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The Decision Theatre Triangle for societal challenges

Insights from Decision Theatres on sustainable mobility and resulting research needs

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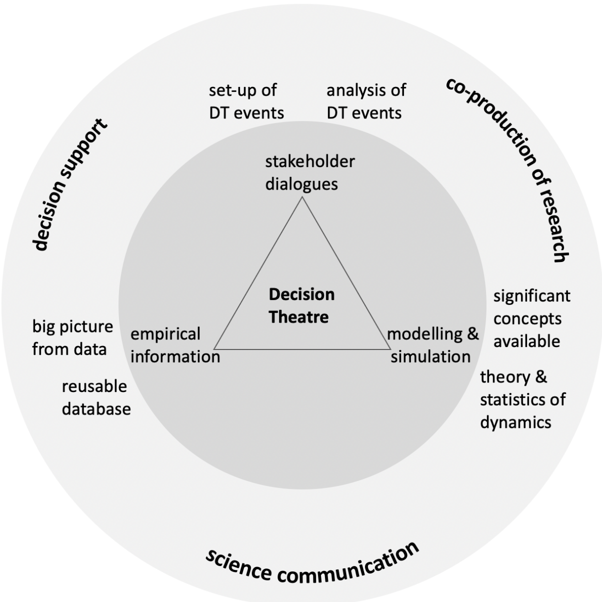

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Insights from Decision Theatres on sustainable mobility and resulting research needs

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Abstract To support discussions about the challenge of a sustainable mobility transition between researchers and stakeholders, such as practice experts, decision makers, and citizens, we have developed and tested an agent-based model and a mobile Decision Theatre set-up. Due to the combination of three elements – a) mathematical modelling and simulation, b) socio-ecological, including socio-economic, data and understanding, and c) a dialogue format based on the former two elements for bringing together researchers and stakeholders – we refer to the method as the Decision Theatre Triangle. This paper presents insights gained with the sustainable mobility case and, based on these, outlines research needs for turning this method into an easy-to-set-up instrