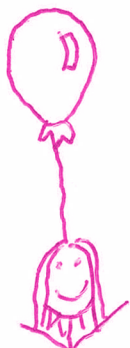
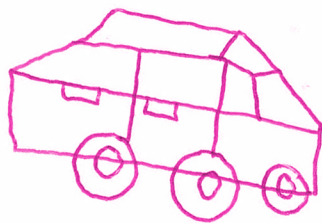
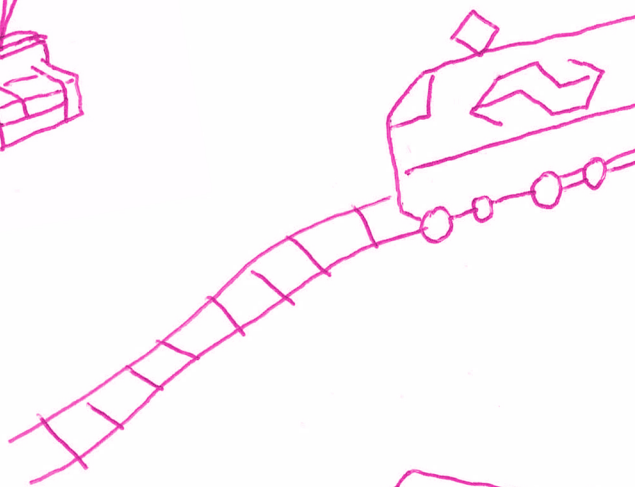
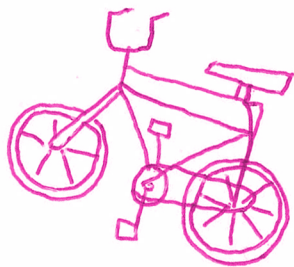
Viertens verwenden wir das agentenbasierte Modell, um Partizipation im zweiten und dritten Schritt der DMDU-Analyse einzusetzen: Explore und Choose (Kapitel 5). In einem Rollenspiel, in dem Studierende die Rolle von Entscheidungsträger:innen übernehmen, untersuchen wir, ob die Teilnehmenden in der Lage sind, Entscheidungen auf der Grundlage von Modellergebnissen zu treffen, die durch eine qualitative Diskussion über nicht im Modell enthaltene Aspekte ergänzt werden. Wir führen den gleichen Workshop zweimal mit zwei verschiedenen Gruppen von Studierenden durch, eine Gruppe von der Wirtschaftsfakultät einer allgemeinen Forschungsuniversität, die andere mit Studierenden einer technischen Universität.

Wir stellen fest, dass die Teilnehmenden das Modell nutzen können und Entscheidungen auf der Grundlage der Modellergebnisse treffen können, wobei sie die Komplexität des Systems anerkennen. Wir beobachten, dass die Teilnehmenden ihre Rollen gut annehmen, die Aufgaben gewissenhaft ausführen und während des gesamten Workshops engagiert sind. Außerdem sind sich die Teilnehmenden bewusst, dass das Modell nicht alle Aspekte des Systems abbildet, und sind in der Lage, Aspekte zu diskutieren, die nicht enthalten sind. Die Teilnehmenden neigen jedoch dazu, hauptsächlich auf den durchschnittlichen Modal Split zu achten, was darauf hindeutet, dass die Ergebnisse, die den Teilnehmenden präsentiert werden, und die Benutzeroberfläche, über die diese Ergebnisse präsentiert werden, sorgfältig ausgewählt werden müssen. So wird verhindert, dass sie die Unsicherheit ignorieren. Trotz ihres unterschiedlichen Hintergrunds stellen wir keinen signifikanten Unterschied zwischen den Leistungen der beiden Gruppen fest. Die Ähnlichkeit der Gesamtleistung der beiden Gruppen deutet darauf hin, dass diese Art von Workshop auch mit Teilnehmenden unterschiedlichen Hintergrunds und ohne

Modellierungserfahrung durchgeführt werden kann.

Mit diesem neuartigen Ansatz zur partizipativen Entscheidungsfindung unter großer Unsicherheit zeigen wir, dass eine Aktivität mit Rollenspielelementen ein vielversprechender Ansatz ist, um modellbasierte Entscheidungsfindung mit Teilnehmenden mit unterschiedlichem Hintergrund zu erkunden. Wir stellen fest, dass die Teilnehmenden das Was-wäre-wenn-Denken hinter DMDU-Ansätzen verstehen, in der Lage sind, Strategien in einem unsicheren Kontext zu erwägen, und dem Modell genug vertrauen, um Entscheidungen zu treffen. Die Teilnehmenden interagierten nicht nur mit dem Modell, sondern berücksichtigten auch Aspekte außerhalb des Modells, um Schwachstellen wie exogene Einflüsse oder zukünftige Ereignisse zu diskutieren. Zusätzlich zu dem neuartigen partizipativen Modellierungsprozess, der quantitative Simulationsmodelle und qualitative Überlegungen rund um das Modell kombiniert, tragen wir eine ganzheitliche Systemperspektive bei, die die aktuelle Forschung zur Modellierung von Mobilitätswenden ergänzt.

Abschließend trägt diese Forschung einen neuartigen Ansatz bei, um das Problem der Transformation zu einer nachhaltigeren Mobilität anzugehen. Wir bauen auf decision-making under deep uncertainty und partizipative Modellierung, um Entscheidungsträger:innen in die Lage zu versetzen, das Problem zu formulieren, das System zu modellieren, Strategien zu entwickeln und diese Strategien unter Berücksichtigung der Unsicherheit zu beraten. Indem wir DMDU-Prozesse unter Einbeziehung von Stakeholdern entwerfen, durchführen und auswerten, machen wir die ersten Schritte zur Etablierung einer Praxis für partizipatives DMDU.



# 1

## INTRODUCTION

Mobility is a central part of living in urban areas. However, the current mobility systems also negatively affect the livability of these urban areas through emissions, congestion, unsafety, and large amounts of space required for roads and parking.

### 1.1. MOBILITY TRANSITIONS

The need to transition the transport system to more sustainable functioning is widely acknowledged, yet the transition has been slow (Banister et al., 2011; UN, 2021). 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). Transitions are highly complex processes with non-linear interactions between actors with a high degree of uncertainty in the development of external conditions, system interactions, and unfolding of final outcomes (Köhler et al., 2018).

Transitioning to a more sustainable mobility system is a challenging policy issue, as is evidenced by past cases in which policies turned out to be ineffective or to produce unintended negative consequences (Berger et al., 2014). Making changes in the mobility system is often costly and has impacts over a long time horizon. The mobility system involves many actors, such as policymakers, transport providers, and users. These actors often hold diverging perspectives on the problem and may favor different courses of action (Jittrapirom et al., 2021). On top of that, there is uncertainty about the system's current state, how the future might unfold and affect the system, and what values to consider. Therefore, the transition of the urban mobility system towards more sustainability is a complex societal challenge.

The field of transition studies can be divided into two main clusters: theoretical and applied transition studies (Yücel, 2010). Theoretical transition studies focus on developing a general understanding of transition processes. The Multi-Level Perspective (Rip and Kemp, 1998; Geels, 2002), the Technological Innovation Systems Approach (Hekkert et al., 2007; Bergek et al., 2008; Negro et al., 2008; Markard

et al., 2015), Strategic Niche Management (Schot and Geels, 2008; Weber et al., 2002), and Transition Management (Loorbach, 2010; Loorbach et al., 2015) are considered foundational theoretical frameworks in the field of transition studies. Even though these frameworks are considered the main frameworks for transition studies, many researchers borrow frameworks from other fields or develop their own, often based on or combined with those four foundational frameworks (Zolfagharian et al., 2019). Applied transition studies build on the theoretical studies and focus on specific transition problems using the concepts and methods derived from theoretical transition studies. Applied transition studies rely on a broad range of methodological approaches due to the empirically broad and interdisciplinary nature of the field of transitions (Köhler et al., 2019).

## 1.2. DECISION-MAKING FOR TRANSITIONS

Decision-making for transitions requires dealing with the system's complexity, multi-actor context, and uncertainty. Planning situations with these characteristics are considered wicked problems (Rittel and Webber, 1973). Therefore, we draw on transition modeling, stakeholder engagement, and decision-making under deep uncertainty in this research.

We consider various actors in this study. We use the term actor for a person, or group of persons, that has an interest in the system being analyzed and is concerned about the outcomes of the system. We characterize actors by whether they have a stake in the outcome of the policymaking process and by whether they have decision-making power. We use the term stakeholder to refer to anyone being affected by a decision. Decision-makers have an influence on the problem situation and its development.

### 1.2.1. TRANSITION MODELING

Transitions modeling has emerged in recent years to investigate the complexity of transitions and support decision-making for transitions (Halbe et al., 2015; Holtz et al., 2015; Köhler et al., 2018). Uncertain, complex systems reveal the limitations of human reasoning through mental models (e.g., Sterman, 1989; Brehmer, 1992; Diehl and Sterman, 1995; Atkins et al., 2002). Mental models are event-based, have an open-loop view of causality, ignore feedback, do not account for time delays, and are often insensitive to non-linearity (Sterman, 1994; Schaffernicht, 2019). Thus, mental simulation of complex systems is challenging to the point of being infeasible. Dynamic models are helpful to understand and explore emergent phenomena as a result of the interactions of parts of the system and their relation as well as the underlying processes, thus aiding human reasoning (Holtz et al., 2015).

Efforts have been made to model transitions in various domains (Köhler et al., 2018; Moallemi and de Haan, 2020), including transport. These mobility transition studies have a strong technology focus and mainly investigate the development of a single innovation, such as electric vehicles (Hoekstra and Hogeveen, 2017; Zolfagharian et al., 2020), hydrogen cars (Köhler et al., 2010), or alternative fuel

## 1.2. DECISION-MAKING FOR TRANSITIONS

vehicles in general (Kwon, 2012). However, recent mobility phenomena such as Mobility-as-a-Service, ride-hailing services, or micro-mobility sharing combine novel ICT technologies and novel or existing transport technologies. Additionally, only a few models have explicitly dealt with the uncertainty of transitions (Moallemi and Köhler, 2019). So, a recent review of agent-based mobility transition models (Mehdizadeh et al., 2022) calls for theory-driven and validated models that consider multiple transitions simultaneously and combine preference- and price-based policies. Therefore, there is a need for a theory-based model of the whole transport system that simulates social interactions, endogenous interactions between transport modes, and the emergence of innovations and is suitable for exploring a wide range of policies under uncertainty.

### 1.2.2. PARTICIPATORY MODELING

Modeling with stakeholders is an established way of addressing wicked problems (Voinov et al., 2016; Mingers, 2011), incorporating different perspectives and knowledge, gathering support, and forming shared formalized representations of reality. Engaging stakeholders in the modeling process can facilitate the development of a shared understanding of the problem or situation to be addressed, and foster ownership of the problem formulation and the actions that must be taken (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 recognize the uncertainty inherent in data and methods (Cockerill et al., 2009). Actors can be involved in any component of a participatory modeling process, but it is unlikely that any particular actor is involved in all of them (Voinov et al., 2016).

### 1.2.3. DECISION-MAKING UNDER DEEP UNCERTAINTY

Mobility planning involves deep uncertainty. Decision problems characterized by deep uncertainty can be considered a particular type of wicked problem (Kwakkel et al., 2016b). Deep uncertainty describes situations where 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).

Decision-making under deep uncertainty rests on three key ideas: exploratory modeling, adaptive planning, and decision support (Kwakkel and Haasnoot, 2019). The first key idea is exploratory modeling. Rather than trying to reduce the uncertainty through heroic assumptions or misplaced probabilistic quantification, one should explore the consequences of the various currently irreducible uncertainties for decision-making when faced with deep uncertainty (Bankes, 1993; Bankes et al., 2002). As such, the idea of exploratory modeling is rooted in what-if scenario thinking (van der Heijden, 1996; Amer et al., 2013; Wright and Cairns, 2011). Indeed, scenario thinking helps decision-makers, to choose options that perform reasonably well under a wide range of conditions (Gong et al., 2017; Parker et al., 2015).

The second key idea is adaptive planning (Haasnoot et al., 2024). Plans should be designed to be adapted over time in response to how the future may unfold. How a plan is designed to adapt in the face of potential changes in conditions is announced simultaneously with the plan itself rather than the often witnessed *ad hoc* modifications to plans in response to surprise. This adaptability is a key means of ensuring that the plan can meet its objectives across a wide range of plausible futures. While the future unfolds, many deep uncertainties are being uncovered. By carefully monitoring for specific signals, decision-makers can adapt the plan's implementation to either mitigate undesirable developments or seize opportunities in a pre-specified and timely manner (Walker et al., 2001; Kwakkel et al., 2010a). Increasingly, adaptive planning also results in plans being conceived as sequences of actions, or policy pathways, where subsequent actions on the pathway are to be taken depending on how the future unfolds (Haasnoot et al., 2013; Wise et al., 2014).

The third key idea is decision support. Rather than seeing models and their results as tools for identifying the best decision, modeling and model use is an iterative process that facilitates learning across the problem's alternative framings and stakeholder preferences and trade-offs (Herman et al., 2015). So, in a typical decision-making under deep uncertainty process, candidate policy decisions are analyzed by stress-testing them over a wide range of uncertainties. The uncertainties are then characterized by their effect on the performance of the various candidate decisions. Performance of a candidate decision here refers both to the trade-offs among a set of objectives and the performance over the set of scenarios (*i.e.*, decision robustness (McPhail et al., 2018)). Suppose that none of the candidate policy decisions produces adequate results for the involved stakeholders. In that case, this triggers the reframing of the problem by expanding the set of candidate decisions, modifying the uncertainties being considered, and/or changing the key objectives.

A variety of approaches rooted in these three key ideas 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). DMDU approaches generally include a generic set of elements that are part of a process with three general steps: frame, explore, and choose (Marchau et al., 2019b). Within DMDU, models are intended to be used as exploration tools for generating and examining possible futures instead of being used as prediction tools (Marchau et al., 2019a).

### 1.3. KNOWLEDGE GAP

Decision-making under deep uncertainty and modeling with stakeholders are both approaches that can contribute to coming to decisions in relation to wicked problems. Both offer model-based support for multi-stakeholder decision-making. This shared aim offers a basis for benefiting each other. Participatory modeling focuses on incorporating different perspectives and knowledge and gather support (Voinov et al., 2018). Participation also aims to foster ownership of the problems and necessary actions to resolve them among the participants (Franco

## 1.4. RESEARCH AIM & QUESTIONS

and Montibeller, 2010; de Gooyert et al., 2022). A shortcoming of participatory techniques is that they rarely focus on uncertainty or restrict it to variability in input parameters to the model (Voinov et al., 2016).

DMDU predominantly focuses on the analytics of decision problems and less on stakeholder processes and the creation of transformative agency (Malekpour et al., 2020). Most DMDU approaches implicitly or explicitly assume one single (virtual) decision-maker who represents all interests and is capable of unilaterally taking all actions of all parties involved (Bosomworth et al., 2017; Kwakkel et al., 2016b; Wise et al., 2014). Although there have been some efforts to consider multiple actions, objectives, or actors in the analysis (Herman et al., 2014; Gold et al., 2023), major questions remain on using these analytics effectively to support multi-actor decision-making on deeply uncertain, complex decision problems (Döll and Romero-Lankao, 2017; Kwakkel et al., 2016b; Tuckett et al., 2015; Zulkafli et al., 2017).

It remains a challenge how to use the capabilities of modeling and participatory approaches for DMDU processes to increase the effectiveness of scientific advice and improve decision recommendations (Moallemi et al., 2020b). By combining approaches that have previously not been used together, we can harness their strengths and mitigate their shortcomings. Developing structured approaches combining participatory modeling and DMDU is challenging. Yet, designing, executing, and evaluating DMDU processes involving stakeholders is needed to establish a practice of participatory DMDU.

### 1.4. RESEARCH AIM & QUESTIONS

This research aims to design and evaluate a theory-informed approach for participatory decision-making under deep uncertainty for wicked problems. This approach will be applied to case studies related to the urban mobility transition in the Netherlands. The Netherlands has a well-developed multimodal mobility system. While there is a strong emphasis on cycling, walking, and public transport, the car remains the dominant mode of transport. National policies set the framework for local mobility policy, but municipalities are responsible for local transport policies, infrastructure, and public space management. The municipality, therefore, has a key role. Other actors include transport providers and citizens.

This research belongs to the cluster of applied transition studies, using the Actor-Option framework (Yücel, 2010) as a theoretical basis for modeling the mobility system with stakeholders.

To reach our aim, we answer the following questions:

#### 1. What are the benefits and challenges of combining participatory modeling and decision-making under deep uncertainty?

We start this research by analyzing how well DMDU addresses wicked problems and identifying the shortcomings of DMDU. Engaging stakeholders is a promising direction for overcoming these shortcomings. By presenting a general structure for a participatory DMDU process and the potential benefits of engaging stakeholders, this sub-question sets a research agenda. The

remainder of the thesis contributes to this research agenda through urban mobility transition case studies.

**2. What is a feasible approach for combining participatory modeling and decision-making under deep uncertainty for generating climate-neutral urban mobility solutions?**

Through a case study with the municipality of The Hague, the Netherlands, this sub-question presents a novel approach for generating policies supported by and within the municipality, focusing on the first two DMDU steps (Frame and Explore).

**3. Which concepts and relations explain the transition of the urban mobility system behavior towards climate neutrality?**

The previous question qualitatively addresses the first two steps of the DMDU process. We aim to build on this in two ways: first, to address the last step of the DMDU analysis (Choose), and second, to incorporate a quantitative analysis since these kinds of analyses are at the heart of the DMDU literature. To this end, we develop an agent-based transitions model that can be used in participatory workshops.

**4. What is a feasible approach for combining participatory modeling and decision-making under deep uncertainty for deliberating climate-neutral urban mobility solutions?**

With the help of the agent-based model, we design a workshop for exploring the model results and deliberating policy choices to carry out the latter two steps of the DMDU process (Explore and Choose).

## 1.5. APPROACH

The first research question is addressed by analyzing the current state of decision-making under deep uncertainty. By analyzing to what extent DMDU addresses the characteristics of wicked problems, we identify the shortcomings. Using the three general steps of a DMDU analysis (Frame, Explore, and Choose), we provide a general structure for participatory DMDU processes and lay out the benefits of engaging stakeholders for each step.

The second research question is addressed through a case study focusing on the first two DMDU steps (Frame and Explore). We develop a novel qualitative approach combining participatory modeling and DMDU to support the municipality of The Hague in generating robust policies that are supported within the municipality. Through this approach, participants formulate objectives and goals, identify causal mechanisms by creating Causal Loop Diagrams, and identify potential interventions. With a set of possible futures, the interventions are then stress-tested to evaluate their robustness.

For the third research question, we develop an agent-based model that can be used in participatory settings. The model is based on the Actor-Option framework (Yücel, 2010). The Actor-Option framework is a generic transition modeling framework that conceptualizes change as a result of actor decisions.

## 1.6. CASE STUDY AREA

The abstraction level of the framework facilitates establishing empirical links with the real-world policy-making context. Moreover, the framework covers processes of internal changes of actors and options in the system rather than just depicting the system's state. This model simulates user choices under different policies and uncertainties and how this influences the modal split.

For the fourth research question, we use the agent-based model to employ participation in the second and third steps of the DMDU analysis (Explore and Choose). Through participatory workshops, we investigate whether the participants are able to make decisions based on the information they get from the model. Further, we enrich the model output with a qualitative discussion on aspects not included in the model.

### 1.6. CASE STUDY AREA

The approach developed in this thesis is applied to one case study area. A suitable case study for this research is an area that is large enough to display the dynamics and complexity involved in mobility transitions. Therefore, a large and dense metropolitan area with connections to other cities is required to not only consider movements within one city, but also between neighboring municipalities. Further, a suitable case study encompasses a wide range of transport modes.

We chose the municipality of The Hague, the Netherlands, as the case study area for this research. On top of fulfilling the requirements for exhibiting complexity, the municipality of The Hague has clear ambitions for transitioning towards more sustainable mobility. The Hague is the third largest city in the Netherlands, with about half a million inhabitants. The city has a well-developed public transport network, including trams, buses, and connections to the national rail system. As part of the Randstad metropolitan region, The Hague is closely connected to Rotterdam, Amsterdam, and Utrecht, forming one of Europe's most densely populated and economically significant urban areas.

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 mobility sector. The research team contacted the municipality and started a collaboration that explored how participatory modeling, taking uncertainty into account, can support the municipality's decision-making.

### 1.7. OUTLINE

In Chapter 2, we address the first research question by analyzing the current state of decision-making under deep uncertainty, identifying the shortcomings, and providing a general structure for participatory DMDU processes. We lay out the potential benefits of engaging stakeholders for each step and identify four challenges in establishing a practice of participatory DMDU. In Chapter 3, we address the second research question through a case study focusing on the first two DMDU steps (Frame and Explore). In this study, we support the municipality of The Hague in generating robust policies that are supported within the municipality through a

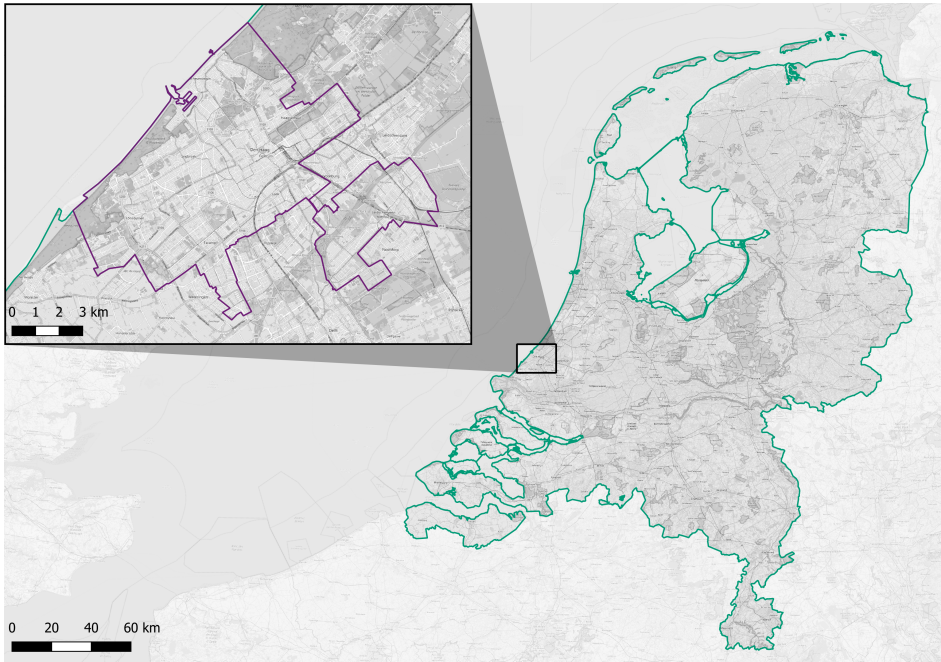
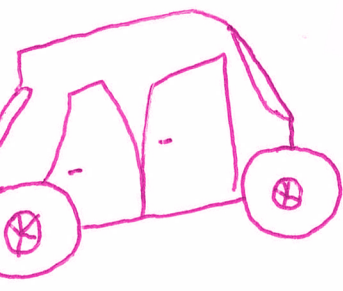
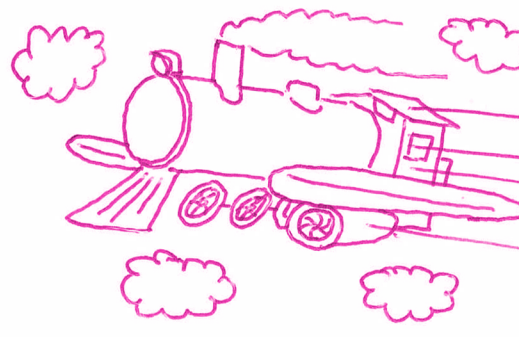
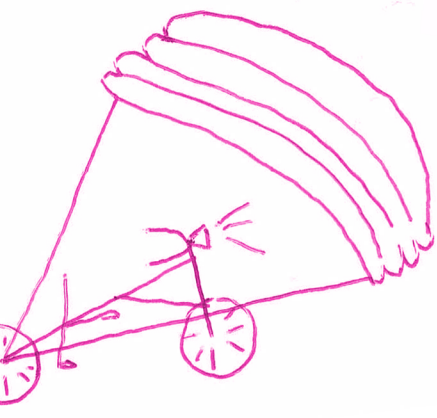
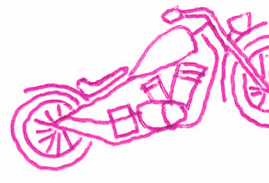
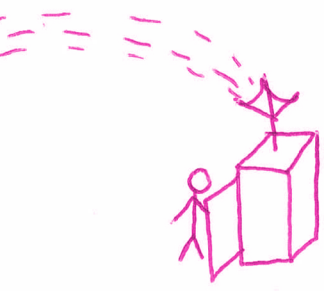
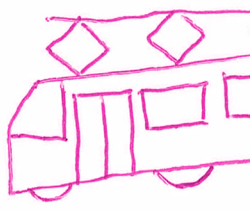


Figure 1.1: Map of the Netherlands with a detailed inset highlighting the city of The Hague

novel qualitative approach combining participatory modeling and DMDU. In Chapter 4, we address the third research question with an agent-based model that can be used in participatory settings. This model simulates user choices under different policies and uncertainties and how this influences the modal split. In Chapter 5, we address the fourth research question by using the agent-based model to employ participation in the second and third steps of the DMDU analysis (Explore and Choose). Through these four studies, we aim to contribute novel approaches to participatory decision-making under deep uncertainty. We discuss the results in Chapter 6 and conclude by answering the research questions and presenting recommendations for future research in Chapter 7.





# 2

## TOWARDS PARTICIPATORY DECISION-MAKING UNDER DEEP UNCERTAINTY: BENEFITS AND CHALLENGES

In the Introduction, we identified the need to address complex societal problems involving various stakeholders and deep uncertainty. We start this research by showing how well decision-making under deep uncertainty (DMDU) addresses wicked problems. In this chapter, we identify the shortcomings of the current DMDU literature and the benefits of involving stakeholders in DMDU. Doing so enables us to set a research agenda to which the remainder of this thesis contributes.

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*Decision-making under deep uncertainty (DMDU) provides a set of tools and methods to find resolutions for complex wicked problems, which requires considering multiple actors and uncertainty. However, not all characteristics of wicked problems are typically addressed by the DMDU toolkit. We identified three key shortcomings: the focus on analytical techniques, a lack of attention to sense-making of analytical artifacts with the various parties to a decision, and no attention to coming to a decision. Engaging stakeholders in the DMDU process is a promising direction for overcoming these shortcomings. This study addresses the need for a formalized approach to participatory DMDU. As such, we provide a general structure for participatory DMDU processes and present the potential benefits of engaging stakeholders for each step. We present four challenges in establishing a practice of participatory DMDU: 1) selecting promising projects, 2) designing valuable processes, 3) developing and documenting methods, and 4) evaluating transparently.*

### 2.1. THE NEED FOR PARTICIPATORY DECISION-MAKING UNDER DEEP UNCERTAINTY

Addressing complex societal challenges requires dealing with many stakeholders and uncertainty about the current state of the system, how the future might unfold and affect the system, and what values to consider. Additionally, diverging understandings of the system and the uncertainties among the stakeholders might further amplify the uncertainty. A further challenge is that decision environments change, and perceptions of actors evolve. Planning situations with these characteristics are considered wicked problems (Rittel and Webber, 1973).

Decision problems characterized by deep uncertainty can be considered a particular type of wicked problem (Kwakkel et al., 2016b). Deep uncertainty describes situations in which decision-makers and other relevant stakeholders do not know or cannot agree upon the system and its boundaries, the outcomes of interest and their prioritization and desirability, or the probabilities for uncertain key variables and parameters (Lempert et al., 2003). A variety of model-based methods and tools have emerged over the last decade to support decision-making under deep uncertainty (DMDU) (Marchau et al., 2019a). Within DMDU, instead of being used as prediction tools, models are intended to be used as exploration tools for generating and examining possible futures (Marchau et al., 2019b). Robust Decision Making is a foundational example of DMDU (Lempert et al., 2003). In this approach, policy options are stress-tested over a wide range of future scenarios using computational tools. Another example is Adaptive Policy Making (Walker et al., 2001), in which plans are designed to be adapted as the future unfolds. Those adaptations are built into the plan as opposed to *ad hoc* modifications in reaction to surprise. A third exemplary DMDU approach is Dynamic Adaptive Policy Pathways, which involves exploring alternative sequences of decisions over time (adaptation pathways) to reveal lock-ins, lock-outs, and path dependencies, and how these interact with plausible future scenarios (Haasnoot et al., 2013).

Modeling with stakeholders is an established way of dealing with wicked problems (Voinov et al., 2016). Engaging stakeholders aims to create a shared understanding of the problem or situation at hand as well as produce ownership of the problem formulation and actions that need to be taken among the participants (Franco and Montibeller, 2010). Participants in participatory modeling processes can better accept ambiguity and uncertainty inherent to complex problems as well as the reality that there might not be a simple solution (Cockerill et al., 2009). Mikulskiene and Pitrenaitė-Zilėnienė (2013) summarize the main advantages of stakeholder involvement: to bring existing knowledge, to create new knowledge, to create consensual knowledge, to secure policy implementation, and to stimulate a learning process for future actions. We use the term stakeholder to refer to anyone affecting or being affected by a decision. Hereby, we can differentiate between decision-makers and other stakeholders. Further, we consider (local) experts who might not be affected by a decision at all.

Participatory modeling and decision-making under deep uncertainty are both useful approaches to deal with wicked problems. Both aim to offer model-based

support for multi-stakeholder decision-making. This shared aim offers a basis for benefiting each other. Bojórquez-Tapia et al. (2022) highlight the importance of stakeholder engagement, knowledge co-production, and deliberative processes for DMDU approaches. Most DMDU processes make use of some type of deliberation with analysis (Lempert, 2019). So far, in the application of DMDU methods, stakeholders and experts have been consulted in order to gather information about the context of the decision, or they were involved in problem formulation, decisions on performance metrics, shaping of scenarios or pathways (Stanton and Roelich, 2021). However, the focus of the DMDU literature predominantly is on the analysis and analytical tools used by researchers and less on stakeholder processes and the creation of transformative agency (Malekpour et al., 2020). While there are some efforts to consider multiple actions, objectives, or actors (e.g., Herman et al., 2014; Gold et al., 2023), most DMDU approaches implicitly assume one single (virtual) decision-maker who represents all interests and is capable to unilaterally take all actions of all parties involved (Bosomworth et al., 2017; Kwakkel et al., 2016b; Wise et al., 2014). If a decision process ignores the willingness and ability of actors to act according to the plan, this poses a major risk to the plan's success. While there has been substantial work on the topic, major questions remain on how to effectively support multi-actor decision-making on deeply uncertain, complex decision problems through modeling (Döll and Romero-Lankao, 2017; Kwakkel et al., 2016b; Tuckett et al., 2015; Zulkafli et al., 2017). It remains a challenge how to use the capabilities of modeling and participatory approaches for DMDU processes in order to increase the effectiveness of scientific advice and improve decision recommendations (Moallemi et al., 2020b).

In this paper, we explore the intersection of the methods and tools for participation and decision-making under deep uncertainty. According to Voinov et al. (2018) a *tool* is defined as a technique to carry out a particular function to achieve a specific goal. Tools are defined, documented, do not change through use, and are external to their users. In comparison, they define a *method* as a way of doing something that can be supported by one or several tools. We contribute to establishing a practice of participatory DMDU by providing a general structure for involving stakeholders in DMDU, benefits of engaging stakeholders, and four research challenges.

We begin by introducing the characteristics of wicked problems and the key ideas underpinning DMDU and the main DMDU approaches in section 2.2. Following this, we analyze to what extent the characteristics of wicked problems are addressed by the DMDU methods and tools available in section 2.3. We introduce participatory modeling in section 2.4, followed by a review of past DMDU studies in which stakeholders were engaged. We then present methods that could potentially be used to involve stakeholders. We present a basic structure of a participatory DMDU process in section 2.5. Based on the generic set of elements that DMDU approaches follow, we present how participation can add to it. We conclude with a research agenda.

### 2.2. RESOLVING PROBLEMS IN COMPLEX SYSTEMS

In this section we characterize the problems that decision making under deep uncertainty (DMDU) is typically used for, the key ideas of DMDU, and its main methods and tools.

#### 2.2.1. COMPLEX SYSTEMS AND WICKED PROBLEMS

A DMDU analysis is useful when the future world, the system, and/or the outcomes have the potential for surprise due to their complexity (Marchau et al., 2019b). This complexity stems from the involvement of multiple actors with potentially conflicting values and views on the problem, institutional complexity, ethical complexity, and a multidisciplinary field of experts working within the system. Together, this gives rise to uncertainty about the system and its boundaries, and the proper scope of the analysis. In addition, there is typically uncertainty about the future.

A prominent characterization of this kind of decision situations is as wicked problems (Rittel and Webber, 1973). These problems are hard to define, there is no simple solution and straightforward policy response, they are highly interlinked with other systems and problems, and require political judgment. Rittel and Webber (1973) characterize wicked problems by the following ten properties:

1. There is no definitive formulation of a wicked problem
2. Wicked problems have no stopping rule
3. Solutions to wicked problems are not true-or-false but good-or-bad
4. There is no immediate and no ultimate test of a solution to a wicked problem
5. There is no opportunity to learn by trial-and-error, every solution attempt counts significantly
6. There is no exhaustively describable set of potential solutions or permissible operations
7. Every wicked problem is essentially unique
8. Every wicked problem can be considered to be the symptom of another problem
9. The existence of a discrepancy representing a wicked problem can be explained in numerous ways and this explanation determines the nature of the problem's resolution
10. The planner has no right to be wrong

This conceptualization of wicked problems was expanded by introducing the term “super wicked” to characterize a new class of global environmental problems (Levin et al., 2012). Later, it was also used to assess COVID-19 (Auld et al., 2021). Super wicked problems have four key features: time is running out, those who cause the problem also seek to provide a solution, the central authority needed to address them is weak or non-existent, and irrational discounting occurs that pushes responses into the future (Levin et al., 2012). These features make this a fairly specific class of problem.

In the context of consulting work, [Camillus \(2008\)](#) found that if the following five characteristics are present in a strategy-related issue, executives agree that they have a wicked problem on their hand: many stakeholders with different values and priorities, the roots are complex and tangled, the problem is difficult to come to grips with and changes with every attempt to address it, there is no precedent, and nothing to indicate the right answer to the problem. This characterization is mainly related to a business and strategy context.

Another similar concept is “societal messes”. Messes are dynamic situations that consist of complex systems of changing problems that interact with each other ([Ackoff, 1979](#)). Messy problem situations are ill-defined problems with contested objectives, several interested parties with different perspectives on the problem, many uncertainties, and a lack of reliable data ([Mingers, 2011](#)).

Ultimately, all these concepts describe similar situations. We decided to continue with the notion of wicked problems since it applies to a multitude of domains and is established and used in DMDU research. Criticism of the notion of wicked problems has noted that it mainly serves as a rhetorical tool and highlights the difficulty of the problem and does not offer much practical guidance on working on it ([Gilligan and Vandenberg, 2020](#)). [Gilligan and Vandenberg \(2020\)](#) further argue that the ten criteria can easily generate so many reasons a project might fail that failure becomes inevitable, thus creating paralysis for policy makers. However, for our purpose it is a useful guiding framework, highlighting features that need to be addressed.

### 2.2.2. DECISION-MAKING UNDER DEEP UNCERTAINTY

A body of literature has emerged comparing the various methods for supporting decision-making under uncertainty (e.g., [Hall et al., 2012](#); [Kwakkel et al., 2016a](#); [Matrosov et al., 2013](#); [Roach et al., 2015, 2016](#); [Moallemi et al., 2020a](#); [Bartholomew and Kwakkel, 2020](#)). In turn, this has given rise to various typologies and frameworks that specify the key ideas underpinning these various methods, paving the way for an informed selection of methods given case-specific considerations ([Herman et al., 2015](#); [Kwakkel and Haasnoot, 2019](#)). Following [Kwakkel and Haasnoot \(2019\)](#), decision-making under deep uncertainty rests on three key ideas: exploratory modeling, adaptive planning, and decision support.

The first key idea is exploratory modeling. In the face of deep uncertainty, rather than trying to reduce the uncertainty by either heroic assumptions or misplaced probabilistic quantification, one should explore the consequences of the various presently irreducible uncertainties for decision-making ([Bankes, 1993](#); [Bankes et al., 2002](#)). This idea of exploring the consequences of uncertainty is rooted in the idea of what-if scenario thinking ([van der Heijden, 1996](#); [Amer et al., 2013](#); [Wright and Cairns, 2011](#)) as popularized through the pioneering work of Shell in the late 1960s ([Bradfield et al., 2005](#)). Scenarios are (plausible) descriptions of what the future might look like. Scenario thinking is a means for thinking about possible threats and opportunities that the future might hold and their impacts on an organization, business, or system. When making decisions, scenario thinking helps choose options that perform reasonably well under a wide

## 2.2. RESOLVING PROBLEMS IN COMPLEX SYSTEMS

range of conditions (Gong et al., 2017; Parker et al., 2015).

When applying scenario thinking to problems characterized by deep uncertainty, there is a need to use model-based scenario approaches (Cordova-Pozo and Rouwette, 2023). Human reasoning through mental models about uncertain, complex systems is fallible (e.g., Sterman, 1989; Brehmer, 1992; Diehl and Sterman, 1995; Atkins et al., 2002). Mental models are event-based, have an open-loop view of causality, ignore feedback, do not account for time delays, and are insensitive to non-linearity (Sterman, 1994; Schaffernicht, 2019). In complex systems, the aggregate dynamics, however, are due to accumulations, feedback, and time delays, with nonlinear interactions among them. Thus, mental simulation of complex systems is challenging to the point of being infeasible. Models aid human reasoning about such systems because models are much better at systematically deriving the consequences from sets of hypotheses (i.e., possible alternative realizations of the uncertainties) about the functioning of complex systems (Sterman, 2002). The appropriateness of model-based scenario approaches is further strengthened by the need to systematically explore the impact of a large number of interacting uncertainties, which through large scale computational experimentation has become feasible in recent years (c.f., Lamontagne et al., 2018).

Exploratory Modeling uses computational experimentation for analyzing uncertain, complex systems (Bankes, 1993; Bankes et al., 2002, 2013; Moallemi et al., 2021). In the presence of deep uncertainty, one should explore the consequences of the various presently irreducible uncertainties for decision-making by developing a set of models that covers the key uncertainties and is constrained by the available data and knowledge. A single model drawn from the set is a computational what-if experiment that reveals how the real-world system would behave if the specific assumptions about the uncertainties in this model were correct. A single what-if experiment is typically not informative. At most, it suggests the plausibility of specific outcomes. So, exploratory modeling involves systematically generating and analyzing large ensembles of computational experiments. Thus, exploratory modeling involves searching through the set of models using (many-objective) optimization algorithms, sampling from the set using computational design of experiments, and global sensitivity analysis and rule induction to reveal patterns within the set (Kwakkel, 2017; Bryant and Lempert, 2010; Halim et al., 2016).

The second key idea is adaptive planning. Plans should be designed from the outset to be adapted over time in response to how the future may unfold. The way a plan is designed to adapt in the face of potential changes in conditions is announced simultaneously with the plan itself rather than the often witnessed *ad hoc* modifications to plans in response to surprise. The flexibility offered by adaptive plans is a key means of ensuring that the plan can meet its objectives across a wide range of plausible futures. While the future is unfolding, many deep uncertainties are being resolved. By carefully monitoring this, decision-makers can adapt the plan's implementation to either mitigate undesirable developments or seize opportunities in a pre-specified and timely manner (Walker et al., 2001; Kwakkel et al., 2010a). Increasingly, adaptive planning also results in plans being conceived as se-

quences of actions, or policy pathways, where subsequent actions on the pathway are to be taken depending on how the future unfolds (Haasnoot et al., 2013; Wise et al., 2014).

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The third key idea is decision support. Rather than seeing models and their results as tools for identifying the best decision, modeling and model use is seen as an iterative process that facilitates learning across the problem's alternative framings and stakeholder preferences and trade-offs (Herman et al., 2015). So, in a typical decision-making under deep uncertainty process, candidate policy decisions are analyzed by stress-testing them over a wide range of uncertainties. The uncertainties are then characterized by their effect on the performance of the various candidate decisions. Performance of a candidate decision here refers both to the trade-offs among a set of objectives and the performance over the set of scenarios (i.e., decision robustness (McPhail et al., 2018)). Suppose none of the candidate policy decisions produces adequate results for the involved stakeholders. In that case, this triggers a reframing of the problem by expanding the set of candidate decisions, modifying the uncertainties being considered, and/or changing the key objectives.

There is a wide range of decision-making under deep uncertainty methods rooted in these three ideas. The foundational method is Robust Decision Making (RDM) (Lempert et al., 2006; Groves and Lempert, 2007). RDM introduced the process of iteratively stress-testing candidate decisions using exploratory modeling. RDM starts from an initial set of policy options. Many Objective Robust Decision Making (MORDM) replaces this with searching for promising policy options using many-objective evolutionary algorithms (MOEA) in a single reference scenario (Kasprzyk et al., 2013). Multi-scenario MORDM expands on this by repeating the search for several alternative future states of the world (Watson and Kasprzyk, 2017). These alternative future states are selected to represent challenging conditions for the solutions found for the initial reference scenario (Eker and Kwakkel, 2018). Many Objective Robust Optimization (MORO) takes this idea one step further, still by shifting from searching for Pareto optimal policies in one or more reference scenarios to searching for Pareto optimal robust policies across a larger ensemble of scenarios (Hamarat et al., 2014; Kwakkel et al., 2015; Trindade et al., 2017). Multi-scenario multi-objective robust optimization enables the consideration of optimality in individual scenarios while also retaining robust performance over many scenarios (Shavazipour et al. (2021)).

The various decision-making under deep uncertainty methods all focus on improving the robustness of the candidate policies. But precisely what is meant by robustness? Loosely speaking, robustness is a metric that summarizes how well a policy is performing over a set of exogenous scenarios. More specifically, robustness metrics can be categorized into regret metrics and satisficing metrics (Lempert and Collins, 2007). Regret describes the difference between the performance of a policy option in a specific state of the world and the performance of the best possible option in that same state. Satisficing aims at maximizing the number of states in which a policy option meets a minimum performance threshold (Kwakkel and Haasnoot, 2019).

### 2.3. MERITS AND SHORTCOMINGS OF DMDU FOR WICKED PROBLEMS

In this section, we analyse to what extent the key ideas of DMDU and the methods rooted in them address the ten characteristics of wicked problems (Rittel and Webber, 1973). For each characteristic, we discuss DMDU methods and ideas that touch upon it to uncover shortcomings of DMDU in addressing wicked problems. In light of this, we identify three overarching shortcomings.

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#### 2.3.1. TO WHAT EXTENT DOES DMDU ADDRESS THE WICKED PROBLEM CHARACTERISTICS?

First, for wicked problems, there is no definitive problem formulation. The information needed to understand a problem depends on ideas for solving it. To fully describe the problem, one would need all conceivable solutions ahead of time. So, formulating the problem is a problem in itself since how the problem is formulated frames the direction of the solution (Rittel and Webber, 1973). In classical decision theory, the problem formulation is designed to conform to the chosen modeling approach (Tsoukiàs, 2008). The chosen approach will affect the predictions of the consequences of alternative solutions and thus also which solutions are considered optimal (Quinn et al., 2017). There are three similar approaches from the DMDU literature relevant here. All three employ multiple analyses in parallel to accommodate multiple problem framings. The first approach is rival framings which allows for exploring multiple alternative problem formulations and the formulation's impact on the outcomes of interest (Quinn et al., 2017). The second approach is using parallel RDM analyses, each reflecting a different worldview. The goal is to identify solutions that are robust to different stakeholder values and beliefs about the nature of the problem and acceptable solutions (Lempert and Turner, 2021). The third approach is the Perspectives method (Haasnoot et al., 2011, 2012). Perspectives are perceptual screens through which people interpret the world and that guide actions. Applied to deep uncertainty analyses, the uncertainties, impacts, and policies get mapped onto each perspective. Both worldviews and perspectives use scenario-style thinking to reflect plausible alternative ways in which stakeholders might view the world.

Second, for wicked problems, there is no stopping rule. There are no criteria for a sufficient understanding of the problem, no ends to causal chains, and there could always be a better solution to the problem. Work is usually terminated for external reasons like budget and project time constraints (Rittel and Webber, 1973). While projects still have to stop at some point, DMDU methods can help create a plan that performs well in the longer term. For example, dynamic adaptive policy pathways (Haasnoot et al., 2013) conceptualizes an adaptive plan as a sequence of short-term decisions towards long-term goals. Should critical conditions occur under which the current plan does not hold, it is possible to make new decisions. Low-regret options are also very suitable to deal with this non-stopping rule. Regret here is taken to mean the difference between a policy's performance in a specific state of the world and the performance of the best possible option in that state

of the world. A low-regret option minimizes the maximum regret across the states of the world (Kwakkel and Haasnoot, 2019). For the non-stopping rule this means that even if the project has to stop at some point, we have found policies that perform reasonably well for many ways that the future may unfold after the formal project duration has stopped.

Third, in resolving wicked problems, solutions are not true or false, but good or bad (Rittel and Webber, 1973). DMDU adheres to this idea in two ways. The first way is the emphasis on the idea of robust satisficing. That is, in the face of uncertainty, decision makers should look for solutions that perform well enough across a wide range of possible futures, typically using a variety of different robustness metrics (McPhail et al., 2018). This enables the various parties to deliberate policies and assess which policies are ‘better or worse’, or ‘good enough’. The second way DMDU addresses this characteristic is through the analysis of trade-offs. With the introduction of the MORDM-framework, there has been a strong insistence in the DMDU literature on moving from the *a priori* imposition of a single measure of goodness, to an *a posteriori* analysis of trade-offs across a wider range of relevant outcomes of interest. This makes the value discussion explicit.

Fourth, there is no immediate and ultimate test of a solution to a wicked problem. Wicked problems and any solutions have consequences over an extended, possibly unbounded, period of time. It is, therefore, impossible to understand the full consequences on all affected lives ahead of time or within a certain period (Rittel and Webber, 1973). While one can never know if all solutions and their consequences are being considered, exploratory modeling enables us to consider many policies and their effects on the system. This does not fully address the issue of repercussions over an unbounded period of time, but does move beyond established scenario planning approaches. In addition, adaptive planning enables one to react to changes and repercussions in the system, and provides a process for dealing with long timescales and unintended consequences through adaptivity, monitoring, and reassessment.

Fifth, every policy implemented to combat wicked problems is consequential and leaves a trace that cannot be undone. Therefore, there is no place for trial-and-error (Rittel and Webber, 1973). This property plays a significant role in the DMDU literature. Because of the high-stakes nature of decisions for wicked problems, robust decision-making emphasizes extensive iterative stress testing of candidate decisions. This stress testing, or scenario discovery, aims to reduce the scenarios under which undesirable outcomes occur as much as possible. Moreover, by expanding the number of scenarios that are being considered, and thus expanding also the number of uncertainties that are considered jointly, robust decision-making helps expand the scope of futures that is being considered instead of prematurely narrowing this down to either, e.g., a high, low and business-as-usual scenario, or a premature focus on scenarios that are deemed most likely. The experiment of Gong et al. (2017) suggests that using (model-based) scenarios rather than forecasts to communicate uncertainty can encourage the choice of robust strategies. It is important to consider how choosing one course of action might exclude others. Besides this, the importance of path dependency, lock-in and lock-out for

### 2.3. MERITS AND SHORTCOMINGS OF DMDU FOR WICKED PROBLEMS

planning was a key motivation for developing dynamic adaptive policy pathways. Adaptive planning can help to make path dependency and lock-ins more transparent (Kwakkel et al., 2016b). Thus, DMDU provides tools to mitigate the risks of harmful consequences.

Sixth, there is no exhaustive set of potential solutions or permissible operations. With ill-defined problems and hence ill-definable solutions, the set of feasible policies relies on judgment, trust, and credibility (Rittel and Webber, 1973). In RDM, the status quo is part of the analysis. Different courses of action are compared to the status quo, focusing on finding Pareto-improving moves instead of trying to find the true optimal solution, which might not exist or exist beyond the analyzed solution space. For example, scenario discovery in RDM reveals vulnerabilities of candidate policies which can inform judgment on feasibility. Likewise, considering many objectives explicitly and simultaneously in MORDM can aid planners in avoiding inadvertently ignoring aspects of the problem by focusing on pre-specified alternatives or a narrow definition of what is considered optimal (Kasprzyk et al., 2013). Based on an initial set of promising solutions, a many-objective optimization can be performed for a reference scenario. This is not necessarily to find the best solution but to start the process of iterative stress testing and learning in search for feasible policies.

Seventh, Rittel and Webber (1973) argue that every wicked problem is unique and, therefore, it is important not to select a solution prematurely. Despite two problems seeming similar, it is never guaranteed that particularities do not invalidate commonalities. For example, applying the same mobility policies from one city to a similarly sized city might seem feasible, however differences in travel patterns or land use might outweigh similarities in city size, street layout, and public transport network. DMDU is a problem-solving approach and therefore does not have specific solutions for classes of problems. Still, DMDU is vulnerable to this pitfall, owing to its origin. DMDU is predominantly applied in the water domain in the USA and the Netherlands (Stanton and Roelich, 2021), and as such, DMDU techniques exhibit inherent traces of these contexts. For example, the adaptation pathway approach originated in the Netherlands which has a history of close to 1000 years of consorted action in water management. Institutional stability, necessary for following pathways and executing adaptive plans is thus taken as a given. Countries where such institutional stability cannot be assumed might therefore struggle in successfully applying this approach.

Eighth, every wicked problem can be considered the symptom of another problem. There will be links to other problems, and problems should be settled on a high level (Rittel and Webber, 1973). This property is closely related the first two properties (*i.e.*, no definitive problem formulation and no stopping rule). Therefore, ideas from the DMDU literature on multiple problem framings, adaptive planning, and low-regret solutions are also relevant here. Moreover, a fundamental idea of DMDU is that the aim of decision support is to aid learning by the analysts and the various parties to a decision, rather than dictate a solution. This learning also includes learning about various ways of framing the problem and their implications for the kinds of solutions that then are promising.

Ninth, when describing problems as discrepancies between the current state and the ideal state of the world, this discrepancy can be explained in numerous ways. The explanation is highly dependent on world views and attitudes, which in turn determine the nature of the resolution (Rittel and Webber, 1973). Models are descriptions of how people believe a system is functioning. Hence, a model is a theory (Lane, 2000a), that encompasses the world views and attitudes that determine the resolution (c.f. Hoekstra, 1998). Using multiple structurally quite different models is a logical extension of the idea of rival framings (Quinn et al., 2017), that has been used by a few researchers (e.g., Cuppen et al., 2021; Pruyt and Kwakkel, 2014). One can search for solutions conditional on the model and re-evaluate these solutions in other models to understand how dependent the efficacy of solutions is on the underlying model (Pruyt and Kwakkel, 2014). Still, this requires sufficient similarity between the models for evaluating given interventions in all of them.

Tenth and last, planners are liable for consequences they generate. While scientists can pose hypotheses that might be refuted later without blaming the scientist, planners have no right to be wrong (Rittel and Webber, 1973). This strong emphasis on avoiding bad outcomes aligns with two ideas in the DMDU literature. First, the iterative stress testing intrinsic in RDM and its variants focuses exactly on identifying the conditions under which undesirable outcomes occur and next changing the policies under consideration in light of this. Second, the focus on robustness and specifically the minimization of regret offers an answer to this characteristic.

In conclusion, the nature of DMDU lends itself well to many aspects of wicked problems. DMDU provides the possibility for an extensive analysis of a problem through the inclusion of multiple problem framings, many policies, a wide range of possible futures and outcomes of interest, and by considering many objectives simultaneously. Further, harmful consequences can be minimized through low regret solutions and adaptability built into the plans. Nevertheless, we also uncovered several shortcomings of DMDU.

### 2.3.2. SHORTCOMINGS OF DMDU

DMDU falls short in three ways when dealing with wicked problems: the focus on the analytical techniques, a lack of attention for the sense-making and guidance for interpreting analytical artifacts with the various parties to a decision, and no attention for how to come to a decision.

The first shortcoming is the focus on analytical sophistication in response to the challenges posed by wicked problems. For example, in response to the challenge of not having a clear problem formulation, DMDU offers analytical techniques for exploring multiple framings. However, this still presupposes the availability of such framings and no guidance is offered on how to arrive at these. Moreover, it assumes that the legitimacy of any frame is not questioned. The elicitation, quantification, and comparison of actual stakeholder views is relevant here and arguably will improve the analysis, yet this has not received much attention in the DMDU literature. Likewise, when using RDM or its variants, the solution space needs to be

## 2.4. PARTICIPATION

closed down which might unintentionally exclude solutions that are acceptable to stakeholders. True, the iterative nature of RDM offers an entry point for addressing this by exploring different problem frames until a framing is found where the resulting solutions are acceptable to stakeholders.

The second shortcoming relates to sense-making and the interpretation of analytical artifacts. For example, in discussing the third characteristic, we highlighted how DMDU focuses on multi-objective trade-offs, but the question remains of how to deliberate given these trade-offs. Moreover, it remains a challenge to facilitate learning among stakeholders about their interpretation of the situation, preferences, levels of acceptable performance, and which consequences must be avoided at all cost. In addition, numbers have a power that non-quantitative arguments lack in current discourse, therefore the playing field needs to be leveled between models and other non-modeled considerations. When DMDU is well applied, it is a form of quantitative storytelling (Saltelli and Giampietro, 2017). To complement it, qualitative storytelling should be elevated to a level where it can have the same impact.

The third shortcoming concerns coming to a decision. Ultimately, one or more policies need to be chosen for implementation. The sixth characteristic relates to trust and transparency, which is known to be essential to let decision-making proceed in the face of wicked problems (Harper et al., 2021). To be confident in the chosen policy, there needs to be trust in the models and outcomes, which might not happen if the decision-makers do not understand the models and results. Further, many parties are equipped, interested, or entitled to judge the solutions, yet none can determine correctness. Judgments are likely to differ based on interests and values of that group. So far, there is not much consideration for conflicting attitudes and values that might guide the decisions.

A common thread running through these shortcomings is the need to enable parties to a decision to collectively deliberate. Therefore, the next section introduces participatory modeling.

## 2.4. PARTICIPATION

Participatory modeling is an established approach for dealing with wicked problems (Voinov et al., 2018; Mingers, 2011). The overall goal typically is to establish ownership and relevance for the stakeholders, create agency to act, and make use of local knowledge. It is generally agreed that decisions can be implemented with less conflict and more success if they are driven by stakeholders (Nutt, 2008; Voinov and Bousquet, 2010) and consider values explicitly (Keeney, 2004). Modeling with stakeholders can allow for the integration of scientific information and local knowledge. Further, it has the potential to enable participants to gain a deeper understanding of the complexity of the system under study, to increase their agreement about causes, and to gain an appreciation of the uncertainties (Cockerill et al., 2009). In order to enable stakeholders to feel a sense of ownership or even have a mandate to act, a high level of participation is required (Basco-Carrera et al., 2017; Franco and Montibeller, 2010).

### 2.4.1. DMDU STUDIES WITH PARTICIPATORY ELEMENTS

While we identified some efforts to include participants in DMDU, no general approach is documented. From the literature, we see that participation mainly happens in problem framing, for knowledge input, and to gain consensus on the final plan. In most of the studies, what was done or which methods were used is not clearly reported. Although the participatory method might not have been the focus or purpose of a study, it would be useful to have clearer reporting of methods that were used to enable other researchers or practitioners to conduct similar processes.

Participants were mainly involved at the beginning and end of a project. At the beginning of projects, participants gave input for the problem framing and conceptualization of the model (Linnerooth-Bayer, 2021; Bhave et al., 2018; Johnson, 2021; Bojórquez-Tapia et al., 2021a,b; Taner et al., 2019; Gamas et al., 2015). Further, participants were included in creating scenarios (Taner et al., 2019; Gamas et al., 2015) and exploring results (Johnson, 2021; Malekpour et al., 2016). Towards the end of a project, participants contributed to the design of a strategy or plan (Linnerooth-Bayer, 2021; Bhave et al., 2018; Johnson, 2021; Lawrence et al., 2019).

All of the studies conducted workshops to engage stakeholders, some with interviews to gather additional information (Linnerooth-Bayer, 2021; Bojórquez-Tapia et al., 2021a; Gamas et al., 2015). In most cases, the goals and outcomes of the process were reported (Bhave et al., 2018; Johnson, 2021; Taner et al., 2019), some studies also describe broad steps taken within the workshops (Lawrence et al., 2019; Bojórquez-Tapia et al., 2021a,b; Gamas et al., 2015). Only two studies report detailed activities that would allow others to conduct a similar process (Linnerooth-Bayer, 2021; Malekpour et al., 2016). It remains, however, unclear in all studies how they facilitated discussions, dealt with conflicting opinions and power structures, or how the role of the participants influenced the outcome and implementation.

### 2.4.2. SUITABLE METHODS FOR PARTICIPATION

There are numerous approaches, types, tools, methods, and evaluation frameworks for modeling with stakeholders (Voinov and Bousquet, 2010; Voinov et al., 2018; Franco and Montibeller, 2010). These studies consider a number of different modeling paradigms and participation methods.

For DMDU specifically, the participatory methods need to be able to deal with high problem complexity and with high problem uncertainty. We can only provide a general selection of methods since the final choice is highly dependent on the context, such as the aim of the study, available resources, or stakeholder characteristics. Methods need to be chosen carefully as small changes in the procedure (or the software used) can result in a completely different process (Rouwette and Franco, 2021).

To propose methods among various categories that are promising for facilitating participatory DMDU, we use the typology by Franco and Montibeller (2010) for problem structuring and decision analysis, and Voinov et al. (2018) for fact-

## 2.5. GENERIC STRUCTURE OF A PARTICIPATORY DMDU PROCESS

finding, as well as qualitative, semi-quantitative and quantitative modeling. Facilitated problem structuring comprises a set of modeling methods that assume different views about the world and use limited quantification. Facilitated decision analysis encompasses methods that help modeling decisions that involve multiple objectives and uncertainty of outcomes (Franco and Montibeller, 2010). Fact-finding focuses on identifying, generating, and communicating relevant data, information, and knowledge. This stage may be relevant throughout a participatory process. In qualitative modeling, participants create conceptual, visual representations of the problem components and their relationships. Modeling methods are considered semi-quantitative if they employ some numerical analyses of the values in the model, but the values themselves are likely to be qualitative. Quantitative modeling methods use formulas and equations and make calculations based on empirical or hypothetical data (Voinov et al., 2018). Below we provide a number of illustrative examples for each category that are suitable to be used within a DMDU analysis.

**Problem structuring:** Strategic Options Development and Analysis, Soft Systems Methodology, Strategic Choice Approach, Dialogue Mapping Approach

**Fact finding:** Interviews, Surveys, Crowdsourcing

**Qualitative modeling:** Rich pictures, Cognitive/concept mapping, Causal loop diagrams, Cultural consensus, Decision-tree analysis

**Semi-quantitative modeling:** Fuzzy cognitive mapping, Social network analysis, Scenario building, Analytic hierarchy process

**Quantitative modeling:** Cost-benefit and other economic analyses, System Dynamics, Bayesian Networks, Agent-based modeling, Integrated Modeling

**Decision analysis:** Multi-criteria decision analysis, Decision trees and simulation, Multi-criteria portfolio analysis

## 2.5. GENERIC STRUCTURE OF A PARTICIPATORY DMDU PROCESS

Approaches for decision-making under deep uncertainty generally include a generic set of elements (Marchau et al., 2019b). These elements are part of a process with three general steps: frame, explore, and choose. The elements do not follow a strict order, and emphasis is put on different elements, depending on the application context.

The first step is to frame the analysis by formulating the problem, and specifying the system structure and its boundaries, objectives and goals, outcome indicators, and policies. The second step is to explore the uncertainties or disagreements about external forces, the system structure, outcome indicators, and valuations of outcomes. Models or expert opinions can be used to investigate the effects of different policies and their vulnerabilities and opportunities in light of the uncertainties. The third step is to choose initial and contingent actions and plan for these actions. In addition to that, a plan to communicate, monitor, and adapt the policy is

defined. During a DMDU process, these three steps are iterated, and the outcomes reexamined (Marchau et al., 2019b).

We use this generic DMDU process as a guiding framework to identify how, when, and why to better integrate both qualitative and quantitative participatory methods with DMDU. Figure 2.1 provides an overview of the potential benefits of including stakeholders in each of the steps and the elements within them. These benefits might be for the participant (or client), or the researcher (or analyst or modeler), or both.

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### 2.5.1. FRAME

The framing step includes four elements, shown in the top part of Figure 2.1. The first element of framing is to formulate the problem. This includes establishing the context, and clarifying constraints on possible actions. This element, the problem formulation, can also be used to identify the people that will be involved in making the decision (decision makers), as well as people that will be affected by it (other stakeholders). Moreover, the practitioners need to choose an analytical approach to follow. This will depend on the context or question at hand, as well as the practitioners' expertise. A benefit of involving stakeholders in this element could be to elicit context-specific knowledge. Communicating the relevance of this problem to stakeholders can help to create ownership of the problem and agency. Involving stakeholders in deciding on the analytical approach could further strengthen their involvement in the process; however, informing them about the chosen approach may also suffice.

The second element of framing is to specify the system structure and the system boundaries. A process of iterative analysis determines the necessary modeling detail to inform decisions around the triggering issue. Given the system demarcation and system structuring, one or more system models can be conceptualized and specified for use in the later steps for examining policy alternatives. Stakeholders can offer context-specific knowledge, such as which parts of the system are most relevant, thus contributing to determining system structure and boundaries.

The third element of framing is to specify objectives and goals, and to identify measurable policy outcomes that are directly linked to the objectives and goals. Whether participants understand the range of objectives, which may or may not be shared by all, will positively affect how relevant they find the participatory DMDU process.

The fourth and final element of framing is to identify alternative policies or policy levers. By involving stakeholders, we can again use their knowledge and ideas. Participants can help identify what has been done in past and ongoing projects, what can be done in the future, and what policy levers are not feasible or desirable.

### 2.5.2. EXPLORE

The exploring step includes three elements, shown in the middle part of Figure 2.1. The first element of exploring is to specify uncertainties or disagreements about external forces, the system response to these external forces or policy changes, outcome indicators, and the relative importance of specific outcomes. Involving

## 2.5. GENERIC STRUCTURE OF A PARTICIPATORY DMDU PROCESS

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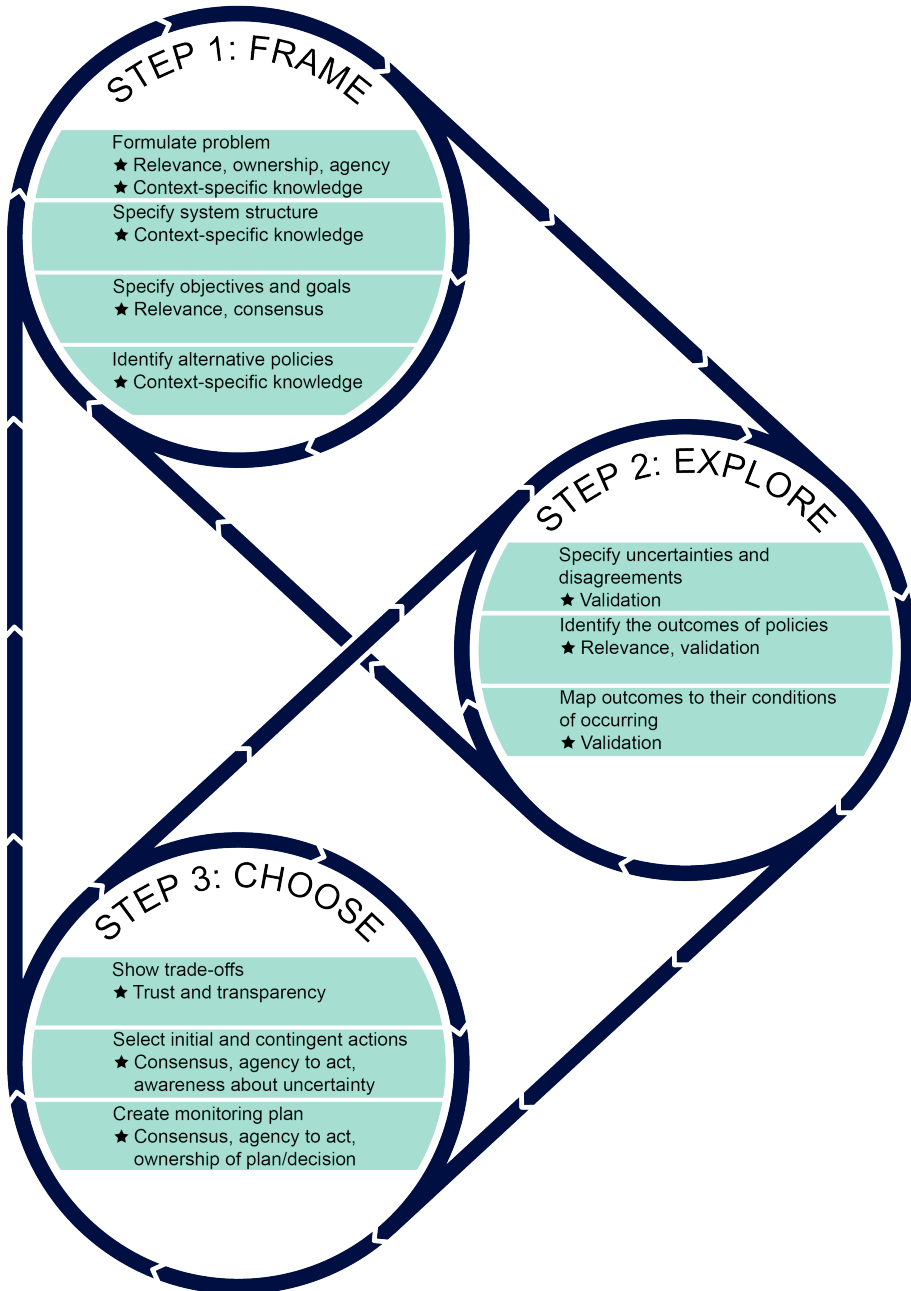


Figure 2.1: The three steps of a DMDU process, the elements within them, and the potential benefits of including stakeholders

stakeholders in specifying these uncertainties can help validate the model and determine which parameter values to explore.

The second element of exploring is to identify the outcomes of policies, their relative importance, and their vulnerabilities (as well as opportunities) given the uncertainties specified earlier. In this way, a broad range of assumptions and circumstances can be studied. Here, the relevance can be improved by identifying which assumptions, circumstances, and repercussions are most relevant to stakeholders.

Based on the RDM process (Lempert, 2019), we add a third element here. The third element is to map the outcomes back to their conditions of occurring (*i.e.*, Scenario Discovery). This process can also benefit from participation in order to learn about what this input-output mapping means in the real world. Stakeholder input can be used to validate whether the discovered vulnerabilities resonate with them.

### 2.5.3. CHOOSE

The choosing step includes three elements, shown in the lower part of Figure 2.1. The first element of choosing is showing which trade-offs were identified during the analysis, thus illustrating the short and long-term effects of policies. There are three levels of robustness trade-offs: trade-offs among objectives contingent on a specific scenario, persistence of trade-off patterns throughout different scenarios, and trade-offs between stakeholders. Differences between stakeholders should be explored, acknowledging that what might be robust for one stakeholder, may decrease the robustness of another (Herman et al., 2014). Participatory activities, such as educative workshops, can help to create transparency and trust in the model and the trade-offs.

The second element of choosing is to select a set of initial actions and contingent actions for future changes. Here, stakeholder engagement can help to build consensus, create awareness about uncertainties, and ultimately create agency to act and implement.

The third element of choosing is to create a plan for communicating, monitoring, and implementing possible policy adaptations. Engaging stakeholders in this step can help in creating a long-term, feasible plan that is possible to maintain within their organization.

## 2.6. CONCLUDING REMARKS

This paper explored the potential for explicitly integrating participation and decision-making under deep uncertainty for dealing with wicked problems. We analyzed how well the ten characteristics of wicked problems are typically addressed by DMDU and identified three shortcomings: the focus on the analytical techniques, a lack of attention for sense-making and guidance for interpreting analytical artifacts with the various parties to a decision, and no attention for how to come to a decision. These shortcomings indicate a necessity to enable decision-makers to deliberate with each other and with other stakeholders. To this end, the participatory DMDU process, as described in section 2.5, shows

## 2.6. CONCLUDING REMARKS

the potential benefit of participation for the outcome of each of the steps. In conclusion, we present four challenges in establishing a practice of participatory DMDU.

### 2.6.1. CONSIDERATIONS FOR SELECTING PARTICIPATORY PROJECTS AND PROJECT ELEMENTS

While our framework offers an overview of the potential benefit of engaging stakeholders throughout a DMDU process, guidance on selecting projects and project elements that can potentially benefit from participation is still lacking. Careful project selection is important because involving stakeholders is time- and resource-intensive. To illustrate the need for selection criteria, we hypothesize that stakeholder engagement's usefulness depends on the application domain and the system boundaries. Particularly, socio-technical systems exhibit wickedness. Participation can elicit human behavior influencing the system, as well as power dynamics, trust, conflicting values, negotiation, and (environmental) justice.

Additionally, asymmetry in observed costs and potential benefits may prevent practitioners from investing in participatory processes. Therefore, attention should go to comparing participatory and non-participatory DMDU practice, as well as exploring the full breadth of long-term project outcomes in light of the benefits identified in this study.

### 2.6.2. CONSIDERATIONS FOR DESIGNING PARTICIPATORY PROCESSES

The three shortcomings in section 2.3 highlight key considerations for designing DMDU processes that include stakeholders. First, such a process should allow for including aspects of the problem that typically are not solved with a model, but can be addressed with participatory modeling, for example, trust issues, power dynamics, stakeholder values, and negotiation. Second, such a process should be transparent on what the used models can and cannot deliver, and on how the results of the DMDU process may influence the wider decision-making arena. Third, such a process should allow for collectively interpreting and making sense of results with a heterogeneous group of stakeholders. Other ways stakeholder engagement can enrich participatory DMDU include opening up the solution space, validating the model(s), enriching qualitative storytelling, and eliciting conflicting attitudes.

### 2.6.3. DEVELOPING METHODS, SCRIPTS AND TOOLS

To stimulate the involvement of stakeholders, practitioners require concrete methods that are easy to replicate or adapt to specific contexts. Many methods that we presented in section 2.4.2 are open for interpretation when it comes to how to actually apply them. Therefore we call for researchers and practitioners to develop and document methods, scripts, and tools for participatory DMDU in a transparent manner.

We note that this call is associated with the risk of creating even more methods separately and tailored to specific cases. These separate methods would lead

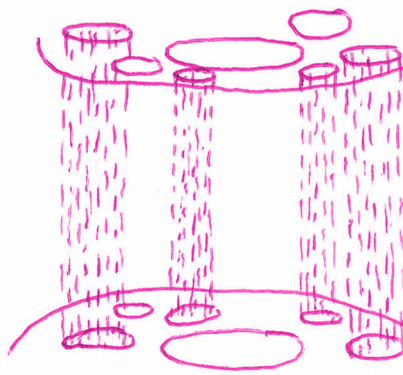
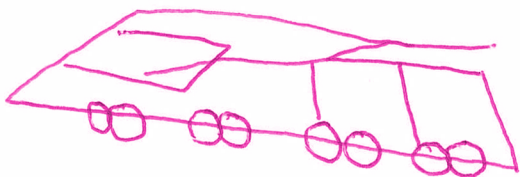
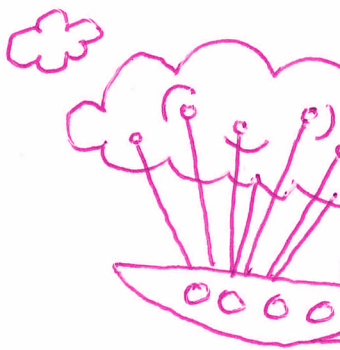
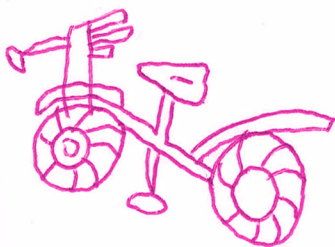
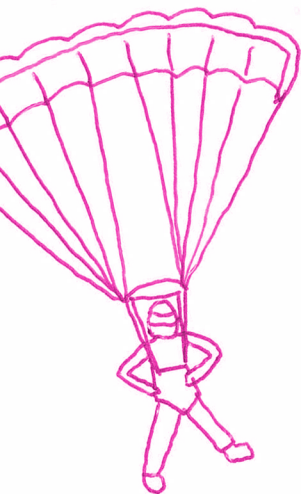
to practitioners needing to unpack them and identify which elements are transferable and applicable to their particular case. Rather than arguing for a specific approach, it would be useful to combine tools in light of the particular problem situation (Kwakkel and Haasnoot, 2019). Experienced practitioners are quite comfortable with combining (elements of) different existing practices once they are familiar with the available options (e.g., Fu et al., 2020). This is a positive development which can help make methods to address uncertainty more available to a wider audience. In light of this, developing transferable training materials and courses is vital.

Good examples of well-documented methods are Group Model Building Scripts which provide step-by-step instructions for a variety of techniques (Hovmand et al., 2012), and ‘thinkLets’, which are small repeatable patterns of interaction for collaborative processes (Briggs et al., 2001). Additionally, facilitation intervention patterns can help to deal with problems arising from the social aspects of collaboration (Alabdulkarim and Macaulay, 2007).

#### 2.6.4. STRUCTURED EVALUATION

Evaluation of participatory DMDU processes allows for establishing best practices and learning in which situations participation adds value and is worth the investment of time and resources. Currently, an evaluation framework for participatory DMDU does not exist. There are, however, examples to draw on from the fields of facilitated modeling (Franco and Rouwette, 2022; Rouwette, 2016) and participatory planning (Hassenforder et al., 2016). We propose that such a framework could include an assessment of the suitability of the problem scope, the impact of participation on the quality of the analysis, implementation success, stakeholder satisfaction, and other potential benefits. Structured evaluation aids in distilling lessons from cross-comparing participatory DMDU projects in varying contexts and, as such, will inform the design of future participatory DMDU activities.





# 3

## MODELING WITH A MUNICIPALITY: EXPLORING ROBUST POLICIES TO FOSTER CLIMATE-NEUTRAL MOBILITY

The previous chapter laid out the benefits and challenges of participatory DMDU. This chapter is the first case study in response to that research agenda. Based on the general structure of a DMDU process from the previous chapter, we carry out the first two steps, Frame and Explore, in a participatory manner with municipal workers from The Hague, the Netherlands. We designed a workshop to frame the problem, create a shared system understanding, and generate possible interventions that were qualitatively stress-tested under different futures. This chapter lays out the workshop design and results and discusses its effects. Additional materials such as the workshop structure and materials can be found in Appendix A.

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*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.*

### 3.1. 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), 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., 2021b; 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 sec-

## 3.2. PARTICIPATORY MODELING UNDER (DEEP) UNCERTAINTY

tion 5.2. Following this, we describe our research design, the model we used, and the case study in section 5.3. We conclude by discussing the process, the outcomes, and implications for policy-making and future research in section 5.5.

## 3.2. 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., 2010b), 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.

### 3.3. 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.

### 3.3. RESEARCH DESIGN

#### 3.3.1. 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.

#### 3.3.2. 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.

### 3.3.3. 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 The Hague, 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.

### 3.3.4. 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., 2025). 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

### 3.3. RESEARCH DESIGN

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, 2000b). 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,

### 3.4. INTERPRETATION OF RESULTS

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).

#### 3.3.5. 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.

### 3.4. 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.

### 3.4.1. 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.

#### 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

#### 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.

### 3.4. INTERPRETATION OF RESULTS

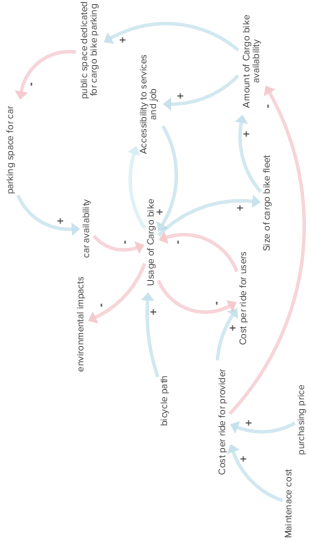


Figure 3.1: Causal Loop Diagram on car use created by the whole group

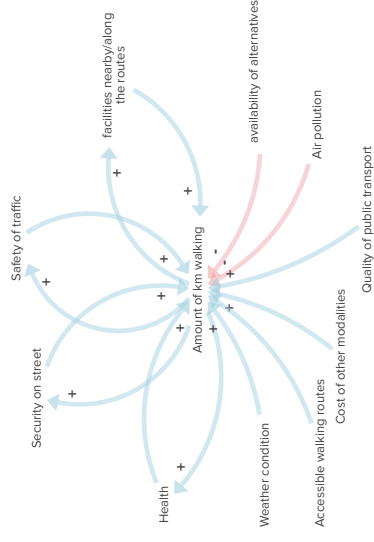
#### CAUSAL LOOP DIAGRAMS

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 Figure 3.1. Participants were then split into groups. The results from the four small groups can be found in Figure 3.2. 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 (Figure 3.3).

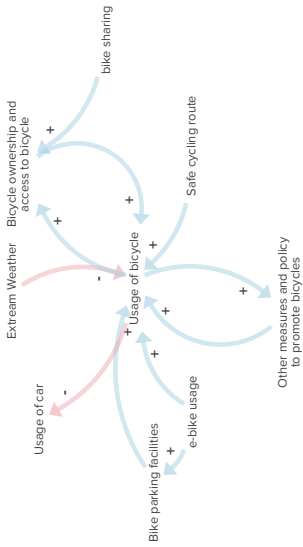
### 3. MODELING WITH A MUNICIPALITY



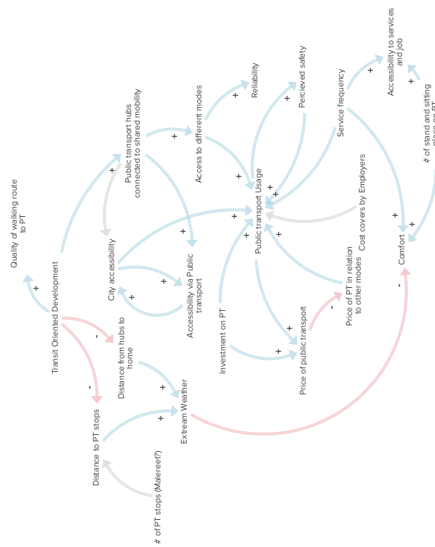
(b) Cargo-bike



(d) Walking



(a) Bicycle



(c) Public transport

Figure 3.2: Causal Loop Diagrams created in the small groups

### 3.4. INTERPRETATION OF RESULTS

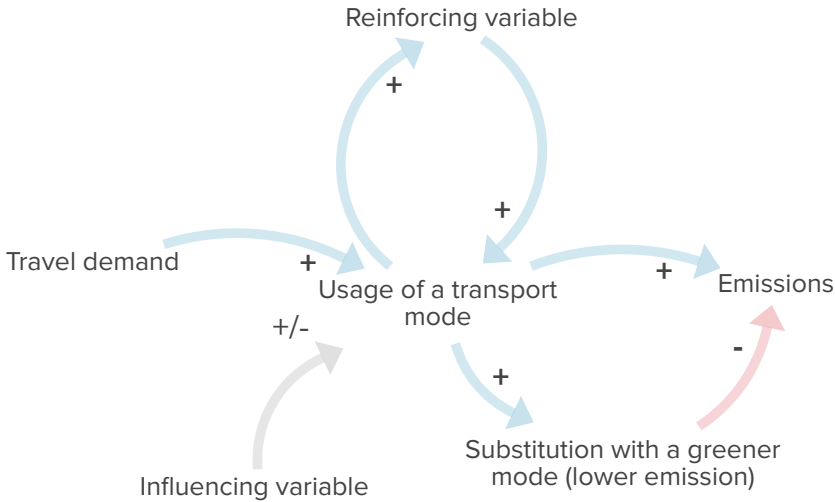


Figure 3.3: Causal Loop Diagram summarizing the key insight

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.

#### 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 3.1). 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.

### FUTURE EVENTS AND TRENDS

The fifth outcome is a wide selection of possible future events and trends that can influence the project (Table 3.2). 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.

### 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 3.2) 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 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 3.3.

#### 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

### 3.4. INTERPRETATION OF RESULTS

3

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**Public transport**

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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

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**Walk, bike, and cargo-bike**

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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**

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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

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**Electric car**

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Every street has a shared electric car

Automatic limit speed of electric vehicles (city center, Scheveningen area, around schools)

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Table 3.1: Interventions for each transport mode

<b>Social</b>
<p>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</p>
<b>Technological</b>
<p>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</p>
<b>Environmental</b>
<p>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</p>
<b>Economic</b>
<p>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</p>
<b>Political</b>
<p>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)</p>

Table 3.2: Potential futures identified with the help of the STEEP framework

### 3.4. INTERPRETATION OF RESULTS

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 level 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

Table 3.3: Robustness evaluation for the intervention ‘Free public transport’

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.

### 3.5. 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.

#### 3.5.1. 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

### 3.5. DISCUSSION AND CONCLUSION

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.

#### 3.5.2. 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.

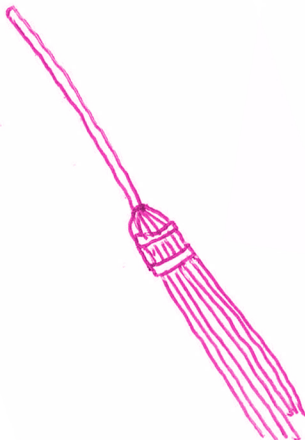
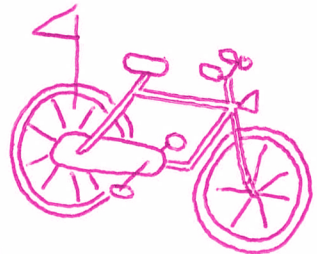
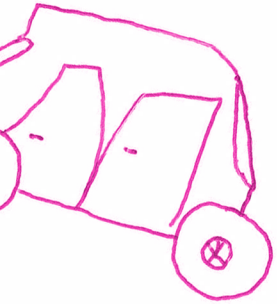
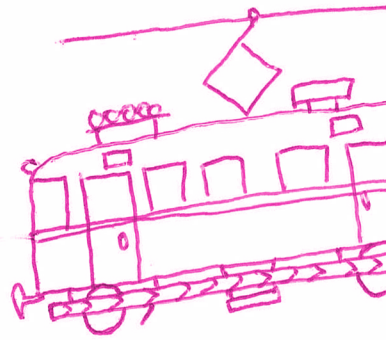
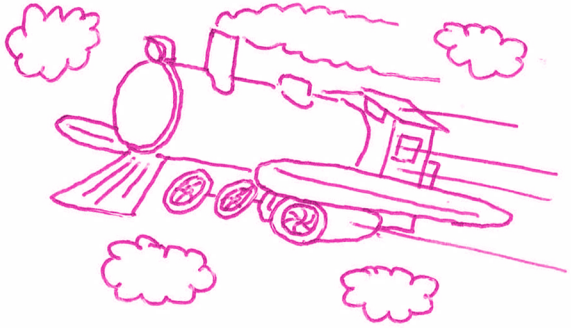
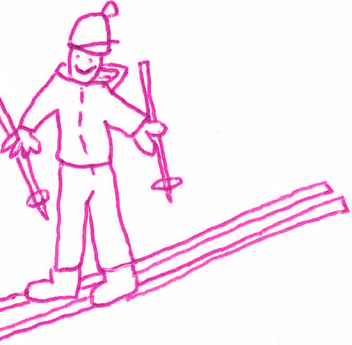
The second challenge arising from the translation to decision-makers is the difference in risk perception and accountability. While students may generate ideas without real-world constraints and feel free to choose policies, decision-makers must consider legal, financial, and political risks. These higher 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.

### 3.5.3. 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.





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# 4

## MODELING A TRANSPORT SYSTEM IN TRANSITION: A CASE STUDY FROM THE HAGUE

The previous chapter qualitatively addressed the first two steps of the DMDU process (Frame and Explore). We aim to build on this in two ways: first, to address the last step of the DMDU analysis (Choose), and second, to incorporate a quantitative analysis since these kinds of analyses are at the heart of the DMDU literature. To do this, we developed an agent-based transitions model that can later be used in participatory workshops. In this way, all three steps will be addressed, and this research complements existing studies. This chapter describes the model and its underlying framework before discussing the results and the model's limitations.

*Decision-making in the context of the mobility transition requires considering a complex system with many actors and uncertainty about the future. Although there have been efforts to model mobility transitions, these tend to focus on individual innovations. There is, however, a need to consider the whole transport system, including the introduction of innovations, endogenous interactions between transport modes, and a wide range of policies. This paper presents a high-level agent-based model designed for participatory use in exploring transport transitions. Building on the Actor-Option framework, the model represents competition between different transport modes and allows the inclusion of new technologies as additional options. We used the agent-based model to explore sustainable mobility transitions for the city of The Hague in the Netherlands and identify three key insights. First, the introduction of an innovation can reduce the share of unsustainable modes (e.g., cars), but may also unintentionally lower the share of sustainable modes (e.g., bikes). Second, the simulation of multiple policies simultaneously revealed symbiotic effects of the policies. Third, adding a parking fee to all car trips emerges as the intervention with the strongest impact on the modal split. We also find that uncertainties, particularly regarding social networks, exert greater influence when modal shifts are more pronounced. By balancing simplicity and explanatory power, the model provides decision-makers with a tool to explore transition dynamics, assess uncertainties, and identify promising policy directions.*

### 4.1. INTRODUCTION

Many cities aim to steer their transport system towards more sustainable functioning. The basis of our understanding of transformation in systems is provided by transition studies, which offer frameworks to analyze the system in transition and ultimately steer it toward more desirable functioning. A transition is a gradual, continuous process of structural change within a society or culture (Rotmans et al., 2001), profoundly altering the system's functioning (de Haan, 2010). Transitions are highly complex processes with non-linear interactions between actors with a high degree of uncertainty in the development of external conditions, system interactions, and unfolding of final outcomes (Köhler et al., 2018). Decision-making in this context requires dealing with a complex system, many actors, and uncertainty about the future and the system itself.

To support decision-making for transitions, transitions modeling has emerged in recent years (Halbe et al., 2015; Holtz et al., 2015; Köhler et al., 2018). Uncertain, complex systems reveal the limitations of human reasoning through mental models (e.g., Sterman, 1989; Brehmer, 1992; Diehl and Sterman, 1995; Atkins et al., 2002). Mental models are event-based, have an open-loop view of causality, ignore feedback, do not account for time delays, and are insensitive to non-linearity (Sterman, 1994; Schaffernicht, 2019). Thus, mental simulation of complex systems is challenging to the point of being infeasible. Dynamic models are helpful to understand and explore emergent phenomena that result from the interactions between parts of the system, thus aiding human reasoning (Holtz et al., 2015).

Efforts have been made to model transitions in various domains (Köhler et al., 2018; Moallemi and de Haan, 2020), including transport. These transport studies have a strong technology focus and often investigate the development of a single innovation, such as electric vehicles (Hoekstra and Hogeveen, 2017; Zolfagharian et al., 2020), hydrogen cars (Köhler et al., 2010), or alternative fuel vehicles in general (Kwon, 2012). However, recent mobility phenomena such as Mobility-as-a-Service, ride-hailing services, or micro-mobility sharing combine novel ICT technologies and novel or existing transport technologies. Additionally, only a few models have explicitly dealt with the uncertainty of transitions (Moallemi and Köhler, 2019). So, a recent review of agent-based mobility transition models (Mehdizadeh et al., 2022) calls for theory-driven and validated models that consider multiple transitions simultaneously and combine various policies. Therefore, theory-based models of the whole transport system are needed, which simulate social interactions, endogenous interactions between transport modes, and the emergence of innovations, and are suitable for exploring a wide range of policies under uncertainty.

This paper presents an agent-based model based on the Actor-Option framework (Yücel, 2010) to address this need for a new integrated model of transport transitions. The Actor-Option framework is a generic transition modeling framework that conceptualizes change as a result of actor decisions. The main components of the framework are actors, options, and mechanisms of change. For the mobility transition, we identify four types of actors: users, providers, regulators, and opinion groups. Options are possible ways to fulfill the function of a socio-

technical system, so in this case, options are the transport modes available in the system. One technology can serve several modes, depending on how it is used. Each option possesses a set of economic, technical, and social attributes. The actors use these attributes to assess the options and inform their decisions. Aspects of the transport system, such as infrastructure and operational schemes, can be described through option properties. Actors, as well as options, undergo change during the transition process. There are three sets of mechanisms of change: the first is related to the dynamics of the options (e.g., economies of scale), the second is related to the actor's perceptions (i.e., learning mechanisms, such as word of mouth), and the third is about the behavioral identity of the actors (e.g., changes in preferences) (Yücel, 2014).

4

Drawing on the Actor-Option framework, we conceptualize the mobility transition and implement this conceptualization as an agent-based model. We apply this model to a case study for the city of The Hague, the Netherlands. We use the model to explore the impact on the modal split of various policy options considered by the municipality. We consider various key uncertainties affecting user choice behavior by applying Exploratory Modeling (Bankes, 1993; Bankes et al., 2013). Exploratory Modeling allows us to systematically test different assumptions to observe a wide range of possible outcomes and learn about system behavior.

The model is deliberately kept at a high level of abstraction rather than fully representing the full transport system in detail. The model is designed to be used in participatory settings with policymakers and other stakeholders. The purpose is to explore uncertainties, dynamics, and potential implications of different mobility policies, rather than providing precise forecasts. The model supports choosing policy directions that merit deeper investigation as opposed to replacing detailed traffic or land-use models. This scoping choice allows the model to serve as a boundary object (Cuppen et al., 2021), facilitating discussion and reflection among stakeholders, while leaving detailed assessment to later, more specialized analyses.

We identify three main insights. First, introducing an innovation impacts the modal share of various transport modes. While it can reduce the share of modes negatively affecting sustainability, it may also reduce the share of sustainable transport modes. Second, introducing multiple policies at once revealed symbiotic effects of the policies. Third, parking fees emerge as a strong intervention that influences mode choice significantly. For this policy, we also observe that the key uncertainties considered in this study have a larger impact if the changes in the modal share are more significant. In addition, we analyzed various uncertainties. The uncertainties surrounding the social network of individual agents have the strongest impact on overall results. The spread of information through the agent population is crucial for the success of an innovative mode.

The paper is structured as follows. First, we introduce the Actor-Option framework. Based on this framework, we describe the agent-based model we developed. Next, we present the results and discuss them before ending with a conclusion.

### 4.2. THE ACTOR-OPTION FRAMEWORK

The Actor-Option Framework provides the following building blocks: actors, options, and mechanisms. The Actor-Option Framework is a general conceptual framework suited for developing qualitative and quantitative models of socio-technical transitions (Yücel, 2014). It was developed based on an extensive literature study on large-scale socio-technical systems and innovation diffusion (Yücel, 2010). The framework has been used to model transitions in waste management (Yücel and Chiong Meza, 2008) and the electricity system (Yücel and van Daalen, 2012; Kwakkel and Yücel, 2012).

Yücel (2010) positions the Actor-Option framework as both an alternative and an addition to the existing frameworks and modeling attempts in transition studies. The abstraction level of the framework facilitates establishing empirical links with a specific real-world policy-making context. Moreover, the framework covers processes of internal changes of actors and options in the system rather than just depicting the system's state.

#### 4.2.1. ACTORS

An actor is a unit of analysis with goals, preferences, resources, and actions. An actor does not necessarily refer to an individual person (Yücel, 2014); an actor can also be an organization, government agency, firm, or pressure group. This broader understanding of what an actor is aligns well with the fact that transitions are multi-actor processes. Transitions are enacted by many actors with different characteristics and therefore involve many kinds of agency (Köhler et al., 2019).

Yücel (2014) identifies four main actor roles: the users who have a need and use available options, providers who provide the necessary means to fulfill that societal need, regulators who set regulations and rules, and opinion groups that can influence the way other actors behave. The actors differ in the decisions they make and the consequences of these decisions.

#### 4.2.2. OPTIONS

An option is a means to fulfill a societal need. In some cases, an option is a physical artifact or technology, but in most cases, it also incorporates how that artifact or technology is used. The options within the transport system are the different modes a user can utilize to fulfill their transport need. In the case of transport, one technology can serve several modes, depending on how it is used (e.g., private car and car sharing).

Each option possesses a set of economic, technical, and social attributes. The actors use these to assess the options and inform their decisions. These are based on variables used in transport choice modeling (Van Wee et al., 2013). In addition, some of their attributes might not be relevant for actors but are needed to assess the system's overall performance according to the transition-characterizing aspects (Yücel, 2010). Other aspects of the transport system, such as infrastructure and the operational scheme (e.g., the timetable of a train) of an option, can also be reflected in the option properties. For example, improving the infrastructure for

an option might shorten travel time or increase comfort.

### 4.2.3. MECHANISMS

Actors and options do not stay the same but undergo change during a transition process. The Actor-Option framework identifies three sets of mechanisms for change.

The first set of mechanisms describes how option properties can change. For these mechanisms, it needs to be specified which option properties can undergo change and how. For example, option properties may change through provider and regulator policies. A change in option properties alters the performance of an option during the choices being made by actors.

The second set of mechanisms is related to the actor's perceptions. Perception refers to an actor's perceived information. Therefore, these mechanisms explain how the information available to an actor changes. Individual learning refers to actors learning about the situation of the system or option availability and properties through observation or experience. Social learning describes the diffusion of information among the actors. And finally, actors can learn from external sources. This mechanism allows novel information to enter the system (Yücel, 2014).

The third set of mechanisms relates to an actor's behavioral identity and is more challenging to define. These mechanisms entail reference point formation and change, commitment formation, and preference structure change. An actor's behavioral identity is difficult to conceptualize because of the difficulty of empirically observing actors' internal decision processes (Yücel, 2010). Therefore, these mechanisms are not represented in this model.

Not all mechanisms are active for all actors and options when using the Actor-Option framework, depending on which ones are relevant for which parts of the system. A mechanism is considered active when it may alter an actor's behavior within the temporal scope of the analysis. A few key points need to be clarified before a mechanism can be activated. First, there needs to be a trigger. A trigger can be either a discrete switch or an external input, determining the strength of the mechanism. Second, the time scale or pace at which the mechanism operates must be specified. And finally, the consequences in the system must be specified (Yücel, 2010).

## 4.3. THE TRANSITIONS MODEL

Based on the conceptualization of the urban mobility system in transition grounded in the Actor-Option framework, we developed an agent-based model to explore the impact of various policies on the modal split. With policies, we mean actions that providers or regulators can take. After laying out the modeling choices and key assumptions, we describe the model. Then, we describe the experimental design of this study.

We use the model for a case study of The Hague in the Netherlands. The Hague is the third largest city in the Netherlands, with about 500 000 inhabitants, and is located close to the sea. The city has a well-developed public transport network,

### 4.3. THE TRANSITIONS MODEL

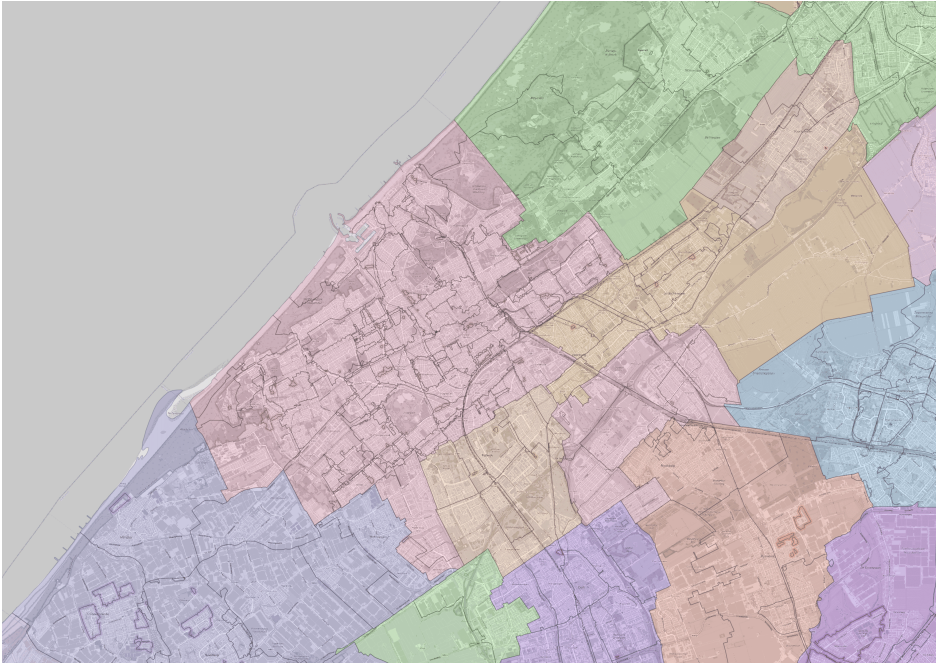


Figure 4.1: The city of the Hague (pink) and surrounding municipalities, adapted from OpenStreetMap

including trams, buses, and connections to the national rail system. As part of the Randstad metropolitan region, The Hague is closely connected to Rotterdam, Amsterdam, and Utrecht, forming one of Europe's most densely populated and economically significant urban areas. Figure 5.1 shows a city map. The map shows the different postcode areas. Different colors represent different municipalities.

Like many other European cities, the city of The Hague aims to become climate-neutral by 2030 (European Union, 2022). A central goal within this mission is to shift towards environmentally friendly transport modes while keeping mobility accessible and affordable for the city's citizens. We regard the modal split over time to investigate the shift from the current dominant modes to other modes.

#### 4.3.1. MODELING CHOICES AND KEY ASSUMPTIONS

The Actor-Option framework specifies four types of actors: users, providers, regulators, and opinion groups. Of these four, only users are endogenous to our model. We focus on the users since their decisions ultimately generate the modal split within the modes made available by the providers and regulators. The characteristics of users are based on mobility survey data (CBS, 2023). Conversely, provider and regulator decisions are used as exogenous input for policies. These choices allow us to use the model for different policy options and in participatory settings. Opinion groups are not represented in this model since they are out of the scope of this study.

We differentiate two sets of options: the base set and the experimental set. The base set represents the options currently present in the city. In our case, these are car, bike, e-bike, public transport, walk, scooter, and motorbike (CBS, 2023). The experimental set encompasses these seven modes and, in addition, an innovation. We decided not to differentiate between fossil-fueled cars and electric cars, as they do not differ in how they are used and the attributes associated with them. Fossil-fueled and electric cars differ in their emissions, but we do not make emission calculations in this study. The substitution of fossil-fueled cars by electric cars has been studied extensively (i.e., Zolfagharian et al., 2020; Jensen et al., 2017; Hoekstra and Hogeveen, 2017). We also do not differentiate between privately owned cars and carsharing since the currently available carsharing services in The Hague require the cars to be returned to their origin. Consequently, privately owned cars and shared cars are used similarly. Each transport mode has a starting cost, cost per kilometer, value of travel time, and comfort associated with it. The value of travel time is a way to express travel time in monetary terms (usually euros per hour) to indicate how much a traveler values a reduction in travel time. We chose these attributes, as they are commonly used in utility functions for mode choices (Van Wee et al., 2013).

We assume that users only re-evaluate the mode choice for habitual trips every few years. Short-term behavior, such as the daily mode choice, is habitual and rarely changes. Change occurs through mid- to long-term decisions that occur every few years (Van Wee et al., 2013). We implement this in our model by using event scheduling.

The two key mechanisms in this model are the change in option properties through policies and learning among users via their social networks. For the first mechanism, one or more policies are activated. Each policy alters an attribute of one or more transport modes. The change in option properties alters the performance of this transport mode during the mode choice, influencing the modal share of that mode over time. The second mechanism, peer-to-peer learning about new transport modes, causes changes in actors' perceptions and allows them to add new modes to their choice set. We assume that this knowledge enters the system through an external source and reaches a group of early adopters. These early adopters have this mode available to them, and, if they use the new mode, spread the knowledge through the social network.

The model does not represent broader systemic effects such as land-use changes, traffic congestion, or public transport reliability that may result from or influence modal shifts. These aspects are outside the scope to keep the focus on the core mechanism of interest: modal choices under uncertainty and social influence. Incorporating detailed traffic dynamics or land-use feedback would add substantial complexity, reducing the model's suitability for participatory use.

#### 4.3.2. 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 full description following the ODD proto-

### 4.3. THE TRANSITIONS MODEL

col (Grimm et al., 2020) can be found in Appendix A. The model is implemented in Python using the MESA library (version 3.2) for agent-based modeling (Masad and Kazil, 2015)<sup>1</sup>. One time step in the model represents three months. The time span covered by the model is 15 years. Therefore, the model runs for 60 time steps.

To account for the stochasticity in the model, we use 10 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 time between mode choice reevaluations of the agents.

#### AGENT POPULATION

The agent population is synthesized using mobility panel survey data for the Netherlands (CBS, 2023). In this survey, respondents report the trips they perform. The mobility panel provides a weight for each respondent based on socio-economic characteristics to indicate how many inhabitants are represented. We take this weight into account when sampling the agent population from the respondents of the mobility panel. We sample 1000 agents in total from the mobility panel data. During the sampling, we ensure that each postcode area gets a representative portion of these 1000 agents based on the number of inhabitants of that postcode area (CBS, 2024). The spatial scope for agents' home locations is the municipal boundary of The Hague. However, the origin and destination locations of the agents' trips can be all over the Netherlands.

After sampling, we assign attributes from the panel data to each agent. First, the home location of each agent is assigned. Second, the mobility panel provides the frequency of use for each transport mode. These frequencies are used to determine the initial set of available modes of an agent. Third, trips are added to each agent. We only take the origin and destination location of each trip from the panel data, not the chosen mode. By neglecting the mode choice from the data, we can validate the initial modal split that the model generates by comparing it to the modal split in the empirical data.

As an additional step, we ensure that each agent has consistent trip chains. This means that if an agent has a trip from A to B and another trip from C back to A, we assume that there must also be a trip from B to C that is missing in the survey data. Likewise, we assume that the first trip begins at the home location and the last trip ends at the home location. If any trip in the trip chain is missing, we add it to the list of trips an agent has to perform. The trip information for each agent is then written into a file that is used as input to the model.

Based on the origins and destinations of all trips of all agents, we create a separate trip file that contains the routes for all trips. To calculate the routes, we use the Google Maps API. This API calculates four types of routes: driving, walking, transit, and cycling. This information was collected on a Monday morning at 9:00 AM, reflecting a typical weekday. For each trip, we calculate all four types of routes (*i.e.*, driving, walking, transit, and cycling) to create four versions of that trip. We only record the travel time and distance for each version of the trip, as this is relevant

<sup>1</sup>The model code can be found at: doi: 10.4121/22388259-6b2f-4af4-af0e-99af216a4e87

for the mode choice in the model. Finally, the trips are written to another file that will be used as input for the model.

### MODEL INITIALIZATION

The input for the model comes from the agent file, the trips file, and the parameters that are set before the run. Upon model initialization, the modes, social network, and agent population are created. Then, the policies are activated.

First, the transport modes are introduced. We regard the following modes: car, bike, e-bike, public transport, walk, scooter, motorbike, and innovation. The innovation is shared micromobility and is parametrized as such. Each transport mode has the following attributes that are set in the parameters:

- Cost per km
- Starting cost
- Value of travel time
- Comfort
- Probability for adoption

The cost attributes, value of travel time, and comfort are used to calculate the utility of the mode choice. The probability of adoption represents different barriers to adopting a mode, like financial commitments, memberships, or licenses. The parameters of transport modes, such as cost and value of travel time, are specific to The Netherlands (Kouwenhoven et al., 2023).

Second, the social network is created. We create a random Watts-Strogatz small-world network (Watts, 1999). Generating this network graph takes four input parameters:

- Number of nodes, in this case representing the number of agents
- Number of initial neighbors
- Probability of rewiring each edge
- Random seed

To create this network graph, a ring is created over the agents before joining each agent with its initial neighbors in the ring. Then, each edge between two agents is rewired or not based on a probability.

Third, the trip versions for all modes are created. In the input data, there are four versions of each trip based on the four route types of the Google Maps API. To get a trip version for each mode that is present in the model, we use travel time and distance from one of the four route types and adjust it as needed. The route type *driving* was used for the modes car, scooter, and motorbike. For scooters and motorbikes, we increased the travel time slightly as they are slower than a car. The route type *walking* was used for the mode walk. The route type *bicycling* was used

### 4.3. THE TRANSITIONS MODEL

for bike, e-bike, and innovation. The travel time for e-bikes and innovation was decreased as they are faster than conventional bikes. The route type *transit* was used for public transport.

Fourth, the agents are created based on the agent input file, as well as the trip versions and the social network that was just created. The agents have the following attributes:

- Home location
- Neighbors in the social network
- Available modes
- Known modes
- Used modes
- Trip choice set
- Chosen trips

The home location is the postcode area that an agent is assigned to. Neighbors are the other agents that this agent is connected to in the social network. Neighbors are not necessarily spatially close, but instead the source of information. Available modes, known modes, and used modes are relevant for the mode choice, which is explained in more detail in the following section. The trip choice set contains all the versions of all trips that the agent can choose from. The agent's choices are recorded in the list of chosen trips. Upon initialization, each agent makes a choice for each of their trips.

Fifth, the policies are activated. Policies are rules that change the properties of the transport mode, for example, increasing or decreasing the cost of a mode or making a new mode available. Multiple policies can be activated at the same time. If a policy introduces a new transport mode, this mode is added to the list of available modes of a randomly selected subset of agents. These agents represent the early adopters who receive the information from outside the modeled social network. The rest of the agents learn about the innovation through the social network. The first mode choice is based on option properties reflecting the current situation. Then, the policies are activated and cause changes in option properties and in subsequent mode choices.

#### MODEL STEP

A time step in the model represents a quarter of a year. At each time step, three activities are performed: learning from neighbors, updating available modes, and choosing a mode. Only after all agents that are performing a step have completed this step does the next step begin. The agents are activated in a random order to avoid artifacts of execution order.

The first activity is learning, which is done by all agents. Each agent iterates through their list of neighbors and checks whether this neighbor has modes in their

list of used modes that the agent does not have in their list of known modes. If so, these modes are added to the list of known modes.

The second activity is updating the available modes, which all agents also do. The available modes can change by adding modes from the known modes and removing unused modes. Adding a new mode from the known modes happens with a probability specific to the mode. The probability of adoption represents different barriers to adopting a mode, like financial commitments, memberships, or licenses. Modes are removed from the available modes if not used in the last four model steps.

The third activity is re-evaluating the mode choice. At any given timestep, only a random subset of agents performs this activity, depending on whether this reevaluation event is scheduled for the agent. For each agent, we schedule a random timestep at which the agent will re-evaluate its mode choices. After having done this reevaluation, the next reevaluation is scheduled. For a given agent, the time between two consecutive mode choice reevaluations is stochastic and depends on the minimum, average, and maximum lifetime of each of the modes available to the agent. In effect, this represents the replacement decision of a given mode (e.g., a car or bike) as triggering a wider reflection by the agent on the modes it wants to use for all its trips. This representation is in line with the assumption that travel behavior is largely habitual.

When an agent is scheduled to reevaluate its mode choices, the agent calculates the utility for each mode of their available modes for each of their trips with the following utility function:

$$U = -c_s - c_d \cdot d - (vtt \cdot t) \cdot m \quad (4.1)$$

The utility  $U$  is calculated with the mode-specific variables starting cost  $c_s$ , the cost per distance  $c_d$ , the value of travel time  $vtt$ , the comfort multiplier  $m$ , and with the trip-specific variables distance  $d$  and travel time  $t$ . To differentiate between modes that must be returned home (such as car or bike) and modes that can be used for only one trip (public transport or innovation), agents make a choice for each round trip. Round-trip means all trips until they are back at their home location. We sum the utilities for each mode for all trips belonging to the round trip. In addition to that, a mixed utility is calculated for the round trip using different modes that do not need to be returned home. Then, the highest utility gets chosen and added to the chosen trip list. The agents that are not selected for the mode choice keep their chosen modes from the previous step.

## MODEL OUTPUT

The model creates time-series data for the modal split at each time step. After each model run, a table of all performed trips of all agents for each time step is written out. In this way, we can analyze the change in the modal split over time.

### 4.3.3. POLICIES

We consider three policies: parking costs, introducing an innovation, and improving bike infrastructure. We chose these policies to explore how a new mode interacts with existing modes and the impact of changing option properties. In this

### 4.3. THE TRANSITIONS MODEL

study, we use the term policies for broader interventions, which in reality involve financial support, planning, and trade-offs. In the model, these policies are implemented as simplified mechanisms that impact the agents' options and the options' characteristics.

The innovation (shared micro-mobility) is parametrized similarly to e-bikes, as it operates similarly. An important difference is that it does not need to be returned to its origin. This policy links to ongoing efforts in the city, as the municipality is engaged in multiple smart and shared mobility projects ([Gemeente Den Haag, 2025b](#)). While the introduction of an innovation is not done by the government, operators require a permit from the municipality to operate in the city ([Gemeente Den Haag, 2020](#)).

For the policy of improving bike infrastructure, we assume that the policy reduces travel times for all modes using bike infrastructure. This policy links to an initiative of the MRDH. Metropoolregio Rotterdam Den Haag (MRDH) is a partnership of 21 municipalities in the metropolitan region of Rotterdam and The Hague. This partnership is working on an initiative to create cycling routes to connect residential areas with areas where many people work. These routes are designed to be wide and easily recognizable, and to minimize crossings to create a fast and smooth bike journey ([MRDH, 2025](#)). In addition, the municipality of The Hague is improving its cycling routes within the city ([Gemeente Den Haag, 2025a](#)). In the model, reducing travel times for cycling ignores the fact that these types of initiatives also increase the comfort (e.g., increased safety through explicit separation, space for cargo-bikes). Since these effects would aggregate in the utility function, the change in travel time suffices for the purpose of this model.

The parking policy adds a fixed cost to all car trips. This cost is equivalent to traveling two kilometers. Parking is an important topic for the municipality of The Hague. Recent parking policy includes introducing parking fees in areas that were previously free to park in and reducing the number of residential parking permits per household ([Gemeente Den Haag, 2024](#)).

#### 4.3.4. EXPERIMENTAL DESIGN

We use exploratory modeling to explore the behavior of the system under different assumptions. Exploratory modeling uses computational experiments to analyze uncertain, complex systems ([Bankes, 1993](#); [Bankes et al., 2002, 2013](#); [Moallemi et al., 2021](#)). When modeling systems that exhibit deep uncertainty, one should explore the consequences of the various uncertainties by investigating the implications of various assumptions. One computational what-if experiment reveals how the system would behave if the specific assumptions of this experiment about the uncertainties were correct. A single what-if experiment is usually not informative; it merely indicates that those specific outcomes are plausible. Therefore, exploratory modeling entails systematically generating and analyzing large ensembles of computational experiments ([Kwakkel, 2017](#); [Bryant and Lempert, 2010](#); [Halim et al., 2016](#)).

We use the Exploratory Modeling and Analysis (EMA) workbench ([Kwakkel, 2017](#)) to run the experiments and analyze the output data. We set up the exper-

iments by identifying the uncertainties, the policies, and the outcome indicators. The four key uncertainties (Table 5.1) are systematically sampled to represent many possible states of the world. A combination of values of the uncertain factors is considered a scenario. We used a full factorial design for the scenarios using four levels for each uncertain factor except the multiplier (three levels), resulting in 192 scenarios ( $4 * 4 * 3 * 4$ ). Each scenario is run for 10 replications, and we take the average over the replications. So, in total, we perform 2560 runs of the model per policy.

We run experiments with no policy active, each of the three policies on their own, and all possible policy combinations. So in total we evaluate 8 policies, resulting in a total of 20480 model runs (8 policies \* 2560 scenarios). The outcomes of interest are the number of trips performed for each transport mode for each time step. Given the number of scenarios and the policies, we can then perform the experiments.

Uncertainty	Description	Levels	Motivation
$k_{social}$	Number of initial neighbors when creating the social network	2, 4, 6, 8	The initial neighborhood size was set to even values required by the algorithm, spanning from sparse to moderately dense local connectivity while keeping $k \ll N$ , which is consistent with typical small-world network studies (Watts and Strogatz, 1998; Newman, 2000)
$p_{social}$	Probability of rewiring when creating the social network	0.2, 0.4, 0.6, 0.8	The rewiring probability was set to 0.2, 0.4, 0.6, and 0.8 to sample topologies ranging from moderately clustered networks with some long-range ties to near-random graphs.
$\alpha_{\Delta t}$	Multiplier applied to the time until the following re-evaluation	0.8, 1.0, 1.2	The multiplier values represent 20% variation around the baseline average time between mode-choice decisions, capturing plausible heterogeneity in decision frequency.
$n_{early-adopters}$	Number of agents that the innovation is added to upon its introduction	25, 50, 75, 100	The number of early adopters ranges between 2.5% and 10% of the 1000-agent population to examine how a small initial user base influences the speed and extent of diffusion, consistent with empirical and theoretical work on innovation adoption (Rogers, 1995).

Table 4.1: Specification of uncertainties and their ranges

## 4. MODELING A TRANSPORT SYSTEM IN TRANSITION

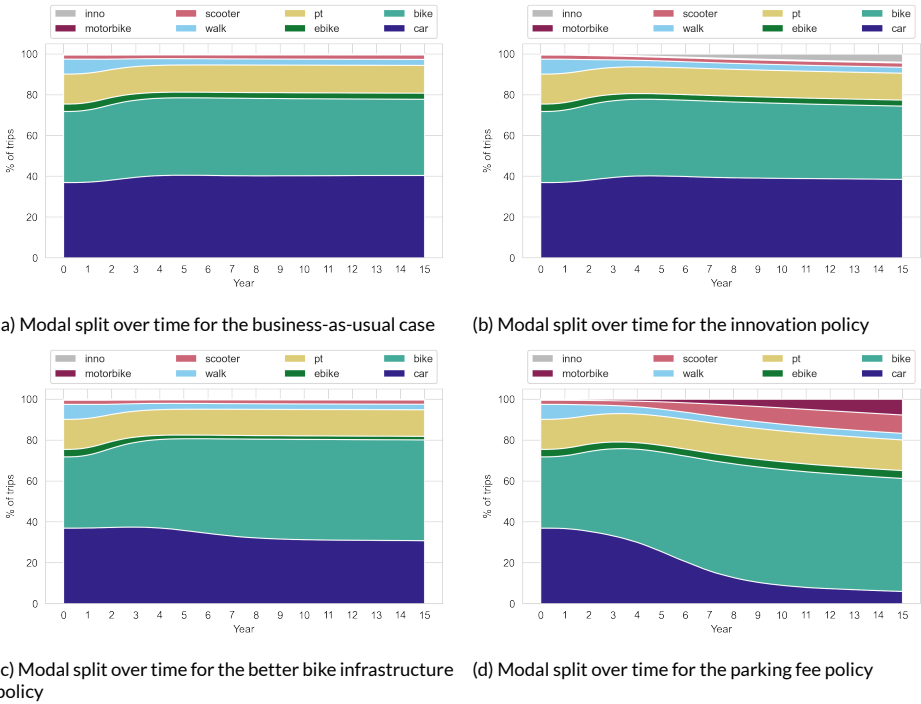


Figure 4.2: Modal splits over time for the business-as-usual case and the policies on their own

### 4.4. RESULTS

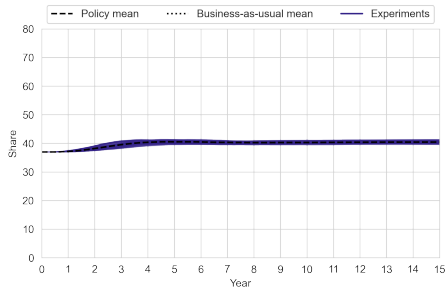
After running the experiments, we analyze the development of the modal share for each transport mode over time across all scenarios and policies. We first present the business-as-usual case and then highlight three main insights of applying the policies: competition between similar transport modes, policies complementing each other, and the significant impact of the parking fee. Following that, we describe the potential impact of the four key uncertainties.

#### 4.4.1. BUSINESS-AS-USUAL CASE

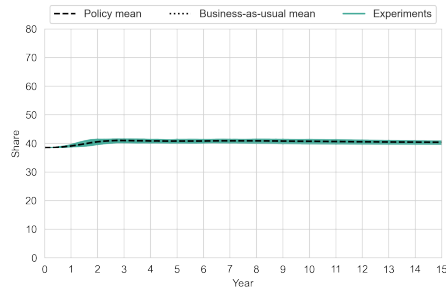
For the business-as-usual case, we ran the model across all scenarios with no active policy. The average modal split across all scenarios and model replications for the business-as-usual case is depicted in Figure 4.2a. The results show that there is very little change in the modal split if no new policies are applied. The ‘innovation’ (shared micro-mobility) is absent in the modal split since it has not been introduced through a policy. No active policies mean that there is no change in the mode characteristics at any time. The only changes happening over time result from agents learning about previously existing modes and starting to use them. These changes are minor.

The modal share for each transport mode can be found in Figure 4.3. Each

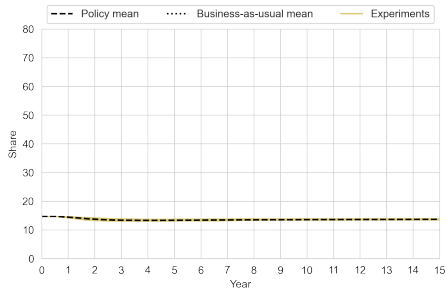
## 4.4. RESULTS



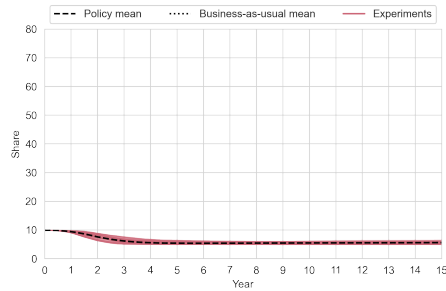
(a) Car share over time



(b) Bike and e-bike share over time



(c) Public transport share over time



(d) Remaining modes (walk, scooter, motorbike) share over time

Figure 4.3: Modal shares over time in the business-as-usual case

line in the graph represents the average over the 10 replications for one scenario. The dotted line in each graph represents the mean value across all scenarios. The key uncertainties are mainly relevant when a change occurs. The changes in the mode choices are very minor; therefore, the experiment outcomes lie very close together.

### 4.4.2. VALIDATION

We validated the model by comparing the business-as-usual results to empirical data and the results of a similar model. First, the business-as-usual case represents the modal share as measured in the ODiN mobility panel survey (CBS, 2023). Table 4.2 compares the modal split in the ODiN data with the initial modal split of the Business-as-usual case as a result of the mode choice upon initialization. We can see that the values are similar. The model overestimates the share of car trips by about 3 percentage points and bike trips by about 6 percentage points, while the walking trips are underestimated by about 4 percentage points. The ODiN data has some transport modes that are not represented in the model, such as taxis or delivery vans; these account for about 3 % of trips. Notably, this corresponds to the overestimation of car trips.

Second, we compared the results of our model to the results of a study with the

	ODiN	BAU
Car	34.10%	36.95%
Bike	29.14%	34.87%
E-bike	5.42%	3.65%
Public transport	14.29%	14.69%
Walk	11.34%	7.34%
Scooter	2.46%	2.02%
Motorbike	0.15%	0.48%
Rest	3.10%	

Table 4.2: Modal split of the mobility panel survey (ODiN) and the business-as-usual scenario (BAU)

4

MATISSE model, which was used for exploratory modeling (Moallemi and Köhler, 2019). Even though the two studies use different case studies and, therefore, different data, we found a relational outcome (Collins et al., 2024): similar changes in input causing similar changes in outputs. Both models show similar curves in the model outcomes of the policy scenarios.

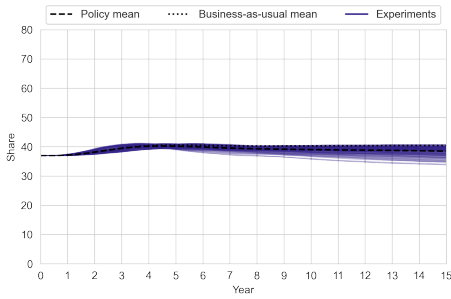
#### 4.4.3. APPLYING THE POLICIES

After the business-as-usual case, we ran the model with the policies. The first mode choice of all agents upon initialization is made without the policies active, representing the current state. Then, the policies are activated, thus affecting all subsequent mode choices. We ran the model separately for each policy and for all possible combinations of policies. We derived three main insights from the results related to unintended side effects, symbiotic effects, and the impact of the parking fee.

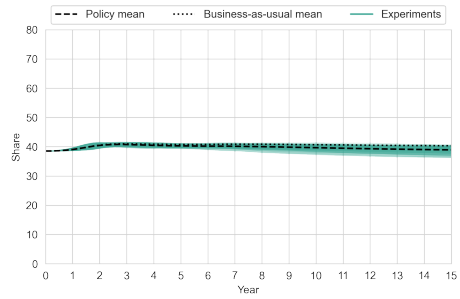
First, we observe that introducing the innovation of shared micro-mobility affects most other modes. A desired effect of the introduction of the new transport mode would be the reduction of car trips. However, in the average modal split across all scenarios (Figure 4.2b), almost no changes are visible. We see a reduction of car trips in several experiments (Figure 4.4a). An undesired effect of the policy would be the reduction of trips with sustainable modes such as bike, e-bike, and walking. In the modal split, we observe a reduction in the share of walking trips and minor changes in the share of bike trips and e-bike trips. Figure 4.4b shows the simulated modal share of bikes and e-bikes combined over time. While the average shares stay fairly constant over time, there is a decline in bike trips in some scenarios.

Second, we observe symbiotic effects when multiple policies are active. Two separate policies can benefit each other in two ways: on the one hand, the policy can incentivize one mode while simultaneously disincentivizing another, and, on the other hand, the policy can create more favorable conditions for a new mode. Simultaneously running the innovation and better bike infrastructure policies together illustrates a situation in which more favorable conditions are created. Indeed, better bike infrastructure creates better conditions for the innovation to be

## 4.4. RESULTS



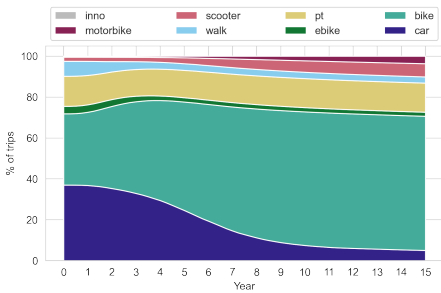
(a) Car share over time



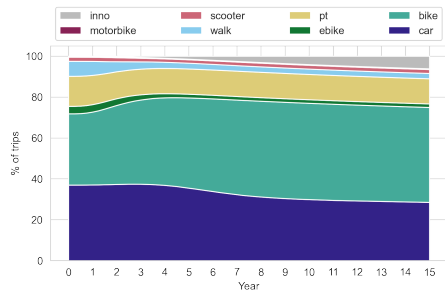
(b) Bike and e-bike share over time

Figure 4.4: Modal shares over time for the innovation policy

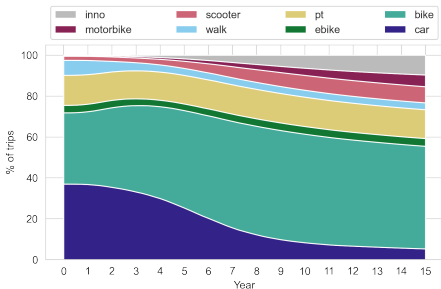
4



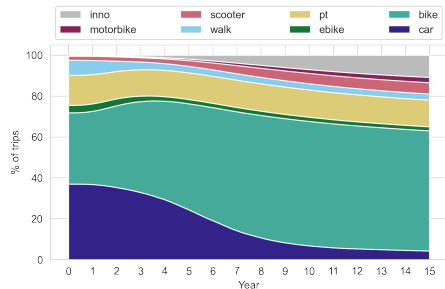
(a) Modal split over time for the policy combination parking fee and better bike infrastructure



(b) Modal split over time for the policy combination better bike infrastructure and innovation



(c) Modal split over time for the policy combination parking fee and innovation



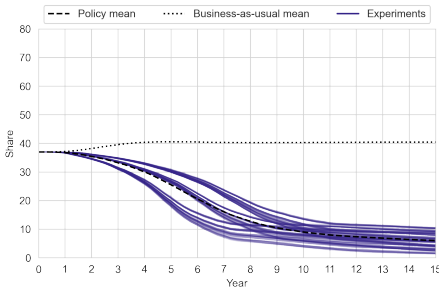
(d) Modal split over time for the combination of all policies

Figure 4.5: Modal splits over time for policy combinations

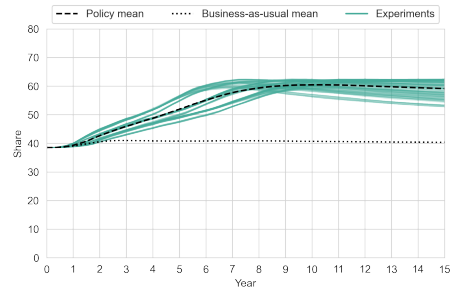
introduced. The policy of creating better bike infrastructure not only decreases the travel times of bikes and e-bikes but also the innovation. Therefore, the innovation reaches a higher modal share when combined with better bike infrastructure than if introduced without the other policy (compare Figures 4.2b and 4.5b).

Third, out of all the policies, the model is most sensitive to the parking fee, vis-

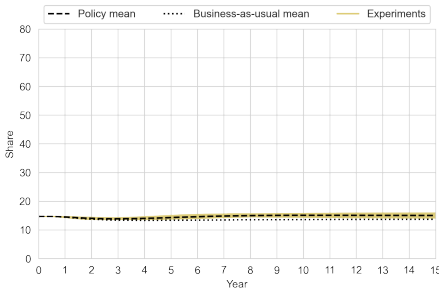
## 4. MODELING A TRANSPORT SYSTEM IN TRANSITION



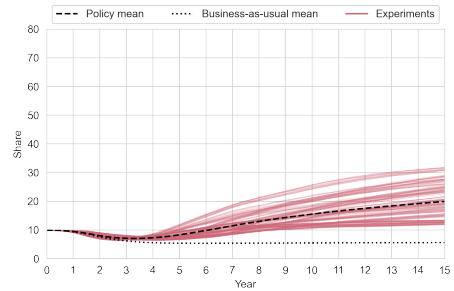
(a) Car share over time



(b) Bike and e-bike share over time



(c) Public transport share over time



(d) Remaining modes (walk, scooter, motorbike) share over time

Figure 4.6: Modal shares over time for the parking fee policy

ible in the modal split (see Figure 4.2d). The parking fee is a fixed cost equivalent to two kilometers of driving. Parking fees emerge as a strong intervention that influences mode choice more significantly than any of the other policies, even when combined with each other (compare Figures 4.2d and 4.5b). The strong impact of this policy leads to a wide range of the modal share for each mode. Figure 4.6 shows the wide ranges of the shares over time across the scenarios.

### 4.4.4. IMPACT OF UNCERTAINTY

Figure 4.7 is a dimensional stacking (LeBlanc et al., 1990; Suzuki et al., 2015; Molina-Perez, 2016) for the modal share of the innovation at the end of the simulation for all scenarios. This figure shows how the four key uncertainties we explored in this study influence the modal share of the innovation. The four key uncertainties depicted are the number of initial neighbors when creating the social network ( $k_{social}$ ), the probability for rewiring when creating the social network ( $p_{social}$ ), the multiplier applied to the time until the next re-evaluation ( $\alpha_{\Delta t}$ ), and the number of early adopters ( $n_{early\_adopters}$ ), as shown in table 5.1.

The first key uncertainty is the number of initial neighbors when creating the social network ( $k_{social}$ ). The higher the number of initial neighbors, the more edges are in the social network, and the more interconnected the network

## 4.5. DISCUSSION

is. Therefore, information spreads faster and has a higher chance of reaching everyone in the network. The heat map shows that a value of 2 or 4 for the number of initial neighbors leads to no or a very small share of innovation trips; higher shares only occur with a value of 6 or 8.

The second key uncertainty is the probability of rewiring during the creation of the social network ( $p_{social}$ ). When creating the social network, all nodes are connected with their  $k$  neighboring nodes and rewired to another randomly chosen node with a probability  $p$ . If this probability is lower, there is more clustering, meaning that neighbors of neighbors are also an agent's neighbors. So, a higher probability means a more diverse set of neighbors, leading to information spreading faster through the network. In the cases of a high  $k_{social}$ , the probability positively affects the final modal share of the innovation.

The third key uncertainty is the multiplier applied to the time until the next re-evaluation ( $\alpha_{\Delta t}$ ). The shorter the time between mode choices, the faster change occurs in the system. This uncertainty has a strong impact when  $k_{social}$  is high. Since learning occurs for all agents at each time step, the number of agents re-evaluating only has an effect if the information has spread well through the social network.

The fourth key uncertainty is the number of early adopters ( $n_{early\_adopters}$ ). The higher the number of early adopters, the more agents get a new mode added to their list of available modes. This uncertainty only impacts when the social network is well-connected (high  $k$  and  $p$  values). Overall, this uncertainty has the least impact on the modal split.

Overall, the uncertainties are dependent on each other. The multiplier and probability of rewiring only impact the results significantly if there is a well-connected network with diverse neighbors to spread information about a new mode.

## 4.5. DISCUSSION

In this study, we set out to develop a model of the whole transport system that simulates social interactions, endogenous interactions between transport modes, and the emergence of the use of innovations. Further, this model needed to be suitable for exploring various policies under uncertainty. In this section, we discuss each aspect of the goal and the model's limitations.

First, we simulated social interactions by using a small-world social network. The review of [Mehdizadeh et al. \(2022\)](#) found that transition models frequently use small-world graphs to model social networks. Our results show that the parameters used to generate such a network are essential for how the modal shares develop over time. Therefore, we hypothesize that using other types of networks, for example, with some agents influencing the agent population more than others or a higher probability of connecting agents with similar characteristics, will also have an impact. The sensitivity of diffusion dynamics to social network structure highlights that transitions are not only driven by policy or infrastructure, but also by how individuals influence each other. This emphasizes the importance of accounting for social interactions in mobility models.

Second, our model allows for interactions between transport modes through

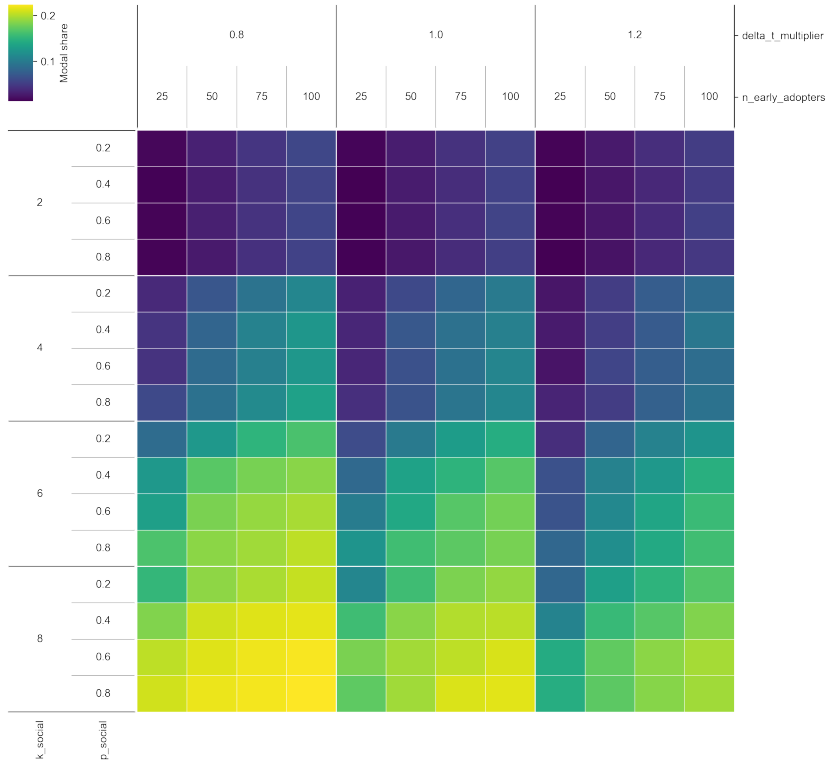


Figure 4.7: Innovation shares at the end of the simulation for all scenarios for all policies active

competition among the modes. We found that introducing an innovation can have desirable and undesirable impacts on the modal share. The city of The Hague aims to become climate-neutral. A central goal within that is to reduce car trips. Introducing an innovation, such as shared mobility, aims to substitute as many car trips as possible. However, the innovation not only negatively affects the number of car trips but also bike trips, which is not desirable for the municipality. A possible solution is to implement policies that simultaneously disincentivize car driving and benefit innovation and other desirable modes, such as cycling.

Third, the structure of the model allows for any transport mode to be added as a combination of option properties. This allows for exploring a wide range of hypothetical transport modes that are or will be developed in the future. Specifically, the model addresses: (1) the initial introduction and adoption of a new transport mode (emergence of its use), (2) whether the innovation, once introduced, gains

## 4.5. DISCUSSION

traction or is adopted by additional users, and (3) the diffusion dynamics, including both successful and unsuccessful adoption paths.

Fourth, it is possible to explore a wider range of policies with this model. In this paper, we simulated 8 policy combinations to demonstrate the capabilities of this model. Other possible policies include disincentivizing cars through speed limits (increasing the travel time of the car) and exploring radical changes in the accessibility of sustainable modes, such as free public transport. Results such as the strong impact of parking fees illustrate that financial incentives and disincentives can have a stronger and more rapid effect on the modal split than infrastructural changes, which is critical for designing short-term transition strategies. Parking fees should be further examined in a more granular manner, carefully considering how to apply fees across space and time. For example, applying high fees to important destinations such as the city center or the beach during peak times may stimulate the use of bikes and public transport. The same holds for the bike infrastructure policy, which here results only in a reduction of travel time. A more fine-grained representation of which routes would be affected and the consideration of improved comfort on those routes might further help in prioritizing which parts of the bicycle infrastructure should be prioritized when making improvements.

Fifth, we explored various key uncertainties. Only a few transition models have explicitly taken uncertainty into account (e.g., [Moallemi and Köhler \(2019\)](#)). The uncertainties we explored mainly impacted the intensity and speed of the diffusion of the innovation. Our analysis revealed the importance of the social network and the time between mode choices. Variations in decision frequency show that timing matters for adoption dynamics, suggesting that policies that make users reconsider their choices more often (e.g., communication campaigns) are a promising avenue for the mobility transition. The number of early adopters affects diffusion speed and reach, which highlights the importance of targeting early adopters strategically in pilot interventions.

We had to make some key assumptions to implement the Actor-Option framework into an agent-based model. One of our goals was to create a model that was simple enough to be used for exploratory modeling and participatory workshops. Simplicity comes at the cost of detail. However, the model is still detailed enough to explore the impact on the modal split for a wide range of policies and transport modes.

The current version of the model has several limitations. First, all agents make decisions through the same utility function. The agents are heterogeneous in their travel demand but not in how much they value different aspects of the decision (e.g., some users might be more cost-sensitive than others). Second, we do not differentiate between fossil-fueled and electric cars. We made this choice since electric cars do not significantly differ from fossil-fuel cars in how they are used and since many studies are researching electric cars ([Mehdizadeh et al., 2022](#)). The difference between fossil-fueled and electric cars matters for emissions; however, electric cars present problems similar to those of fossil-fueled cars regarding land use, noise, and safety. Third, we only implement policies at one moment in time. Policies might have different effects when they are implemented in a staggered man-

ner.

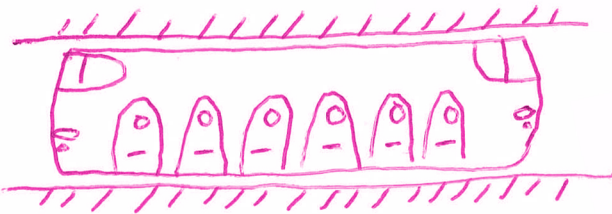
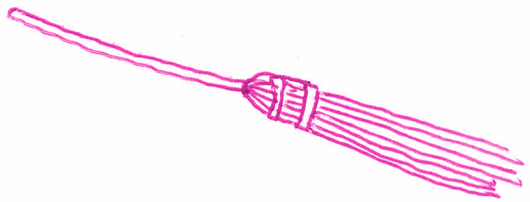
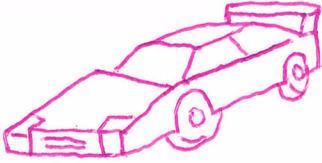
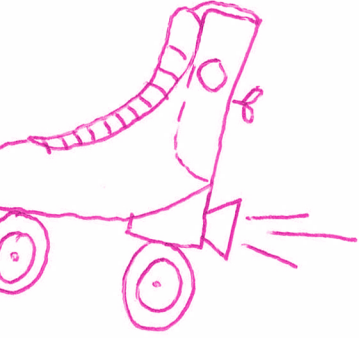
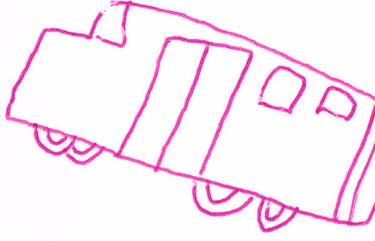
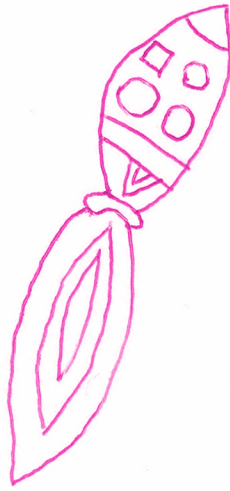
## 4.6. CONCLUSION

In conclusion, we developed an agent-based model to explore the modal shift in light of different policy combinations. As such, it differs from many of the earlier mobility transition models, which only investigate one policy option or one mode at a time. Theoretically grounded in the Actor-Option framework, this model enables us to regard the whole system, let any transport innovation emerge in it, and analyze the interaction of multiple transport modes. Additionally, it has a basic structure for social interaction through peer-to-peer learning. We explored two policies; however, the structure of the model allows for a wide range of policies to explore, depending on the needs of the case.

Further research will look into adding more detail to the model and expanding the exploratory modeling and analysis to include more policies and uncertainties. Potential extensions to the model include integrating traffic congestion, land-use feedback, and reliability aspects. In addition, key details to add to the model are agent attributes to differentiate them beyond their travel demands. Attributes such as attitudes towards flexibility, comfort, and the environment influence the mode choice (Vredin Johansson et al., 2006) and can be used to differentiate the agents beyond their travel demand. Through including agents' attitudes, future modeling efforts can also include attitude changes, as their omission can lead to an underestimation of the effects of unconventional policies (van Wee and Kroesen, 2022). Another detail to add to the agents includes openness to switching modes and learning from others. Making the agents more detailed would further allow us to explore other types of social networks, for example, networks that cluster agents with similar attitudes or that represent real-world cliques. Differentiating between the agents also enables us to further investigate transport mode dynamics, for example, by separating different kinds of car engines. Key uncertainties to consider in future research are external influences, such as fuel prices or shocks to the system, such as a pandemic.

We found that the Actor-Option framework allows us to capture the dynamics among different actors and options. This framework can be tailored toward other mobility studies, policy questions, and goals. The model also allows the inclusion of any configuration of technologies as a new transport mode in the analysis. This agent-based model provides insights into how individual and social decision-making processes shape mobility transitions and gives a high-level direction as the basis for deeper investigation and detailing of policies. The model can be used to aid decision-makers in addressing the wicked problem of mobility transitions by providing insight into the system's dynamics and possible future scenarios, potentially even in participatory settings.





# 5

## PARTICIPATORY MODEL-BASED POLICY EXPLORATION FOR THE MOBILITY TRANSITION

With the help of an earlier version of the agent-based model introduced in the previous chapter, we designed and analyzed a workshop on making policy decisions, carrying out the latter two steps of the DMDU process: Explore and Choose. We executed the workshop twice, each with a group of students. The first group consisted of students with limited experience in modeling and uncertainty; the second group consisted of students with experience. This chapter lays out the workshop design and results and discusses the implications for participatory DMDU. Additional materials such as the workshop structure and materials can be found in Appendix C.

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*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.*

### 5.1. 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), 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., 2021b; 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 sec-

## 5.2. PARTICIPATORY MODEL-BASED DECISION-MAKING

tion 5.2. Following this, we describe our research design, the model we used, and the case study in section 5.3. We conclude by discussing the process, the outcomes, and implications for policy-making and future research in section 5.5.

## 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 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.

### 5.3. RESEARCH DESIGN

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

#### 5.3.1. 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 Figure 5.1).

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.

#### 5.3.2. 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,

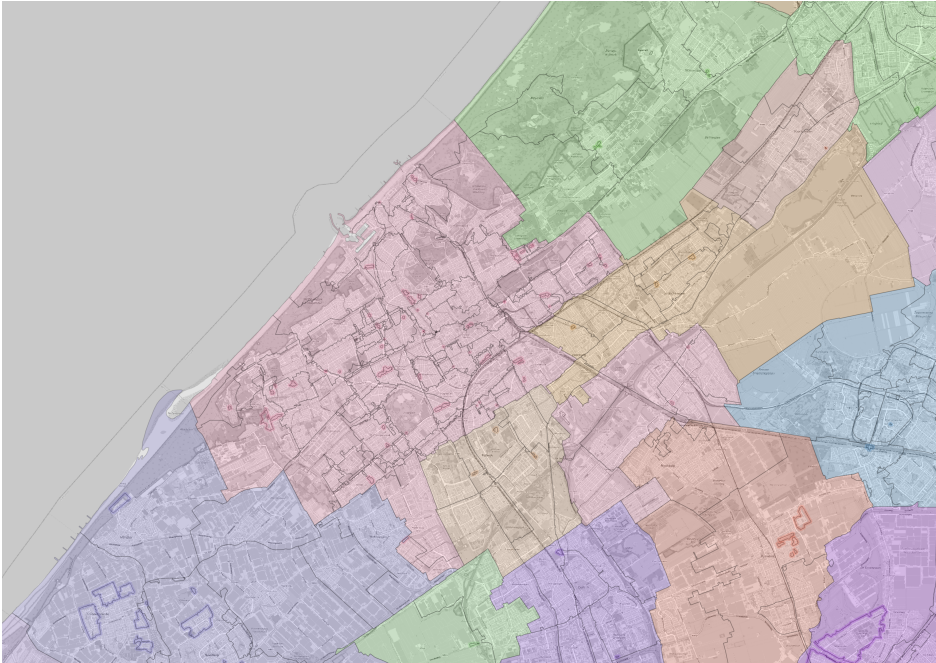


Figure 5.1: The city of Den Haas (pink) and surrounding municipalities, adapted from OpenStreetMap

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.

#### 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. 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.

5

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.

### 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 (Kwakkkel, 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 5.1) 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 5.2). 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

### 5.3. RESEARCH DESIGN

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

Table 5.1: Specification of uncertainties and their ranges

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

Table 5.2: Overview of the policies

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.

### 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 Figure 5.2) and the number of trips for each mode (see example in Figure 5.3).

## 5. PARTICIPATORY MODEL-BASED POLICY EXPLORATION

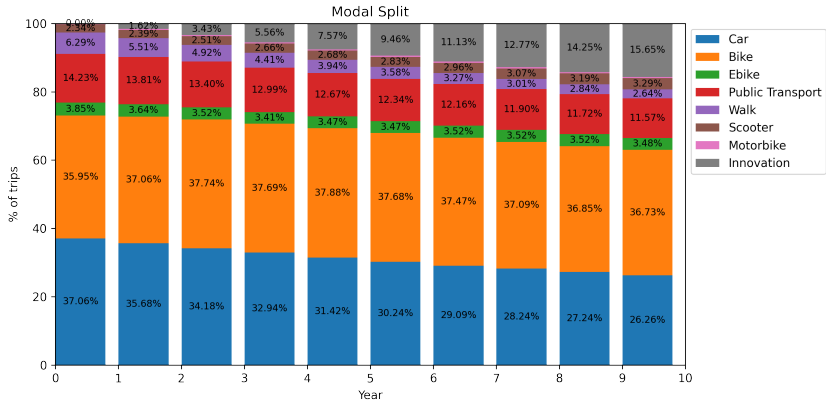


Figure 5.2: Modal split over time for the policies 'Shared micromobility within the city' and 'Improved bike infrastructure'

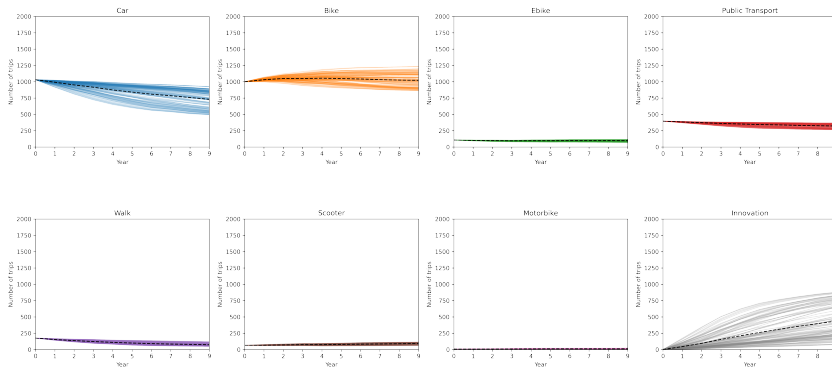


Figure 5.3: Number of trips over time for the policy combination of 'Shared micromobility within the city' and 'Improved bike infrastructure', each line represents one scenario

## 5.3. RESEARCH DESIGN

### 5.3.3. 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.

### 5.3.4. 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 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.

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## 5.4. 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.

### 5.4.1. 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 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. Figure 5.4 illustrates the participants' self-reported familiarity levels. The two groups differed in both categories. Half the participants in Group

## 5.4. RESULTS

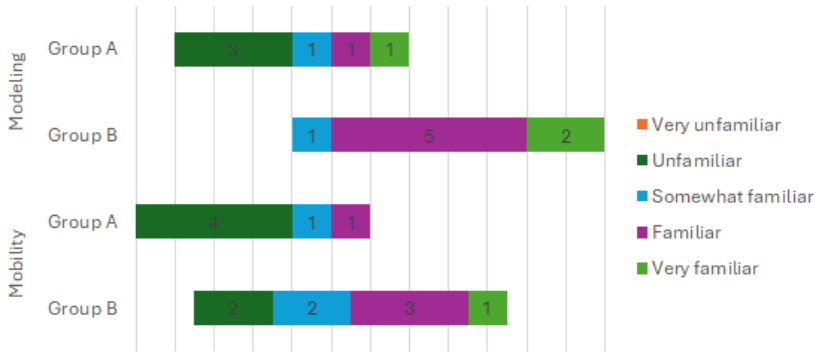


Figure 5.4: Participants' familiarity with modeling and mobility

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.

### 5.4.2. 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 effec-*

*tive. 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.

### 5.4.3. 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.

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

## 5.4. RESULTS

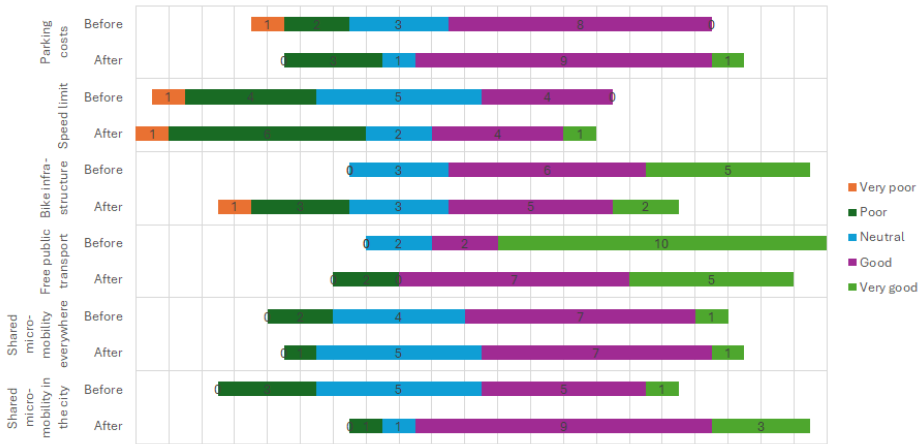


Figure 5.5: Survey answers before and after the workshop for each policy regarding the sustainability effect

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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.

### 5.4.4. 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 (Figure 5.5) and how certain they are about this effect (Figure 5.6). 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, Figures 5.7 and 5.8 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.

## 5. PARTICIPATORY MODEL-BASED POLICY EXPLORATION

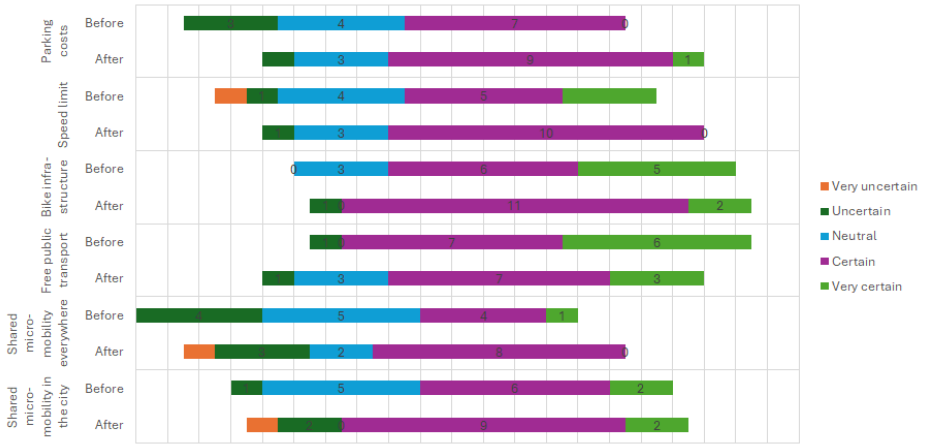


Figure 5.6: Survey answers before and after the workshop for each policy regarding the certainty of the sustainability effect

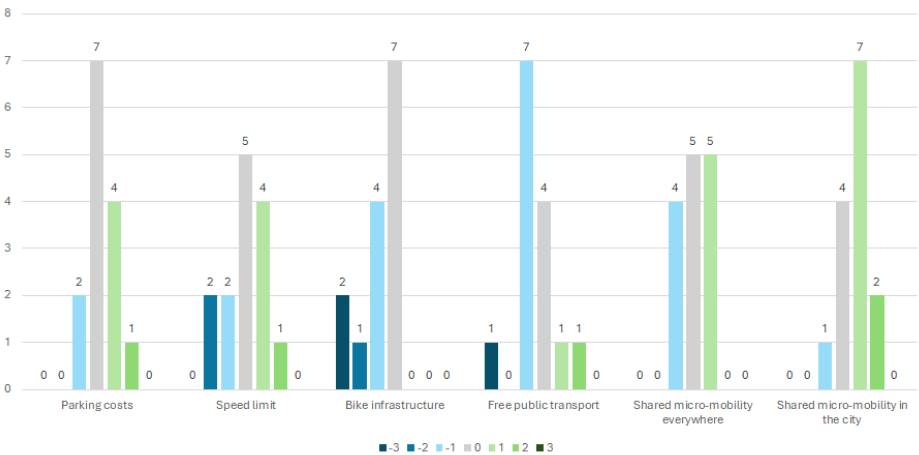


Figure 5.7: Change in the survey answers before and after the workshop for each policy regarding the sustainability effect

## 5.4. RESULTS

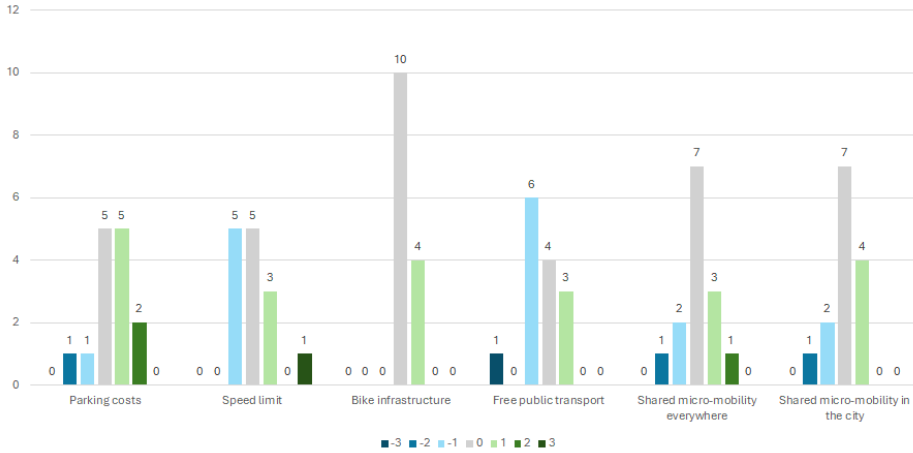


Figure 5.8: Change in the survey answers before and after the workshop for each policy regarding the certainty of the sustainability effect

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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.

### 5.4.5. 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. 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.

### 5.5. 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.

## 5.5. DISCUSSION AND CONCLUSION

### 5.5.1. 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.

### 5.5.2. 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.

### 5.5.3. 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

## 5.5. DISCUSSION AND CONCLUSION

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.



# 6

## DISCUSSION

In this chapter, we reflect on our approach to participatory decision-making under deep uncertainty by discussing how we captured human behavior in mobility transitions and regarded multiple modes and policies. Further, we reflect on the participant selection and the impact of uncertainty. Next, we consider the generalizability of this research and the challenges of establishing a practice of participatory DMDU.

### 6.1. HUMAN BEHAVIOR IN TRANSPORT MODELING

User behavior is crucial for modeling mobility transitions, as users are ultimately the ones causing the modal shift. Previous mobility transition studies have a strong technology focus and often investigate the development of a single innovation, such as electric vehicles (Hoekstra and Hogeveen, 2017; Zolfagharian et al., 2020), hydrogen cars (Köhler et al., 2010), or alternative fuel vehicles in general (Kwon, 2012). Additionally, only a few models have explicitly dealt with the uncertainty of transitions (Moallemi and Köhler, 2019). In this research, we investigated not only a single technology but multiple modes and policies as well as users' reactions to these changes.

The speed of the mobility transition is dependent on both the speed of diffusion of innovations and changes in users' lives and patterns. In Chapter 4, we found that the social network plays a significant role in the model outcomes. Varying the parameters used to create this network impacted the results of the model by varying how connected the agents are and, subsequently, how fast and wide information travels in the network. The modeled social network is a proxy for factors influencing the diffusion potential, such as various communication channels, community adoption thresholds, pilot projects, or education campaigns. While there are studies on how users acquire information and make choices (Vredin Johansson et al., 2006; Verplanken and Knippenberg, 1996; Krizek and Waddell, 2002; Kuhnimhof et al., 2006; Haustein and Hunecke, 2013), there is still a need for empirical work to

better understand how users in a particular case actually learn from another, learn from other sources, and make their mode choices. At the same time, the persistence of car dependence and the difficulty of achieving a more sustainable transport system indicate that the challenge does not only lie in understanding user behavior. Translating empirical insights into effective policies has been proven difficult. Understanding behavior is necessary but insufficient for policy-making; these insights have to be embedded in broader governance and structural reforms, as these conditions shape and constrain individual choices (Banister, 2008; Marsden and Rye, 2010). Moreover, neither governance nor user behavior alone can fully address the challenge, as transport behavior is highly diverse and cannot be captured by a single overarching theory. Instead, a collection of theories has been developed to explain subsets of behavior, such as habits or specific situations (van Acker et al., 2010). This diversity means that there is no silver bullet: policies effective in one context may have limited impact in another. Behavior is also strongly shaped by the environment (e.g., infrastructure, service quality, and policy incentives), which can alter choices in ways not easily anticipated. Human behavior can often only be predicted in specific situations, and significant gaps remain in our understanding of how individuals change their decisions over time and how evolving environments reshape those choices.

6

In addition to diffusion dynamics, long-term change may also happen through changes in users' lives. In the agent-based model, we represented this by having a fraction of agents re-evaluate their choices at every time step. Mobility behavior has inertia, due to habits and commitments such as vehicle ownership. Change happens through mid- to long-term decisions that occur every few years (Van Wee et al., 2013). These life-changing events, such as moving, changing jobs, or having children, influence trip patterns and mode choices. The focus of our model was to explore how modal shifts emerge from changes in option properties and learning among users. The purpose was to have a simple model that is easy enough to use and understand, so it can be used in a workshop with selected policies and exploratory modeling. For this purpose, modeling diffusion dynamics and mode choice dynamics in this way was sufficient. This level of complexity balances credibility and usability: simple enough to explain, but not too simple it becomes useless. Understanding every equation is not necessary; rather, participants can grasp the basic intuition behind the model. Adding more complexity would add more runtime without necessarily adding more insight. This also links to the concepts of design and operator logic, which highlights the distinction of the level of understanding between model designers (i.e., knowing the model, its structure, and the resulting behavior) and model operators (i.e., knowing how to steer the model in the preferred direction, knowing which policies realize which aims) (George P Richardson et al., 1994). Modeling other factors influencing diffusion dynamics and user behavior in more detail might be worthwhile if the goal is to explore policies that use these factors as a leverage point. We explore possible extensions below.

In both the qualitative and quantitative modeling approaches we employed, we made simplifications about user behavior. During the modeling workshops with the municipality (Chapter 3), the participants created Causal Loop Diagrams

## 6.1. HUMAN BEHAVIOR IN TRANSPORT MODELING

to visualize relationships between variables influencing the utilization of different modes of transport. 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. While the Causal Loop Diagrams reveal the relationships among system variables, they only uncover the existence and direction of such relationships and not the intensity of those relationships. The agent-based model in Chapter 4 has a simple decision-making rule based on a utility function. This utility function only covers a small subset of human behavior, but was determined to be adequate for the purpose of the model. Life changes were captured through the periodic re-evaluation of mode choices. A large body of literature on choice modeling for transport covers a wide range of user considerations and behaviors that were not included in this research (Van Wee et al., 2013), such as psychological perspectives (Verplanken and Knippenberg, 1996; Heath and Gifford, 2002; Bamberg and Rölle, 2003; Nordlund and Garvill, 2003; Gatersleben, 2007), economic perspectives (Golob et al., 1981; Small et al., 2024), or geographical perspectives (Dijst, 2019; Susilo and Maat, 2007). Future modeling efforts should also focus on attitude changes, as their omission can lead to an underestimation of the effects of unconventional policies (van Wee and Kroesen, 2022).

The Actor-Option framework describes a set of mechanisms related to behavioral identity. These mechanisms entail reference point formation and change, commitment formation, and preference structure change. An actor's behavioral identity is challenging to conceptualize because of the difficulty of empirically observing actors' internal decision processes (Yücel, 2010). Therefore, we did not include this mechanism in our modeling efforts. Including behavioral identity in mobility transition research would improve the representation of user behavior in the model, reflecting well-established insights from behavioral economics and psychology (Kahneman and Tversky, 1979; Van de Kaa, 2010) and empirical studies in transport behavior (Van Wee et al., 2013; Moleman et al., 2025; Schoenau and Müller, 2017). Actors may have reference points anchored in past experiences and peer behavior, prior commitments that produce path dependencies and lock-ins, and preference structures that change due to learning, social influence, and external shocks. There is some overlap between the concepts of behavioral identity, preferences, social norms, and attitude. Future research should explore the distinction between these concepts, as representing them in a nuanced way in the model might change transition dynamics. Behavioral identity, preferences, social norms, and attitude are interconnected (Ajzen, 2000; Smith and Louis, 2009; Eker et al., 2019; Vredin Johansson et al., 2006; van Wee et al., 2019); however, change in these concepts operates at different time scales and some are easier to change than others. Including these concepts opens up new avenues for interventions, facilitating the transition.

To explore user behavior under varying circumstances, we considered multiple modes and policies. In the modeling workshops with the municipality (Chapter 3), the participants created Causal Loop Diagrams for multiple transport modes and subsequently generated policies influencing the use of those modes. The key con-

tribution of the agent-based model presented in Chapter 4 is the possibility to consider multiple modes and policies simultaneously. Any future transport mode can be added to this model and interact with the existing ones. However, when using this model in a workshop setting (Chapter 5), the number of policies was limited since the model had to be run beforehand. Therefore, the research team chose the policies and not the participants, and we could not use the full potential of the model. In a multi-workshop process, the participants could choose the policies and modes to include, and the model could be run in between workshops. Including multiple modes and policies creates flexibility for decision-makers as they can explore portfolios of policies rather than relying on a single one.

## 6.2. WORKSHOP PARTICIPANTS

Who were the participants, and how did this impact our research? In the workshops with the municipality (Chapter 3), we brought municipal workers from different departments together, which fostered collaboration and brought differing viewpoints and expertise. However, we also noticed homogeneity in participants' values and approach to mobility. The participants were determined to foster sustainability; controversial solutions, such as replacing parking spaces, were accepted readily without considering vulnerable groups or people who might be against a policy. In the workshops with the agent-based model (Chapter 5), students took on the role of government and provider. Here, we noticed that participants were able to use the model outputs for decision-making, but tended to discuss what they were familiar with. As such, we identified a need for diverse participants throughout this research. Future research should pay attention to participant selection as much as possible.

We conducted workshops both within one organization and with participants from two organizations. Within an organization, participants may have shared goals, terminology, and institutional culture, leading to smoother discussions (Besharov and Smith, 2014). Groups of people with similar cultural backgrounds and interests, similar past experiences, or frequently exchanging knowledge often have partially overlapping mental models (Jordan et al., 2018). Focusing on internal priorities and feasibility can lead to fast alignment on goals, but less exposure to alternative perspectives risks blind spots and groupthink (Wegrich, 2019). In a workshop with participants from two organizations, there is more potential for conflicting objectives, interests, and decision-making cultures, which require negotiation. Also, combining different areas of expertise and perspectives has greater potential for innovation and collaboration (Rieley, 2014).

How could a different group of actors have affected the workshop outcomes? A different group of actors might have emphasized different aspects of the mobility transition, such as economic feasibility, technological innovation, or social justice. In both Chapters 3 and 5, we did not observe power imbalances and conflict. A different and more diverse group of actors may require more careful facilitation and adaptation of the methods to mitigate power imbalances and conflicting viewpoints.

How would involving citizens in such a workshop affect the outcomes? Invol-

### 6.3. UNCERTAINTY

ing citizens in the policy-making process is common in the Netherlands, for example, for visioning transport futures (Jittrapirom et al., 2023), but also in other domains such as water and coastal management (d'Hont and Slinger, 2022). When involving citizens in participatory decision-making under deep uncertainty, they may focus more on everyday mobility experience rather than strategic or technical aspects. This focus would bring in a greater variation in mobility needs, revealing blind spots, but might also put greater emphasis on short-term benefits and immediate impacts. The workshop design would need to be adapted to accommodate varying education levels, for example, by using simpler language and deepening the explanation. Policies developed with citizen input may gain greater public support and might be easier to implement. However, citizens hold no formal decision-making power, and decision-makers might not take up their resulting decisions (Eleta et al., 2019).

### 6.3. UNCERTAINTY

Which uncertainties were considered throughout this research? The agent-based model focused on system uncertainties related to the social network and the number of agents making a choice. The flexible nature of the Actor-Option framework allows for the exploration of different uncertainties, but not all. While some uncertainties might, for example, be included as changes in option properties, other uncertainties might have an impact on whether a policy is feasible in the first place. The workshops (Chapters 3 and 5) complemented the model by including exogenous uncertainties. The structure of the workshops allowed for a broader focus on future events and trends, including socio-political shifts, technological advancements, and political changes.

What is the impact of explicitly regarding uncertainty in a participatory setting? In an experiment on the role of biases in scenario planning, Schoemaker (1993) found that scenarios are perceived to be more believable if they are more detailed and cohesive, and that participants accept a wider range of uncertainty after working with scenarios, which lowers overconfidence and tunnel vision. Gong et al. (2017) compared scenarios and forecasts using a decision support tool, finding that participants using scenarios more often chose the strategies that performed well over the full range of uncertainties compared to participants using forecasts. While both groups explored options in a similar manner, those in the scenario group paid more attention to worst-case scenarios. Through a serious game, Akse et al. (2025) found that framing uncertainty positively leads to better multi-actor collaboration, driving sustainable mobility innovations forward. In the workshops with municipal employees, participants found value in the systematic approach to understanding the system and evaluating the robustness of interventions. The workshop demonstrated participants' abilities to think causally, to vary the problem scope, to envision uncertain futures, and to identify unintended consequences. In the workshops with students (Chapter 5), the participants were able to relate policies to possible future events and discuss the results and implications. We also found that the participating students tended to consider average outcomes across scenarios where possible instead of acknowledging the

full range of possible outcomes. From this, we infer that participants are able to discuss uncertainties, but workshops need to be carefully designed to compel participants not to circumvent the uncertainties.

In Chapter 2, we identified the benefits of involving stakeholders in DMDU processes. Which of these benefits did we observe in our empirical work? The benefits for researchers or modelers that we identified include eliciting context-specific knowledge and identifying past, ongoing, or future projects. Engaging stakeholders in DMDU processes allowed us to incorporate possible risks or disruptive future events that might otherwise not be covered by a model developed by experts alone (as demonstrated in Chapters 3 and 5). Expanding participatory DMDU approaches into multi-session processes would allow for more collaboration and iterations of the model and the subsequent decisions and transition pathways. The benefits for participating stakeholders include creating ownership and agency to act, enhancing relevance, and creating trust and transparency. In the workshops with the municipality, participants reported learning and agency to act based on the workshop results. In the workshops in which students used the agent-based model to explore policies, participants reported that they trusted the model. Transparency in the assumptions and model limitations is crucial, especially when the participants are not involved in all parts of the DMDU process.

#### 6.4. GENERALIZABILITY

Throughout this dissertation, we use mobility in The Hague, the Netherlands, as a case study. The Hague is the third largest city in the Netherlands, with about half a million inhabitants, and part of a larger metropolitan area with connections to other cities. The municipality of The Hague has clear ambitions for transitioning towards more sustainable mobility. In applying our approach, we therefore assume a willingness to transition to a more sustainable system. [Rittel and Webber \(1973\)](#) argue that every wicked problem is unique and, therefore, it is important not to select a solution prematurely. Despite two problems seeming similar, it is never guaranteed that particularities do not invalidate commonalities. While the problem of mobility in The Hague is unique, the approach is generalizable to other mobility transition cases as well as cases of other domains. In the current version of our approach, this transition is characterized by a modal shift. Our approach has two elements: the participatory approach to engage stakeholders in decision-making under deep uncertainty, and the model that is subservient to the participatory workshops.

How transferable is our participatory approach to other cases involving mobility in cities, and what conditions must be met for a successful application elsewhere? While the approach was developed and tested in a specific city, it has the potential to be applied in other cities. Many cities face similar mobility transition challenges, but local factors influence the specific application of our approach. Some uncertainties that decision-makers face might be unique to the city, but most uncertainties are faced by cities with similar characteristics. Key factors affecting the transferability are urban characteristics (e.g., city size,

## 6.4. GENERALIZABILITY

connection to other cities, current and potential transport modes, and infrastructure), governance and policy frameworks (e.g., regulatory structures and political willingness to transition), and data availability and quality. Cities with comparable governance structures, policy goals, and economic conditions (such as other Dutch or European cities with strong sustainability agendas) would offer high direct transferability. Cities with different characteristics, for example, larger metropolitan areas with more complex transport networks, cities with different mobility needs and structures, and cities where informal transport (transport offered by private groups or individuals and often not planned by a central authority and under limited regulations) plays a role would require adaptation of the approach. There is potential for applying the approach in diverse urban contexts; however, the approach would need to be refined to the context at hand. Pilot studies in different cities could validate our findings and further develop the approach.

How transferable is our participatory approach to other domains beyond mobility? The approach developed in this thesis has broader applicability. The fundamental challenges that we tackled (e.g., deep uncertainty, stakeholder involvement, system complexity) are common in other domains, such as the energy transition, climate adaptation, water management, or public health policy. Applying the approach to other domains will require adjustments in the data and models used, as well as different stakeholders and decision criteria. There is potential for cross-domain applicability. Interdisciplinary collaborations to refine and test the approach could be a way to apply the approach to other domains.

How transferable is the agent-based model to other contexts? The Actor-Option Framework is a general conceptual framework suited for developing qualitative and quantitative models of socio-technical transitions (Yücel, 2014). The framework's high abstraction level makes it suitable for a wide range of applications. The agent-based model was developed for the context of The Hague with assumptions tailored to that context. However, the core model structure (e.g., agent interactions, policy inputs, option attributes) may be transferable with adaptations. The structure of the model allows for any transport mode to be added as a combination of option properties. This allows for exploring a wide range of hypothetical transport modes that are or will be developed in the future. Key aspects such as mode choice dynamics, responses to policies, and parameter values may need recalibration when applied to other urban settings. Data availability and local conditions affect how well the model can be applied.

To facilitate the transfer of participatory DMDU methods, the DMDU steps can be decomposed into repeatable short elements. Table 6.1 shows the workshop activities from Chapters 3 and 5 and how they correspond to the DMDU steps and their elements. While we covered many of the elements, we did not cover all of them. However, other studies addressed participatory scenario discovery (mapping outcomes to their conditions of occurrence) (Bryant and Lempert, 2010), showing trade-offs (Johnson, 2021), and deciding on plans to be implemented (Bhave et al., 2018; Lawrence et al., 2019). Therefore, collecting these activities in one place would be beneficial in comparing approaches and outcomes. Developing and documenting workshop activities in, for example, the format of scripts

Step	Element	Workshop activities
Frame	Formulate problem	Clarify vision
	Specify system structure	Define system scope Create Causal Loop Diagrams
	Specify objectives and goals	Define objectives and KPIs
	Identify alternative policies	Generate possible interventions
Explore	Specify uncertainties and disagreements	Generate future events using the STEEP framework
	Identify the outcomes of policies	Evaluate possible interventions under different futures Identify policy effects using the output of an ABM Discuss vulnerabilities of policies
	Map outcomes to their conditions of occurring	
	Show trade-offs	
Choose	Select initial and contingent actions	Discuss promising policies
	Create monitoring plan	

Table 6.1: DMDU steps, elements, and corresponding workshop activities

(Hovmand et al., 2012) enables researchers and practitioners to design their own workshops according to their needs.

## 6

## 6.5. CHALLENGES FOR PARTICIPATORY DMDU

In Chapter 2, we defined four challenges for establishing a practice of participatory DMDU: selecting projects, designing participatory processes, developing methods and tools, and structured evaluation. In this section, we reflect on how this dissertation has contributed to each challenge.

The first challenge is to select participatory projects and project elements. Actors can be involved in any component of the modeling process, but are rarely involved in all of them (Voinov et al., 2016). Careful project selection is important because involving stakeholders is time- and resource-intensive. This research showed the potential for participatory DMDU in the context of the mobility transition in a Western European city. More case studies are needed to study the efficacy of the approach and to learn when participation is most beneficial. Additionally, asymmetry in observed costs and potential benefits may prevent practitioners from investing in participatory processes. Therefore, attention should be paid to comparing participatory and non-participatory DMDU practices and exploring the full breadth of long-term project outcomes.

The second challenge is to design participatory processes. In chapter 2, we described initial design considerations for participatory processes: allow for including aspects of the problem that typically are not solved with a model, be transparent on what the used models can and cannot deliver and the influence on the wider decision-making area, and allow for collectively interpreting and making sense of results with a heterogeneous group of stakeholders. We adhered to these principles when designing the workshops of Chapters 3 and 5 as much as possible. Table 6.2 shows how the principles were addressed in this thesis and possible extensions. An established set of design principles would help guide the design of future pro-

## 6.5. CHALLENGES FOR PARTICIPATORY DMDU

cesses. Previous work on design principles for participatory research (Norström et al., 2020; d’Hont, 2020) can be used as a starting point and adapted to participatory DMDU.

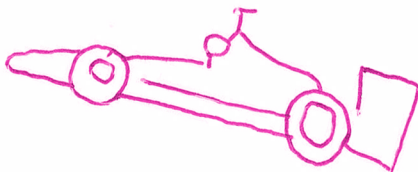
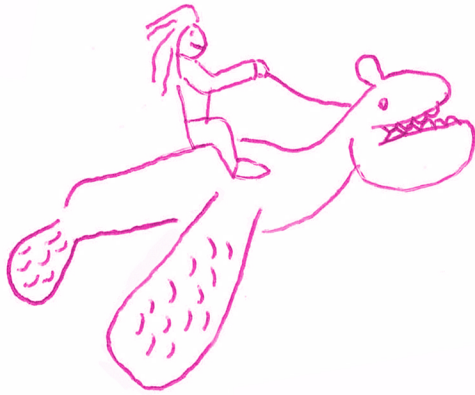
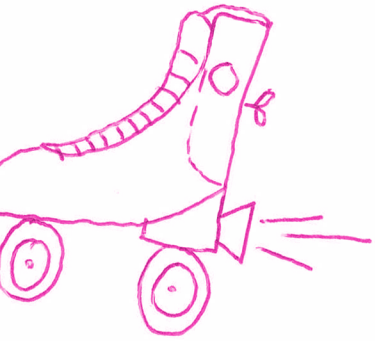
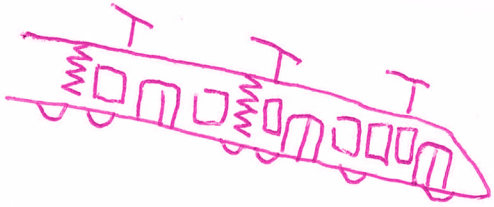
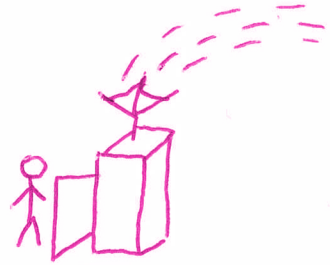
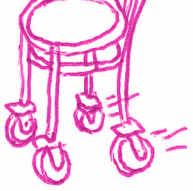
The third challenge is to develop methods, scripts, and tools. To stimulate the involvement of stakeholders, practitioners require concrete methods that are easy to replicate or adapt to specific contexts. It is necessary to develop and document methods, scripts, and tools for participatory DMDU in a transparent manner. To prevent the development of highly specialized and hard-to-transfer approaches, it would be useful to combine tools in light of the particular problem situation (Kwakkel and Haasnoot, 2019). In both the workshops of Chapters 3 and 5, we successfully combined various methods to create a workshop structure that fit the goals of that specific project. More well-documented participatory DMDU processes could ultimately lead to a directory of methods to easily access and design workshops. We provided the groundwork of designing workshop activities that could, for example, be developed into scripts (Hovmand et al., 2012). To contribute a script to the online encyclopedia “Scriptapedia”, elements such as the context and purpose of the script, nature of the task, time, materials, and steps need to be defined. Scripts are assigned a status of development: established, promising, or under development. Scripts become established if they have been applied by multiple teams independently and over time and yield reliable and generalizable results over a wide range of conditions (Scriptapedia, 2018). Our workshop activities would become promising scripts and could then be replicated by another team.

The fourth challenge is the evaluation of participatory DMDU processes to establish best practices and learn in which situations participation adds value and is worth the investment of time and resources. In this thesis, we evaluated the workshops with surveys before and after the workshops, focusing on key insights of the participants. Further work is needed to fully develop an evaluation framework for participatory DMDU. Drawing on previous work, such a framework could evaluate the method suitability (Moallemi et al., 2021), the content and process (Thissen and Twaalfhoven, 2001; Hassenforder et al., 2016), and the impact on actor behavior (Rouwette, 2016). Further aspects to evaluate could include an assessment of the suitability of the problem scope, the impact of participation on the quality of the analysis, implementation success, stakeholder satisfaction, and the potential benefits identified in Chapter 2. More participatory DMDU projects are needed to facilitate cross-comparison across contexts and the design of future activities.

Principle	Current implementation	Future directions
Allow for including aspects of the problem that are typically not solved with a model	Workshops incorporated aspects often overlooked by quantitative models, such as local knowledge, stakeholder experiences, and context-specific constraints.	Iterative refinement of model assumptions using participant insights; integration of missing variables or mechanisms; inclusion of broader system elements such as governance and institutional dynamics.
Be transparent about what the models can and cannot deliver, and their influence on decision-making	Workshops set expectations by communicating the scope, assumptions, and capabilities of the models. While they did not directly influence formal decisions, they supported broader understanding and deliberation on the mobility transition.	Interactive visualization of uncertainties; explicit documentation of how workshop insights can inform policy discussions; structured debriefs clarifying what the model can and cannot reliably support.
Enable collective interpretation and sense-making with heterogeneous stakeholders	Diverse participants contributed to capturing multiple perspectives and facilitated joint reflection on trade-offs, uncertainties, and interactions between policy options. While not directly shaping formal decisions, workshops enhanced shared understanding of the transition context.	Use of interactive visual tools; development of structured deliberation protocols; systematic documentation of stakeholder interpretations and collective learning outcomes.

Table 6.2: Principles of participatory DMDU, how they were addressed in this thesis, and possible extensions





# 7

## CONCLUSION

This research aimed to design and evaluate a theory-informed approach for participatory decision-making under deep uncertainty for wicked problems and applied this approach to case studies related to the urban mobility transition in the Netherlands. First, we analyzed the current state of decision-making under deep uncertainty, identified shortcomings, provided a general structure for participatory DMDU, laid out potential benefits for engaging stakeholders in DMDU processes, and identified four challenges in establishing a practice of participatory DMDU. Second, we conducted a case study focused on the first two DMDU steps: frame and explore. We supported the municipality of The Hague in generating robust policies through a novel qualitative approach combining participatory modeling and DMDU. Third, we developed an agent-based model that can be used in participatory settings. Based on the Actor-Option framework, this model simulates user choices under different policies and uncertainties and how this influences the modal split. Fourth, we used the agent-based model to employ participation in the second and third steps of the DMDU analysis: explore and choose. In a role-playing game where students assumed the role of decision-makers, we investigated whether the participants could make decisions based on model outputs supplemented with a qualitative discussion on aspects not included in the model.

This chapter answers the research questions introduced in Chapter 1. Recommendations for future research conclude this dissertation.

### 7.1. ANSWERS TO THE RESEARCH QUESTIONS

This research was divided into four sub-questions, which we answer in this section.

### RQ 1: WHAT ARE THE BENEFITS AND CHALLENGES OF COMBINING PARTICIPATORY MODELING AND DECISION-MAKING UNDER DEEP UNCERTAINTY?

Approaches for decision-making under deep uncertainty typically include three general steps: frame, explore, and choose. We used this generic DMDU process as a guiding framework to identify the benefits of involving stakeholders. In the framing step, engaging stakeholders can provide context-specific knowledge to the researcher. Communicating the relevance of this problem to stakeholders can help to create ownership of the problem and agency. In the exploring step, stakeholder involvement can improve the relevance of the analysis and aid in validating the model and its outcomes. In the choosing step, participatory activities can help to create transparency and trust in the model and trade-offs, as well as agency to act and implement.

We concluded this research with four challenges in establishing a practice of participatory DMDU:

1. Select promising participatory projects and project elements to justify the time- and resource-intensive involvement of stakeholders.
2. Design valuable processes that allow for including aspects of the problem that typically are not solved with a model, are transparent on what the used models can and cannot deliver and the influence on the wider decision-making area, and allow for collectively interpreting and making sense of results with a heterogeneous group of stakeholders.
3. Develop and document methods, scripts, and tools that are easy to replicate or adapt to specific contexts and that can be combined in light of the particular problem situation.
4. Evaluate participatory DMDU processes transparently to establish best practices and learn in which situations participation adds value and is worth the investment of time and resources.

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### RQ 2: WHAT IS A FEASIBLE APPROACH FOR COMBINING PARTICIPATORY MODELING AND DECISION-MAKING UNDER DEEP UNCERTAINTY FOR GENERATING CLIMATE-NEUTRAL URBAN MOBILITY SOLUTIONS?

In this study, we developed an innovative approach for participatory modeling under deep uncertainty. We illustrated how such an approach can be applied to support the development of a climate-neutral transport system for the city of The Hague. 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. Our focus with this study lies on step 1, 'Frame,' and step 2, 'Explore,' of DMDU.

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

## 7.1. ANSWERS TO THE RESEARCH QUESTIONS

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.

By explicitly linking 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 interrelatedness of interventions and their effects, and a shared understanding of the problem and its scope. We observed that participants were able to think causally, vary the problem scope, envision uncertain futures, and identify unintended consequences. This study demonstrates the potential of the approach to generate interventions and evaluate their robustness in the highly uncertain context of climate-neutral mobility.

### RQ 3: WHICH CONCEPTS AND RELATIONS EXPLAIN THE TRANSITION OF THE URBAN MOBILITY SYSTEM BEHAVIOR TOWARDS CLIMATE NEUTRALITY?

We developed an agent-based model theoretically grounded in the Actor-Option framework, enabling us to regard the system more comprehensively than other studies, let any transport innovation emerge in it, and analyze the interaction of multiple transport modes. The Actor-Option framework specifies four types of actors: users, providers, regulators, and opinion groups. An actor is a unit of analysis with goals, preferences, resources, and actions. An actor does not necessarily refer to an individual person (Yücel, 2014); an actor can also be an organization, government agency, firm, or pressure group. An option is a means to fulfill a societal need. The options within the transport system are the different modes a user can utilize to fulfill their transport need. In the case of transport, one technology can serve several modes, depending on how it is used (e.g., private car and car sharing). Any (new or existing) mode can be described as a combination of attributes. Other aspects of the transport system, such as infrastructure and the operational scheme (e.g., the timetable of a train) of an option, can also be reflected in the option properties. The framework identifies three sets of mechanisms for change, describing how option properties change, how actors learn new information, and how actors' behavioral identities change.

We simplified the rich conceptualization of the Actor-Option framework to make the model suitable for participation. Of the four actor types, only users are endogenous to our model. Provider and regulator decisions are used as exogenous input for policies. Opinion groups are not represented in this model since they are out of the scope of this study. We differentiate two sets of options: the base set and the experimental set. The base set represents the options currently present in the city. In our case, these are cars, bikes, e-bikes, public transport, walking, scooters, and motorbikes. The experimental set encompasses these seven modes

and, in addition, an innovation. Each transport mode has a starting cost, cost per kilometer, value of travel time, and comfort associated with it.

The two key mechanisms in this model are the change in option properties through policies and learning among users via their social network. For the first mechanism, one or more policies are activated. Each policy alters an attribute of one or more transport modes. The change in option properties alters the performance of this transport mode during the mode choice, influencing the modal share of that mode over time. The second mechanism, peer-to-peer learning about new transport modes, causes changes in actors' perceptions and allows them to add new modes to their choice set. We assume that this knowledge enters the system through an external source and reaches a group of early adopters. These early adopters then spread the knowledge through the social network.

We found that policies have a significant impact on simulated outcomes and that learning in social networks is critical to the transition. Combining policies can create symbiotic effects, amplifying their impact. Transition dynamics are sensitive to uncertainties in social learning and timing of mode replacement. Results show that parking-related costs are especially influential in shifting behavior away from car use. In addition, the model assumes that mode choice is habitual; therefore, any changes in the system that force users to change their habits can speed up the transition.

This agent-based model can be used to aid decision-makers by providing insight into simulating transition dynamics and possible future scenarios, potentially even in participatory settings.

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#### RQ 4: WHAT IS A FEASIBLE APPROACH FOR COMBINING PARTICIPATORY MODELING AND DECISION-MAKING UNDER DEEP UNCERTAINTY FOR DELIBERATING CLIMATE-NEUTRAL URBAN MOBILITY SOLUTIONS?

This study contributed a novel approach to participatory decision-making under deep uncertainty. We demonstrated that an activity with role-playing and gaming elements is a promising approach to exploring model-based decision-making with participants of varying backgrounds.

During the workshop, 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. 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 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 that this policy might be vulnerable to and how to mitigate these vulnerabilities. The participants presented their results to the plenary group after the discussion rounds. 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

## 7.2. FUTURE RESEARCH

usefulness of the model results, their experience of the workshop, and what they learned.

The workshops provided us with three main insights: relating to the participants' interaction with the model, the participants' approach to uncertainty, and the applicability to other groups. First, the participants could use the model and make decisions based on the model outputs, acknowledging the system's complexity. The participants took on their roles well, performed tasks seriously, and were engaged throughout the workshop. Second, the participants were aware that the model did not represent every aspect of the system and could discuss aspects that were not included. However, participants tended to mainly pay attention to the average modal split, indicating that 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. Third, despite their differing backgrounds, we found no significant difference between the two groups' performance. Both groups demonstrated understanding of the model - one group through their critical comments and discussion, the other through asking probing questions. The similarity in the overall performance of the two groups suggests that this type of workshop can be done with participants of differing backgrounds with no modeling experience. Participants may not develop a full grasp of the underlying model structure and behavior (design logic), but they can build an understanding of how particular policies affect outcomes (operator knowledge).

## 7.2. FUTURE RESEARCH

We see three main avenues for future research: conducting more case studies to validate and expand our findings, improving our model and future modeling efforts, and addressing the challenges for establishing participatory DMDU.

First, future research should focus on conducting additional case studies to validate the findings of this dissertation in different contexts. More case studies would allow for refining the participatory DMDU approach by testing it across diverse policy environments, system structures, and even domains. For example, it would be interesting to compare cases across countries with different governance structures or apply the approach to other transitions, such as the energy transition. Future studies should also focus on engaging more diverse participant groups, including underrepresented stakeholders or stakeholders opposed to certain sustainable mobility policies, to explore how different perspectives and conflicts influence decision outcomes.

Multi-session workshops with the same group of participants would allow for iteration, reflection, and deeper stakeholder collaboration. Such an iterative process could lead to more robust policies through revisiting assumptions, exploring alternative strategies, and adjusting preferences. Running workshops over a longer time period could also foster stronger relationships between actors, creating a basis for deeper collaboration and trust in the decision-making process, as well as sustained engagement in planning for long-term challenges such as mobility. Moreover, allowing time in between sessions could help refine tools and methods in between the sessions to better adapt them to stakeholders' needs and

the problem situation.

Second, future research should focus on developing interfaces and visualizations for models to help participants engage meaningfully with the uncertainty rather than circumvent it. Meaningful interaction means the participants are able to understand sources of uncertainty and its impact on the analysis, think causally, and learn. Improved user interfaces should balance complexity and usability, ensuring that non-experts can interact with the model without feeling overwhelmed while still understanding how the model works, why it works this way, and engaging with uncertainty. Allowing stakeholders to explore the consequences of their decisions in real-time, through, for example, manipulating key parameters, could foster deeper engagement and ownership of decisions as well as build causal knowledge. For example, such an interface could include the possibility to select a subset of runs, to explore how the input matches output uncertainty, and to understand what drives system behavior and the conditions for vulnerabilities and opportunities. The type of information provided affects actors' performance (Franco et al., 2021) and therefore needs to be chosen very carefully.

Refining the agent-based model to better capture social interactions could provide deeper insights into transition pathways. Modeling user behavior in more detail, including heterogeneity in preferences, risk perception, and behavioral inertia, would improve the model's ability to reflect real-world mobility transitions. Incorporating attitude changes over time, influenced by factors such as policy interventions, social learning, or personal experiences, could lead to more realistic projections of long-term behavioral shifts. Future studies could integrate empirical data from surveys, interviews, or real-world experiments to investigate how social influence and attitude shifts affect the mobility transition.

Third, future research should address the four challenges for establishing a practice of participatory DMDU. Future research should explore criteria and mechanisms for identifying which policy issues or projects are best suited for participatory DMDU, ensuring that stakeholder engagement adds value in contexts of deep uncertainty. More work is needed to develop best practices for structuring participatory engagements. These best practices could ultimately be formulated into a set of design principles. Advancing the methodological toolkit for participatory DMDU, such as refining modeling approaches, integrating diverse data sources, and improving facilitation techniques, can enhance the effectiveness of stakeholder interactions. Documenting these tools well is essential to enable more practitioners and researchers to conduct participatory DMDU processes. Establishing robust evaluation frameworks is crucial for assessing the impact of participatory DMDU, ensuring that processes are not only inclusive but also lead to meaningful, implementable decisions.

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# A

## APPENDIX FOR CHAPTER 3

This appendix includes the structure and materials for the workshops of Chapter 3.

## A.1. STRUCTURE OF THE FIRST WORKSHOP

Table A.1 shows the activities of the first workshop of Chapter 3, along with the estimated time, desired outcome, and method used.

Step	Time	Activity	Outcome	Method
1	15 min	Introduction of the background, goals of the session, agenda, facilitators, and participants	Participants understand background and goals of the session and get to know each other	Presentation
2	25 min	Revisiting the vision of 100 Climate Neutral and Smart Cities	Clear vision	Nominal Group Technique and group discussion
3	20 min	Objectives and KPIs	Clear goals and objectives with measurable KPIs	Nominal Group Technique and group discussion
4	10 min	Break		
5	10 min	Introduce Causal Loop Diagrams	Participants understand Causal Loop Diagrams	Presentation
6	15 min	Collect options	Ranked list of transport modes to regard	Collecting them from the group and voting with stickers
7	15 min	Collect variables	Variables clustered according to themes	Group Model Building Script 'Variable Elicitation'
8	10 min	Break	Facilitator adds variables to Kumu to project them to the group for the next task	
9	25 min	Causal Loop Diagram for most important mode	First draft of system structure	Group Model Building Script 'Initiating and Elaborating a Causal Loop Diagram'
10	20 min	Causal Loop Diagrams for other relevant modes (in small groups)	System structure for other modes	Group Model Building Script 'Causal Loop Diagram from variable list'
11	20 min	Presentation of and reflection on Causal Loop Diagrams	Knowledge exchange between groups	Presentation and discussion
12	10 min	Closing and outlook to the next session	Debrief, reflection	Presentation

Table A.1: Structure of the first workshop

## A.2. STRUCTURE OF THE SECOND WORKSHOP

### A.2. STRUCTURE OF THE SECOND WORKSHOP

Table A.2 shows the activities of the second workshop of 5, along with the estimated time, desired outcome, and method used.

Step	Time	Activity	Outcome	Method
1	5 min	Introduction of the goals of this session and agenda for the day	Participants understand background and goals of the session	Presentation
2	10 min	Objectives from last session	Participants recall objects	Presentation
3	10 min	Aggregated Causal Loop Diagram	Participants understand how CLDs can be used to find interventions	Presentation
4	40 min	Elicitation of possible interventions	List of possible interventions, clustered by mode and type	Participants note them on a template, then share
5	10 min	Break		
6	20 min	Future events based on the STEEP framework	List of future events and trends	Participants note them on post-its, then share
7	35 min	Evaluating the interventions	Consequences of interventions under different futures	Participants fill evaluation template and prepare presentation
8	10 min	Break		
9	30 min	Presentation and Discussion of interventions	Discussion on implications, most promising interventions	Group discussion
10	20 min	Reflection on the session and feedback to us	Reflection	Group discussion
11	10 min	Closing and outlook to the report		Presentation

Table A.2: Structure of the second workshop

### A.3. OBSERVATION

The observer used the following questions and prompts as a guide for the first workshop:

1. List of perspectives
2. Who is participating in this part?
3. Who is not participating in this part?
4. When does communication happen?
5. Who is open to new ideas and in what setting?
6. Considerations about where to delineate the modes
7. Which modes are named (and which are not)?
8. Which variables were disputed/discussed?
9. Which themes emerged?
10. What was subject to discussion?
11. What is there consensus on?
12. What was not discussed?
13. Differences between the groups
14. Reflections of participants
15. Participant satisfaction

The observer used the following questions and prompts as a guide for the second workshop:

1. List of perspectives
2. Who is participating in this part?
3. Who is not participating in this part?
4. When does communication happen?
5. Who is open to new ideas and in what setting?
6. Does the level of abstraction when introducing the CLDs work
7. Consensus, dissensus, confusion during the creation of CLDs
8. Futures and their categories
9. Common themes of futures

### A.3. OBSERVATION

10. Novelty/creativity of futures
11. Are the events positive or negative?
12. Time scale of futures
13. Consequences that were considered
14. How did the participants deal with uncertainty? (skepticism, importance, ignorance, etc.)
15. What was subject to discussion?
16. What is there consensus on?
17. What was not discussed?
18. Reflections of participants
19. Participant satisfaction

## A.4. SURVEYS

Before and after each workshop, participants filled out a survey. On each survey, they noted down their name and function.

### SURVEY BEFORE THE FIRST WORKSHOP

1. What is your field of expertise? (Multiple answers possible)
  - mobility
  - urban planning
  - transitions
  - behavior
  - strategy
  - smart cities
  - policy
  - Others, please specify:
2. What are you expecting as collective outcomes of these workshops? For instance, to create a shared insight into the challenge to reach climate neutrality or to achieve a consensus on specific actions to take.
3. What are you expecting personally in these workshops? For instance, what do you hope to learn or gain from your involvement in the workshop, or what do you think you will contribute?
4. Do you have any particular concerns regarding these workshops? Would you like to share your concern with us? For example, participants may not be able to reach consensus or share their opinion openly.
5. If you have any additional comments you would like to share, please mention them below.

### SURVEY AFTER THE FIRST WORKSHOP

1. What do you consider the key outcomes of this workshop?
2. Did you learn anything new today? If yes, what? (concepts, words, others' perceptions) and in what setting?
3. What was your most valuable (or surprising) insight?
4. Did this workshop enhance your knowledge of the system? If so, how?
5. If you have any additional comments you would like to share, please mention them below.

## A.4. SURVEYS

### SURVEY BEFORE THE SECOND WORKSHOP

1. What are you expecting for today's workshop? For instance, to create a shared insight into the challenge to reach climate neutrality, to achieve a consensus on specific actions to take, to learn something new, or to contribute to the discussions.
2. If you have any additional comments you would like to share, please mention them below.

### SURVEY AFTER THE SECOND WORKSHOP

1. What do you consider the key outcomes of this workshop?
2. Did you learn anything new today? If yes, what? (concepts, words, others' perceptions) and in what setting?
3. What was your most valuable (or surprising) insight?
4. What do you consider the key outcomes of the two workshops?
5. What were the three best features of the two sessions? For instance, activities, facilitation, discussions, or outcomes.
6. What were the three most disappointing features of the two sessions? For instance, activities, facilitation, discussions, or outcomes.
7. Do you have any suggestions for improving the workshops?
8. If you have any additional comments you would like to share, please mention them below.

## A.5. TEMPLATE FOR GENERATING INTERVENTIONS

Figure A.1 shows the template used for generating interventions and noting down the characteristics of each intervention. The space in the top right was used to place stickers for voting. This template was printed in A5 format.


What?		
Mode	Type	
Who?	When?	
Objectives		

Figure A.1: Template for generating interventions

## A.6. TEMPLATE FOR EVALUATING INTERVENTIONS

### A.6. TEMPLATE FOR EVALUATING INTERVENTIONS

Figure A.2 shows the template used for evaluating the interventions under different futures. This template was printed in A3 format.

Intervention	Consequences
--------------	--------------



Future	Impact
Future	Impact
Future	Impact
Future	Impact
Future	Impact

Figure A.2: Template for evaluating interventions

## A.7. INFORMED CONSENT FORM

### A.7. INFORMED CONSENT FORM

Before the workshops, all participants signed an informed consent form in accordance with the TU Delft Human Research Ethics Council (Figures [A.3](#) and [A.4](#)).

**Delft University of Technology**  
**HUMAN RESEARCH ETHICS**  
**INFORMED CONSENT**

You are being invited to participate in a research study titled 'On the Move to Climate Neutral mobility'. This study is being done by Karoline Führer from the TU Delft and Peraphan Jittrapirom from the Radboud University Nijmegen in collaboration with the municipality of The Hague.

The city of Den Haag and researchers from the 'On the Move' project are organizing two workshops to facilitate knowledge co-creation on the city's transport system. The workshop aims to elucidate the complexity of the city's transport system and explore possible sets of policy levers or pathways toward a climate neutral mobility system in 2030. The process will help to surface diverse understanding and opinions on the subject among the participants. Throughout this process, we aim to embrace different types of uncertainty, such as those that may occur when participants cannot know or cannot agree on certain parts of the system or future contextual events (such as availability of a new technology or a shift in travelers' preferences) that may affect implementation of policy levers and their effectiveness. The research will take place in two workshops of about three hours each. The data will be used to create a report of the workshops to be used in the further planning of the '100 Climate Neutral Cities' project of the municipality. Further, the data will be used for scientific publication. We will be asking you to provide input to the questions and tasks in the workshops. In the first workshop, we will first frame, delineate, and formulate the challenges to reach the climate neutrality vision and what it means for the mobility sector. Second, we will define our understanding on the complexity of the transport system by using a qualitative modelling technique. In the second workshop, we focus on identifying the uncertainties that are relevant for this project. We imagine different futures and test the alternative courses of action against these futures. We also discuss how these courses of action can be protected from failing under different future circumstances.

To the best of our ability your answers in this study will remain confidential. We will minimize any risks by storing data safely and anonymising any data that might be published.

Your participation in this study is entirely voluntary and you can withdraw at any time. You are free to omit any questions or tasks in the workshops.

Corresponding researcher:  
Karoline Führer  
k.j.fuhrer@tudelft.nl

Figure A.3: Informed Consent Form (Page 1)

## A.7. INFORMED CONSENT FORM

PLEASE TICK THE APPROPRIATE BOXES	Yes	No
<b>A: GENERAL AGREEMENT – RESEARCH GOALS, PARTICIPANT TASKS AND VOLUNTARY PARTICIPATION</b>		
1. I have read and understood the study information dated [08-05-2023], or it has been read to me. I have been able to ask questions about the study and my questions have been answered to my satisfaction.	<input type="checkbox"/>	<input type="checkbox"/>
2. I consent voluntarily to be a participant in this study and understand that I can refuse to answer questions and I can withdraw from the study at any time, without having to give a reason.	<input type="checkbox"/>	<input type="checkbox"/>
3. I understand that taking part in the study involves: Audio recordings that will be partly transcribed, photos of the session, a survey questionnaire completed by myself	<input type="checkbox"/>	<input type="checkbox"/>
<b>B: POTENTIAL RISKS OF PARTICIPATING (INCLUDING DATA PROTECTION)</b>		
4. I understand that taking part in the study involves the following risks: conflict among the participants and contested opinions that might induce stress. I understand that these will be mitigated through the facilitation and guidance of the workshops and the possibility to withdraw participation at any point.	<input type="checkbox"/>	<input type="checkbox"/>
5. I understand that personal information collected about me that can identify me, such as my name and function in the organisation, will not be shared beyond the study team.	<input type="checkbox"/>	<input type="checkbox"/>
6. I understand that the (identifiable) personal data I provide will be destroyed at the end of the project.	<input type="checkbox"/>	<input type="checkbox"/>
<b>C: RESEARCH PUBLICATION, DISSEMINATION AND APPLICATION</b>		
7. I understand that after the research study the de-identified information I provide will be used for a report and a journal article. Within the municipality, the outputs of these workshops will be used within the '100 Climate Neutral Cities' project.	<input type="checkbox"/>	<input type="checkbox"/>
8. I agree that my responses, views or other input can be quoted anonymously in research outputs.	<input type="checkbox"/>	<input type="checkbox"/>

Signatures		
_____	_____	_____
Name of participant [printed]	Signature	Date
I, as researcher, have accurately read out the information sheet to the potential participant and, to the best of my ability, ensured that the participant understands to what they are freely consenting.		
_____	_____	_____
Researcher name [printed]	Signature	Date
Study contact details for further information: <i>Karoline Führer, k.j.fuhrer@tudelft.nl</i>		

Figure A.4: Informed Consent Form (Page 2)



# B

## APPENDIX FOR CHAPTER 4

### B.1. ODD PROTOCOL

The model description follows the ODD (Overview, Design concepts, Details) protocol for describing individual- and agent-based models (Grimm et al., 2020).

#### B.1.1. PURPOSE AND PATTERNS

The model aims to explore the consequences of various transport policies and the introduction of novel transport modes to understand how different policy and innovation configurations affect the mobility transition. The general patterns this model displays are changes in the number of trips per transport mode depending on the policy. If a mode is changed to make it more attractive to users (e.g., lower cost or shorter travel time), we expect more trips performed with this mode, and vice versa.

#### B.1.2. ENTITIES, STATE VARIABLES, AND SCALES

The following entities are included in the model: agents representing users of the transport system and the global environment representing the transport system.

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 them, and a list of trips that they perform. A trip has an origin and destination location, and a distance and travel time for each mode. Further, all agents are connected in a small-world social network. The social network does not represent spatial proximity, but rather how information spreads through the system. The state variables that change over time are the mode choices for each trip.

The global environment is the model containing the transport mode entities and policy definitions. Each transport mode has a cost per distance, a starting cost, a value of travel time, and comfort. Policies are the rules that create change. Each possible policy and its impact on transport mode or agent variables is defined in the model environment.

The model's spatial extent is the Netherlands at a postcode-level resolution. Agents are located within the city of The Hague but are able to make trips to other locations. The temporal scale of the model is one-quarter of a year per model tick. This timescale is sufficient to represent the slow change in habitual travel choices.

### B.1.3. PROCESS OVERVIEW AND SCHEDULING

This model represents the mode choice of user agents. Upon initialization, all agents choose from the modes available to them a mode for each of their trips based on the utility calculated from the distance and travel time of the trip and the characteristics of the mode.

At every time step, all agents are activated in a random order, and they do two things.

First, all agents learn from the agents that are on their list of neighbors. If an agent's neighbor has a mode in their list of used modes that this agent does not know about yet, that mode is added to this agent's list of known modes.

Second, all agents update their list of available modes. These are all the modes they can choose from when choosing a mode for each of their trips. Each mode has a probability of moving from a known mode to an available mode. This probability reflects the barrier to taking up that mode (e.g., financial commitments, memberships, or required skill). In addition to adding known modes to available modes, modes that have not been used in the last few model ticks are removed from the available modes.

In addition, agents update their mode choices from time to time. The basic assumption is that mode choice behavior is habitual and only changes infrequently. A major known driver for updating mode choices is when a mode available to an agent is in need of replacement (Rodrigue, 2024). We implement this mechanism using event scheduling. Each agent schedules the timestep at which it will next re-evaluate its mode choices. The time between two mode choice updates is drawn randomly from a triangular distribution. The distribution differs between modes and reflects the minimum, average, and maximum lifetime of that mode. The agent draws values for all its modes and uses the lowest number for its next re-evaluation of its mode choices.

### B.1.4. DESIGN CONCEPTS

Design concepts describe how concepts that characterize ABMs were implemented in this model.

The first design concept describes the basic principles. This model follows the basic principles of the Actor-Option framework, as described in section 4.3.1. The user agents make their choices based on utility maximization. Change comes about through changes in option properties and, subsequently, user choices.

The second design concept is emergence, describing how system behavior can emerge from agent behavior. The key outcomes of the model are the number of trips performed with each transport mode. These results emerge from the individual choices of each agent for each of its trips, depending on mode characteristics.

The third design concept identifies the agents' responses to stimuli. Agents

## B.1. ODD PROTOCOL

choose among different transport modes. Their set of modes to choose from is influenced by the modes their neighbors in the social network have available to them. Their choice of transport mode is affected by the characteristics of the trip they choose their mode for, and the characteristics of the mode. Based on these two sets of characteristics, the agent identifies the mode with the highest utility for each of their trips.

The fourth design concept defines the objective measure. Agents calculate the utility for each mode for each trip with the following utility function:

$$U = -c_s - c_d \cdot d - (vtt \cdot t) \cdot m \quad (\text{B.1})$$

The utility  $U$  is calculated with the mode-specific variables starting cost  $c_s$ , the cost per distance  $c_d$ , the value of travel time  $vtt$ , the comfort multiplier  $m$ , and with the trip-specific variables distance  $d$  and travel time  $t$ .

The fifth design concept describes how agents change their decision-making methods. This is not represented in this model.

The sixth design concept is prediction. The agents' actions in this model are not based on explicit estimates of future conditions.

The seventh design concept is sensing and addresses the information agents know and use in their behavior. The agents know which trips they perform and the trip characteristics, as well as the modes they have available to choose from and the mode characteristics. These are the variables needed to calculate the utility. Agents sense their neighbors' available modes and update their own accordingly. This represents learning and the diffusion of information through the social network.

The eighth design concept is interaction. Apart from sensing their neighbors' available modes, the agents in this model do not interact.

The ninth design concept is stochasticity. In this model, the agents are activated in a random order, while each agent has random times between mode choice re-evaluations. Another source of stochasticity is the social network, whose creation includes probability.

The tenth design concept is collectives. There are no collectives implemented in this model.

The eleventh design concept is observation and describes how information is collected and analyzed. The information collected is all agents' trips with their chosen transport at each time step. These trips are written out with their origin, destination, distance, travel time, and chosen mode. Based on this, we can observe the changes in modal split over time and the development over time for the number of trips of each mode. This output data corresponds to commonly collected mobility panel data, where trips and the corresponding mode of respondents are collected multiple times over a longer time period.

### B.1.5. INITIALIZATION

Initialization of the model includes creating the agent population, connecting the agents in the social network, and parameterizing the transport modes.

When generating the agent population, each agent gets assigned a home location, a list of available modes, and a list of trips. This population synthesis is done before running the model, and the agent population is read as a file upon initializing the model. The agents are then connected in a Watts-Strogatz graph representing the small-world social network. Agents are first connected to  $k$  neighbors, and each edge is then randomly reconnected with a probability  $p$ . Finally, the transport modes are initialized with their parameters.

The initialization of this model is case-specific. The agent population is based on mobility panel data (CBS, 2024). The parameters of transport modes, such as cost and value of travel time, are specific to The Netherlands (Kouwenhoven et al., 2023).

## B.2. SUPPLEMENTARY TABLES

Table B.1 shows the average modal share at the end of the simulation for each mode under each policy scenario.

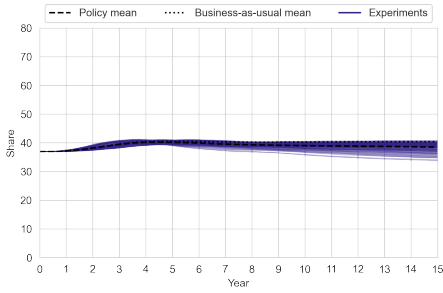
Mode	BAU	bi	pc	in	bi+pc	bi+in	pc+in	all
car	40.42	5.98	30.82	38.49	4.99	28.50	5.27	4.24
bike	37.38	55.28	49.30	35.97	65.62	46.43	50.18	58.77
ebike	2.98	3.84	1.73	2.95	1.98	1.73	3.79	1.96
pt	13.66	15.01	13.01	13.20	14.25	12.30	14.09	13.06
walk	2.94	3.22	2.68	2.91	3.02	2.61	3.36	2.99
scooter	2.16	8.95	2.09	2.09	6.46	1.92	7.90	5.52
motorbike	0.46	7.71	0.36	0.41	3.67	0.34	5.75	2.62
inno	0.00	0.00	0.00	3.98	0.00	6.17	9.67	10.85

Table B.1: Mode shares at the final model step under different policy scenarios. Policy key: bi = bike infrastructure; pc = parking cost; in = introduction of an innovation.

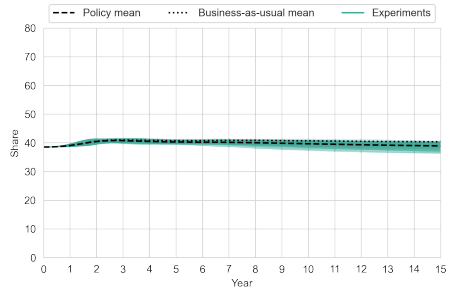
## B.3. SUPPLEMENTARY FIGURES

Figures B.1 to B.5 show the shares over time for all modes for all policies.

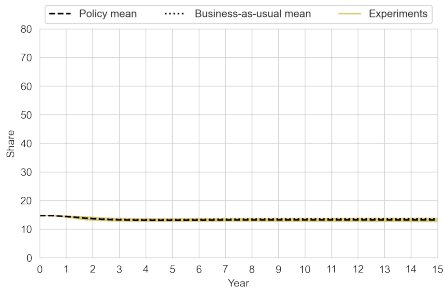
### B.3. SUPPLEMENTARY FIGURES



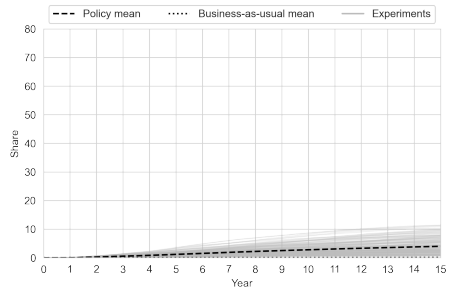
(a) Car share over time



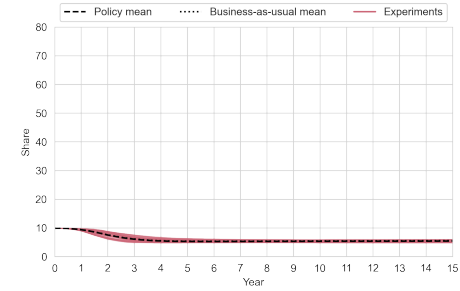
(b) Bike and e-bike share over time



(c) Public transport share over time

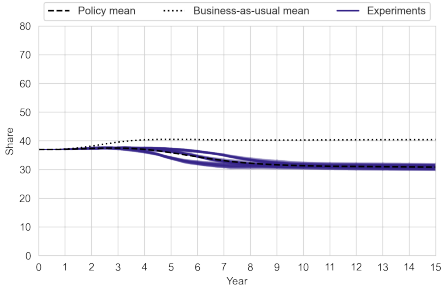


(d) Innovation share over time

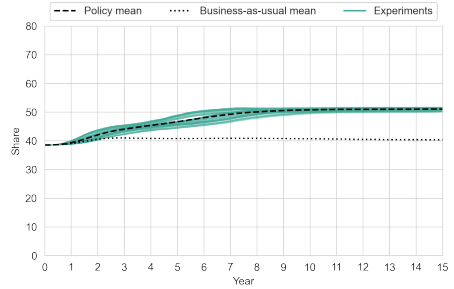


(e) Remaining modes (walk, scooter, motorbike) share over time

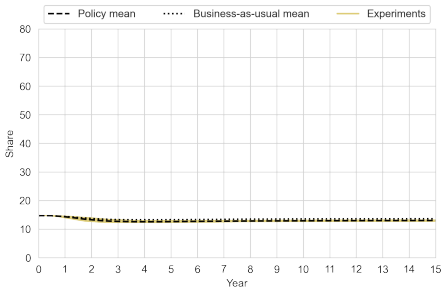
Figure B.1: Modal shares over time for the innovation policy scenario



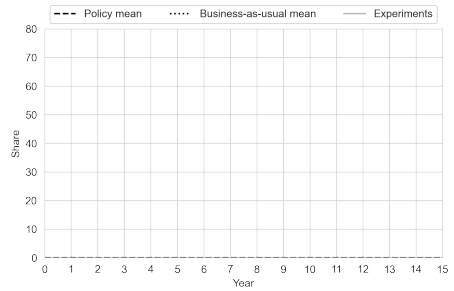
(a) Car share over time



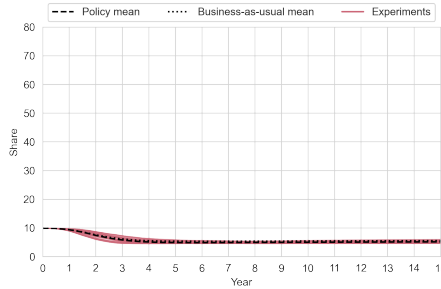
(b) Bike and e-bike share over time



(c) Public transport share over time



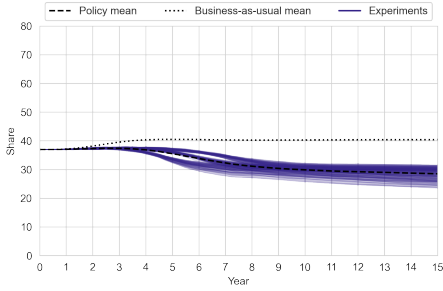
(d) Innovation share over time



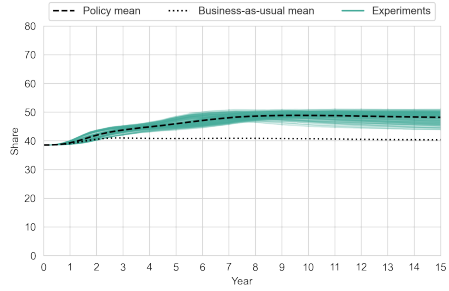
(e) Remaining modes (walk, scooter, motorbike) share over time

Figure B.2: Modal shares over time for the bike infrastructure policy scenario

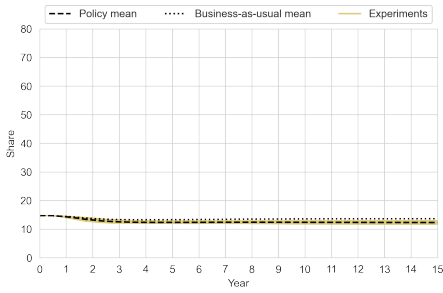
### B.3. SUPPLEMENTARY FIGURES



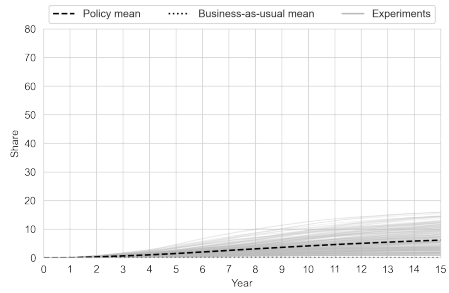
(a) Car share over time



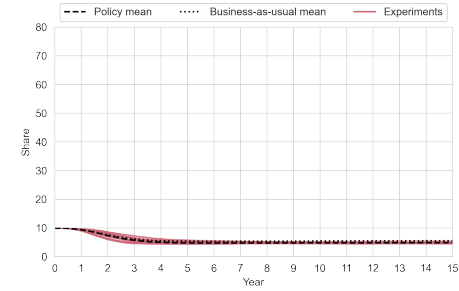
(b) Bike and e-bike share over time



(c) Public transport share over time



(d) Innovation share over time



(e) Remaining modes (walk, scooter, motorbike) share over time

Figure B.3: Modal shares over time for the combined bike infrastructure and innovation policy scenario

## B. APPENDIX FOR CHAPTER 4

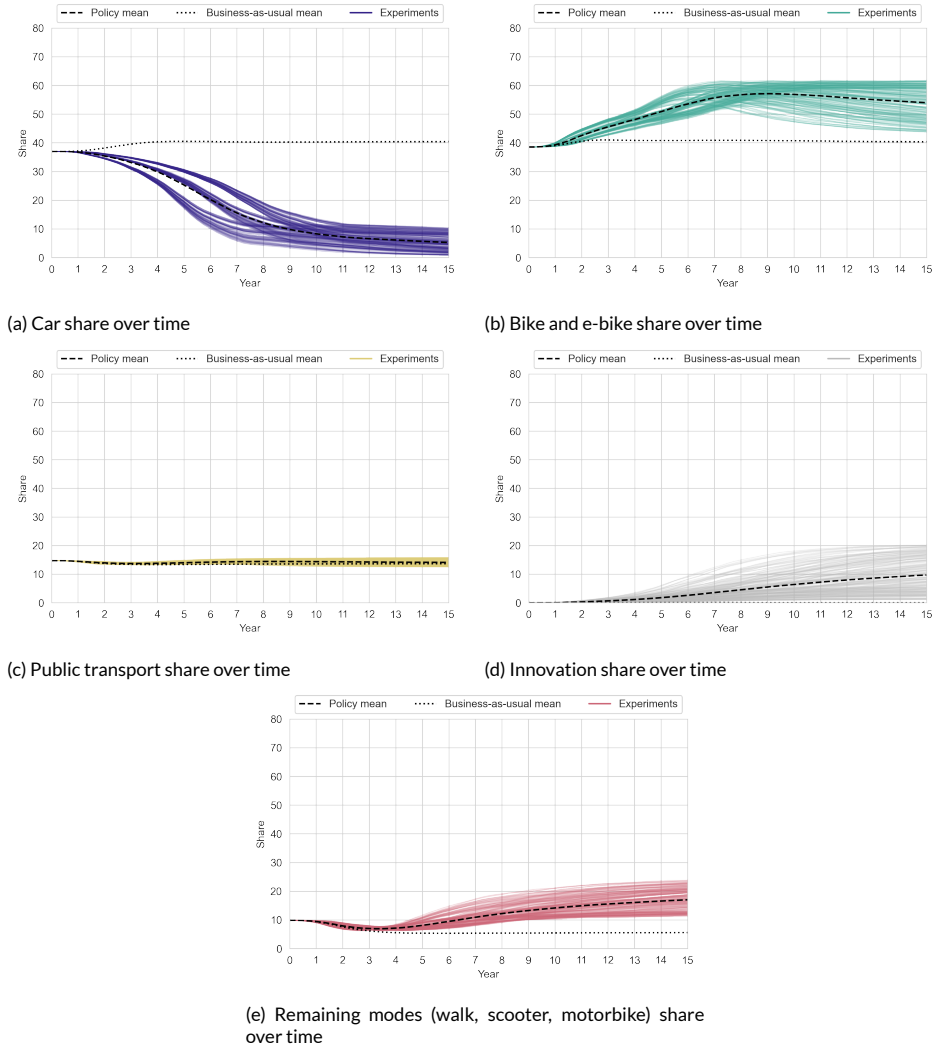
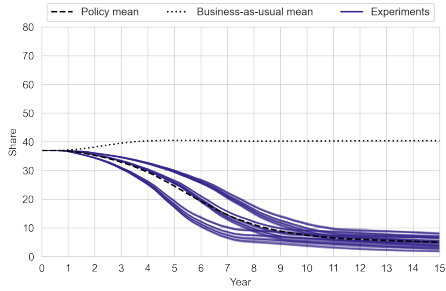
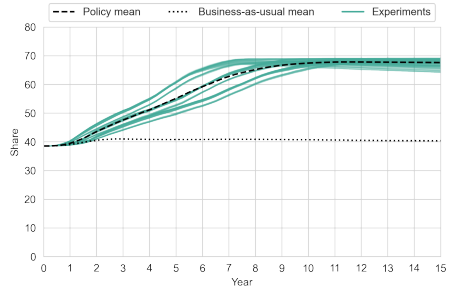


Figure B.4: Modal shares over time for the combined parking cost and innovation policy scenario

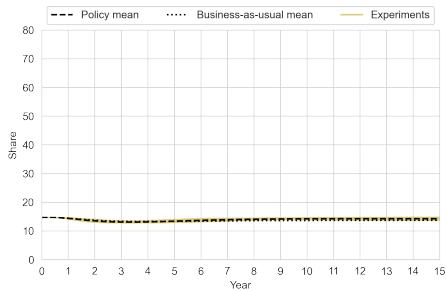
### B.3. SUPPLEMENTARY FIGURES



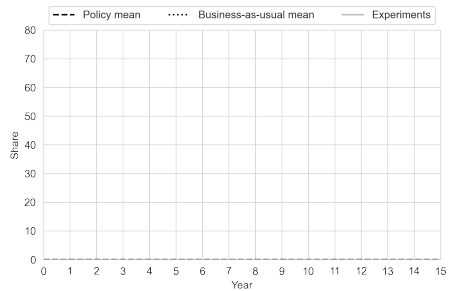
(a) Car share over time



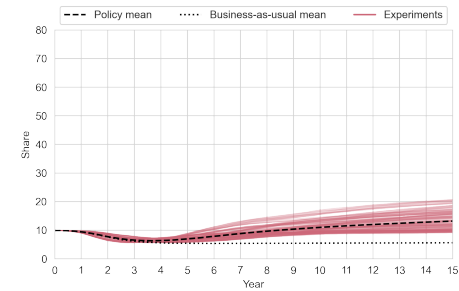
(b) Bike and e-bike share over time



(c) Public transport share over time



(d) Innovation share over time



(e) Remaining modes (walk, scooter, motorbike) share over time

Figure B.5: Modal shares over time for the combined parking cost and bike infrastructure policy scenario



# C

## APPENDIX FOR CHAPTER 5

This appendix includes the structure and materials for the workshops of Chapter 5.

## C.1. STRUCTURE OF THE WORKSHOP

Table C.1 shows the activities of the workshops of Chapter 5, along with the estimated time, desired outcome, and method used.

Step	Time	Activity	Outcome	Method
1	5 min	Introduction of goal and objectives of the workshop and participants	Participants understand the goal and objectives and get to know each other	Presentation
2	5 min	Introduction of case study	Participants understand case study context	Presentation
3	10 min	Explanation of the ABM	Participants understand the model	Presentation, map, figurine
4	10 min	Explanation of the model outputs	Participants can read the model outputs	Presentation
5	5 min	Assign roles	Roles are assigned	Hand out envelopes with name badges and role descriptions
6	10 min	Break	Transfer model output PDF to participants	
7	5 min	Task introduction	Participants understand the task	Presentation
8	20 min	Decision round 1	Exploration of policies, filling out decision template	Discussion in pairs using the model outputs
9	20 min	Decision round 2	Exploration of policies, filling out decision template	Discussion in pairs using the model outputs
10	20 min	Plenary presentation of results	Knowledge exchange and discussion of results	Group discussion
11	20 min	Reflection on the model results, workshop experience, suggestions for improvement	Reflection	Group discussion

Table C.1: Structure of the first workshop

## C.2. OBSERVATION

### C.2. OBSERVATION

The observer used the following questions and prompts as a guide:

1. List of perspectives
2. Who is participating in this part?
3. Who is not participating in this part?
4. When does communication happen?
5. Who is open to new ideas and in what setting?
6. Which questions came up during the introduction?
7. Considerations about which policies to choose
8. Are the participants able to understand the model outputs and discuss them?
9. What considerations beyond the model come up? (e.g., capacity, funding, public acceptance, accessibility)
10. What was subject to discussion during the plenary presentation of choices?
11. What is there consensus on?
12. What was not discussed?
13. Differences between the groups
14. Reflections of participants
15. Participant satisfaction

### C.3. SURVEYS

Before and after each workshop, participants filled out a survey.

#### SURVEY BEFORE THE WORKSHOP

1. Name
2. What is your study program and expected year of graduation?
3. Which bachelor program did you follow?
4. How familiar are you with mobility and modeling?
  - Mobility
    - Very unfamiliar
    - Unfamiliar
    - Somewhat familiar
    - Familiar
    - Very Familiar
  - Modeling
    - Very unfamiliar
    - Unfamiliar
    - Somewhat familiar
    - Familiar
    - Very Familiar
5. Please note down some ideas that you have to make urban mobility more sustainable
6. Please rate the following six policies on their impact on sustainability. (The following two questions were asked for each policy.)
  - What impact on sustainability do you think this policy will have?
    - Very poor
    - Poor
    - Neutral
    - Good

### C.3. SURVEYS

- Very good
- How certain are you about this impact?
  - Very uncertain
  - Uncertain
  - Neutral
  - Certain
  - Very certain

### SURVEY AFTER THE WORKSHOP

1. Name
2. What is your study program and expected year of graduation?
3. Please rate the following six policies on their impact on sustainability. (The following two questions were asked for each policy.)
  - What impact on sustainability do you think this policy will have?
    - Very poor
    - Poor
    - Neutral
    - Good
    - Very good
  - How certain are you about this impact?
    - Very uncertain
    - Uncertain
    - Neutral
    - Certain
    - Very certain
4. Were there any policies that were not covered but should have been? If so, which?
5. Are you satisfied with the results of the workshop?
6. Are you satisfied with the interactions during the workshop?
7. What were your key insights today?
8. Any other comments?

## C.4. WORKSHOP MATERIALS

These photos show objects used in the workshops: the map used to explain the case study context (Figure C.1), the name badges indicating the group and role, and the pens used to document the decisions and considerations (Figure C.2).



Figure C.1: Photo of the map and figurine

## C.4. WORKSHOP MATERIALS

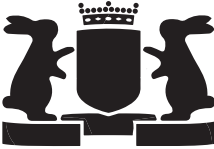


Figure C.2: Photo of the badges and pens

## C.5. ROLE DESCRIPTIONS

Each participant received an envelope with a name badge indicating the group (color of the badge) and role (icon of the badge), along with a role description. Figure C.3 shows the role description of the government and Figure C.4 shows the role description of the provider.

## C.5. ROLE DESCRIPTIONS



You are a representative of the city government of Den Haas. As such, your goal is to best represent the interests of the inhabitants of the city. Your city has limited funds.

### **Objective**

Transition towards more sustainable mobility by substituting trips with high-emission modes through lower-emission modes while keeping the transport system accessible for everyone.

### **Policies**

You have three policies to choose from. You may also choose to do nothing.

#### Increase parking costs

A fixed parking costs is added to all car trips. You hope that this makes driving a car less attractive while bringing more income to the city. You are concerned about low-income citizens.

#### Speed limit

More speed limits in the city that make all car trips 10% slower. You hope that this makes driving a car less attractive. You are concerned about traffic jams and disgruntled citizens.

#### Better bike infrastructure

You improve the city's bike infrastructure. Better cycling paths and traffic light optimised routes make cycling 5% faster. You hope that this makes bikes and e-bikes more attractive. The costs for this policy are estimated to be fairly high.

Figure C.3: Role description for the government

# DHT

You are a representative of the city's transport provider. You operate the buses, tram, metro, and work closely with the national train provider.

## **Objective**

Be profitable and have a good public image to retain and possibly expand your ridership.

## **Policies**

You have three policies to choose from. You may also choose to do nothing.

### Free public transport

Public transport becomes free for all inhabitants of Den Haag. You hope that this makes your buses, trams, and metro more attractive. Your concerns regarding this policy are how it will be funded and whether you have enough capacity for the new ridership.

### Introduce shared micromobility everywhere

You provide shared micromobility (e-kickscooters and e-bikes) in the city. Users of this sharing scheme can take and leave the bikes wherever they please. This makes the service available to all users at all times. However, this might require a big fleet to have the service available everywhere and you might need to relocate the bikes regularly.

### Introduce shared micromobility within the city limits

You provide shared micromobility (e-kickscooters and e-bikes) within the city limits. This means that the bikes can only be picked up and left within the city limits, therefore excluding trips that go beyond the city limits. Some users might be excluded from this service, but it most likely requires a smaller fleet and less relocation costs.

Figure C.4: Role description for the provider

## C.6. TEMPLATES FOR POLICY EVALUATIONS

### C.6. TEMPLATES FOR POLICY EVALUATIONS

Figure C.5 shows the template used for evaluating the policies based on the model outputs. This template was printed in A3 format.



Which policy did you choose?

Provider	Government
----------	------------

Before looking at the model outputs

Why did you choose this policy and what results are you expecting? Which potential risks do you foresee?

Provider	Government
----------	------------

Look at the model outputs

What is the effect of the two policies? Does this align with your objectives?

Are there any future events this policy is vulnerable to that might make this policy ineffective? If so, how?  
How can these vulnerabilities be mitigated?

Figure C.5: Policy evaluation template

## C.7. INFORMED CONSENT FORM

### C.7. INFORMED CONSENT FORM

Before the workshops, all participants signed an informed consent form in accordance with the TU Delft Human Research Ethics Council (Figures C.6 and C.7).

**Delft University of Technology**  
**HUMAN RESEARCH ETHICS**  
**INFORMED CONSENT**

You are being invited to participate in a research study titled 'Model-based decision-making for the mobility transition'. This study is being done by Karoline Führer from TU Delft.

In this workshop, we will use an agent-based model to explore different policies that municipalities and providers can implement. The case will be a stylised version of The Hague. Participants will be assigned roles (municipality or provider) and deliberate in groups of two which policies to choose from a predefined set of choices. In addition to the dynamics captured by the model, participants will also be encouraged to qualitatively discuss aspects of the policies that are not captured by the model. The aim of this study is to enable participants to understand model outputs and deliberate the effects of policies given the uncertainty inherent in the system. The data collected will be used for a scientific publication on participatory decision-making under deep uncertainty.

To the best of our ability your answers in this study will remain confidential. We will minimize any risks by storing data safely and anonymising any data that might be published.

Your participation in this study is entirely voluntary and you can withdraw at any time. You are free to omit any questions or tasks in the workshops.

Corresponding researcher:  
Karoline Führer  
k.j.fuhrer@tudelft.nl

Figure C.6: Informed Consent Form (Page 1)

## C.7. INFORMED CONSENT FORM

PLEASE TICK THE APPROPRIATE BOXES	Yes	No
<b>A: GENERAL AGREEMENT – RESEARCH GOALS, PARTICIPANT TASKS AND VOLUNTARY PARTICIPATION</b>		
1. I have read and understood the study information dated [26-04-2024], or it has been read to me. I have been able to ask questions about the study and my questions have been answered to my satisfaction.	<input type="checkbox"/>	<input type="checkbox"/>
2. I consent voluntarily to be a participant in this study and understand that I can refuse to answer questions and I can withdraw from the study at any time, without having to give a reason.	<input type="checkbox"/>	<input type="checkbox"/>
3. I understand that taking part in the study involves: Audio recordings that will be partly transcribed, photos of the session, a survey questionnaire completed by myself	<input type="checkbox"/>	<input type="checkbox"/>
<b>B: POTENTIAL RISKS OF PARTICIPATING (INCLUDING DATA PROTECTION)</b>		
4. I understand that taking part in the study involves the following risks: conflict among the participants and contested opinions that might induce stress. I understand that these will be mitigated through the facilitation and guidance of the workshops and the possibility to withdraw participation at any point.	<input type="checkbox"/>	<input type="checkbox"/>
5. I understand that personal information collected about me that can identify me, such as my name and email address, will not be shared beyond the study team.	<input type="checkbox"/>	<input type="checkbox"/>
6. I understand that the (identifiable) personal data I provide will be destroyed at the end of the project.	<input type="checkbox"/>	<input type="checkbox"/>
<b>C: RESEARCH PUBLICATION, DISSEMINATION AND APPLICATION</b>		
7. I understand that after the research study the de-identified information I provide will be used for a journal article.	<input type="checkbox"/>	<input type="checkbox"/>
8. I agree that my responses, views or other input can be quoted anonymously in research outputs.	<input type="checkbox"/>	<input type="checkbox"/>

<b>Signatures</b>		
_____	_____	_____
Name of participant [printed]	Signature	Date
I, as researcher, have accurately read out the information sheet to the potential participant and, to the best of my ability, ensured that the participant understands to what they are freely consenting.		
_____	_____	_____
Researcher name [printed]	Signature	Date
Study contact details for further information: <i>Karoline Führer, k.j.fuhrer@tudelft.nl</i>		

Figure C.7: Informed Consent Form (Page 2)



# ACKNOWLEDGEMENTS

Doing a PhD is rarely an easy ride, but thanks to many people who contributed to this work and supported me, I managed to stay on track.

I would like to start by thanking my team of promotors for their guidance, support, and encouragement. Jan, thank you for all the knowledge and advice you shared, not just on all things modeling and DMDU, but also on design furniture and where to get the best apple cake in Delft (for the interested reader: Kobus Kuch). I will never forget another Oxford comma and will probably continue wondering for a long time whether I should be writing instead. Floortje, thank you for asking the right questions to get my thoughts where they needed to go, and for the writing afternoons to get those thoughts on paper. I appreciate how you encourage creativity, whimsy, and fun in research. Etiënne, thank you for being an endless well of papers and kindness, and for one of my favorite drawings on the cover. (I am sorry for asking whether it was a manatee.) Els, thank you for your support in the first half of my PhD trajectory. Your pragmatic approach to always setting out the next few steps really helped to get this research started.

Thank you to the members of my committee for their interest in my thesis and valuable comments. Jill, I think I have left every conversation with you with a new insight. Gerdien, during On the Move consortium meetings and discussions, you always brought a fresh perspective. Rob, thank you for providing an inspiring and supportive research environment. And finally, Jonathan, thank you for your feedback on my research and nice chats over dinner during the IST conference in Oslo.

I consider myself lucky to have been part of a great project team within the On the Move project. Thank you to Rob and Vincent for making this research possible and leading the project. I am grateful to Peraphan (Top) for the pleasure of organizing and running several workshops together. Your collaboration, creativity, and reliability made the work very enjoyable. Ruben, thank you for sharing the PhD journey in the On the Move project. Femke, it was a pleasure collaborating on the paper on visioning future transport systems. To the other researchers in the project, Jaap, Fanchao, Kristel, and Josefa, as well as the whole project consortium, I am deeply grateful for the inspiring meetings and discussions of ideas over the years.

I am thankful to the partners of the municipality of The Hague, especially Lilian, Anne, and Bregtje, for opening the door for this project. Thank you for your openness, enthusiasm, and interest in this research.

Over the course of this research, many people participated in the various workshops. Many thanks for sharing your time, knowledge, and insights – without you, this participatory research would not have been possible. An additional thank you to the participating artists of the drawings on the cover and inside this thesis for bringing this participatory cover to life.

A very special thank you to the wonderful community of Policy Analysis PhDs for sharing this PhD journey and making it much more enjoyable, particularly Adrien, Alessandro, Astha, Damla, Jin, Joos, Liz, Mikhail, Omar, Palok, Pouria, Ruth, Thorid, Zusanna, and everyone else. Over the years, I had amazing office mates, who all had two wonderful things in common: chatting with them was a little too enjoyable when I should have been writing, and there was always a steady supply of snacks. For this, I am thankful to Ignasi, Nely, Kai, Sofia, and Willem.

I also want to thank the wider community of TPM for the pleasant research environment. A special thank you to Martijn for collecting everyone for lunch every day, showing up to the beers, and just generally being a source of kindness and good advice. Thank you to Nihit and Haiko for the great experience of teaching together. I learned a lot from that.

A big thank you to the best paranymphs a girl could ask for: Irene and Isabelle. I am really happy I got to share this whole PhD journey with you. Irene, thank you for making me celebrate all the big and small successes (ideally with stroopwafels), walking laps around the building to air out the brain in the final weeks, and the many conversations over coffees and beers. Thank you also for your shared love of ACRONYMS: Acknowledging Creative Researchers Overenthusiastic Naming Yielding Masterpieces. Isabelle, the queen of TPM, thank you for being a constant ray of sunshine, laughs, and fun conversations. You brought optimism and smart insights whenever they were most needed – proof that wit and competence can coexist perfectly. Having both of you by my side meant a lot to me.

Thank you to my friends for their enthusiasm and support, even (or especially) when they had little idea what I was talking about. To my friends in Rotterdam, thank you for all the long nights of dancing and deep conversations. Leroy, Pawel, and Kasia – thank you for being like another family away from home. I probably owe you a lot of my sanity during the lockdown. To my friends in Berlin, thank you for cheering me on from afar. Marie and Isi, you were embarrassingly proud of me from the moment I found out I would do a PhD. Anna, thank you for being there for me since primary school – your friendship and support mean the world to me.

I believe that my love for transport must have been ignited at one of the countless train festivals I visited with my family. I want to thank my parents for their love and support, and for not asking too often when I would be done. You taught me that family isn't necessarily something you are born into, but something you build with love. To my older sister Kathi, I am so grateful to have you as a role model. I can only aspire to be as caring and responsible as you. To my younger siblings, Benni, Sahra, and Ester, being your older sister has been a great source of joy and learning. To my nieces, Clara and Ella, thank you for all the fun and laughter you bring to everything you do. I am in awe of how smart and thoughtful you are. Sarahlinde, you feel like a part of this family and I am grateful for your enthusiasm for me to learn Dutch (sorry I learned the Dutch version and not the Flemish one). I am also lucky to have a wonderful family-in-law. Ale Sr. and Ale Jr., thank you for your jokes, support, and travels in the last few years.

## ACKNOWLEDGEMENTS

And finally, Marta, I am forever grateful to have you as my partner in the business of life. Thank you for your love, your constant support, your insistence on talking about feelings, and your unwavering commitment to silliness. Life with you is simply delightful, and you make me happy every day.

*Karoline Führer*  
*Rotterdam, October 2025*



# ABOUT THE AUTHOR

Karoline Führer was born in 1995 in Berlin. She has always been fascinated by how transport systems work and shape daily life. After obtaining a BSc. and MSc. in Industrial Engineering and Management from TU Berlin with a specialization in transport planning, she became a PhD candidate in the Policy Analysis section at the Faculty of Technology, Policy, and Management at the TU Delft. In her research, Karoline engaged stakeholders in the modeling process for the mobility transition while explicitly taking uncertainty into account. She designed and analyzed participatory modeling workshops that build on concepts such as systems thinking and decision-making under deep uncertainty. Karoline's skills include stakeholder management, workshop facilitation, qualitative and quantitative modeling, and data analysis – especially for envisioning and planning future transport systems.

## PEER-REVIEWED PUBLICATIONS

1. Karoline Führer, Floortje M. d'Hont, Etiënne A.J.A. Rouwette, Jan H. Kwakkel (2025). Participatory model-based policy exploration for the mobility transition. *Transportation Research Interdisciplinary Perspectives*, 34, 101683. (Part of this dissertation)
2. Führer, K., Kwakkel, J. H., d'Hont, F. M., & Rouwette, E. A. J. A. (2025). Modeling a transport system in transition: A case study from The Hague. (Under review, part of this dissertation)
3. Führer, K., Kwakkel, J. H., d'Hont, F. M., Rouwette, E. A. J. A., & van Daalen, C. E. (2025). Towards Participatory Decision-Making under Deep Uncertainty: Benefits and Challenges. *International Journal of Technology, Policy and Management*, 25(2). (Part of this dissertation)
4. Führer, K., Jittrapirom, P., d'Hont, F. M., Rouwette, E. A. J. A., & Kwakkel, J. H. (2024). Modeling with a municipality: Exploring robust policies to foster climate-neutral mobility. *Transportation Research Interdisciplinary Perspectives*, 27, 101206. (Part of this dissertation)
5. Jittrapirom, P., Bekius, F., & Führer, K. (2023). Visioning future transport systems with an integrated robust and generative framework. *Scientific Reports*, 13(1), 4316.
6. Bischoff, J., Führer, K., & Maciejewski, M. (2019). Impact assessment of autonomous DRT systems. *Transportation Research Procedia*, 41, 440–446.

## PRESENTATIONS

1. Führer, K., Kwakkel, J. H., d'Hont, F. M., & Rouwette, E. A. J. A. (2024). Modeling a transport system in transition: A case study from The Hague. *International Sustainability Transitions Conference*. Oslo, Norway.
2. Führer, K., Jittrapirom, P., d'Hont, F. M., Rouwette, E. A. J. A., & Kwakkel, J. H. (2023). Modeling with a municipality: Exploring robust policies to foster climate-neutral mobility. *Benelux Chapter Symposium of the System Dynamics Society*. The Hague, The Netherlands.
3. Führer, K., Jittrapirom, P., d'Hont, F. M., Rouwette, E. A. J. A., & Kwakkel, J. H. (2023). Modeling with a municipality: Exploring robust policies to foster climate-neutral mobility. *Annual Meeting of the Society for Decision Making under Deep uncertainty*. Delft, The Netherlands.
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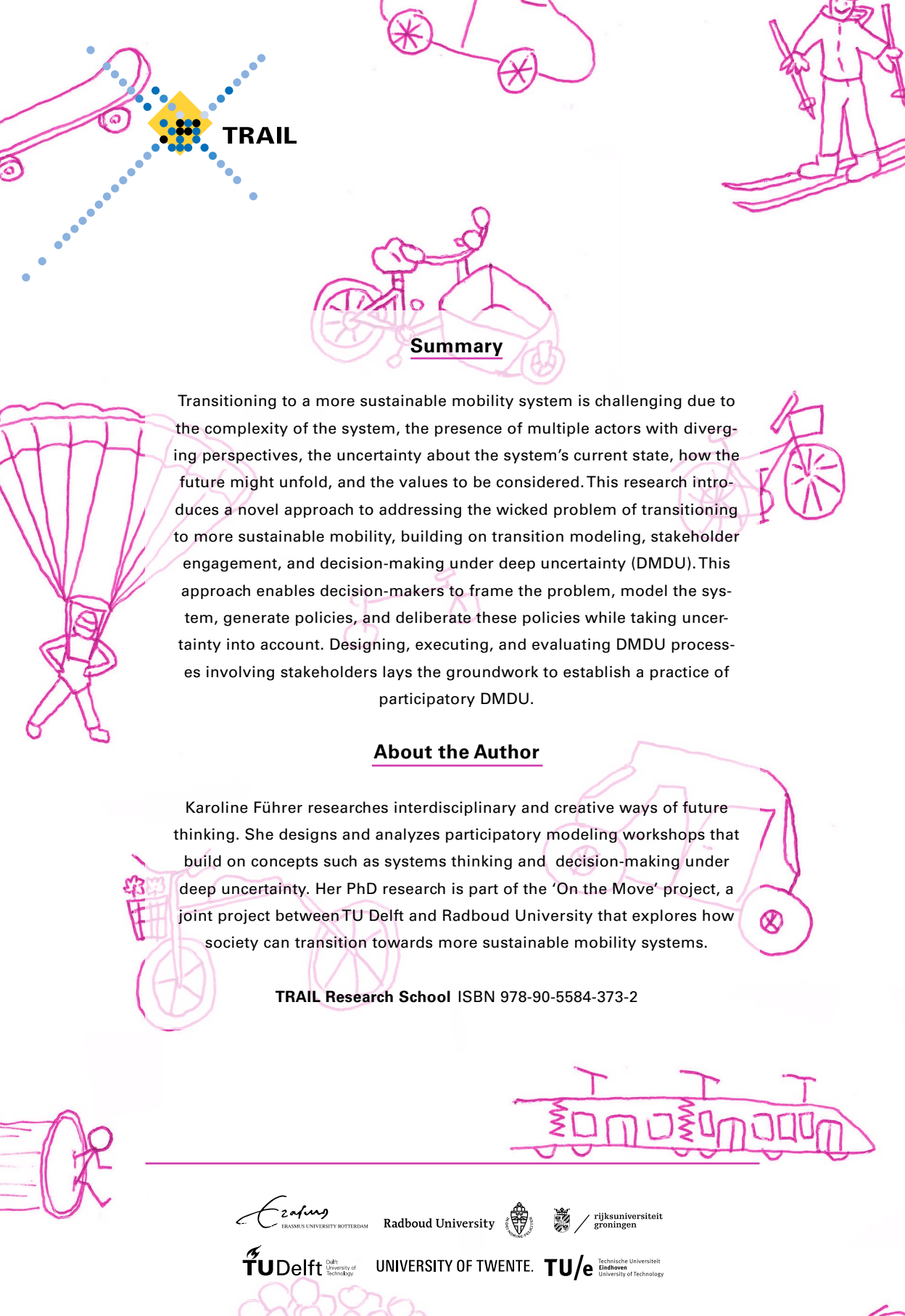
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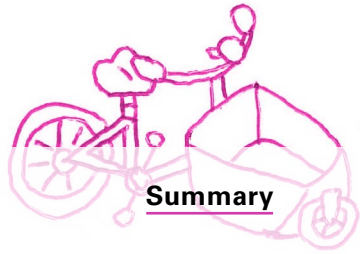
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## Summary

Transitioning to a more sustainable mobility system is challenging due to the complexity of the system, the presence of multiple actors with diverging perspectives, the uncertainty about the system's current state, how the future might unfold, and the values to be considered. This research introduces a novel approach to addressing the wicked problem of transitioning to more sustainable mobility, building on transition modeling, stakeholder engagement, and decision-making under deep uncertainty (DMDU). This approach enables decision-makers to frame the problem, model the system, generate policies, and deliberate these policies while taking uncertainty into account. Designing, executing, and evaluating DMDU processes involving stakeholders lays the groundwork to establish a practice of participatory DMDU.

## About the Author

Karoline Führer researches interdisciplinary and creative ways of future thinking. She designs and analyzes participatory modeling workshops that build on concepts such as systems thinking and decision-making under deep uncertainty. Her PhD research is part of the 'On the Move' project, a joint project between TU Delft and Radboud University that explores how society can transition towards more sustainable mobility systems.

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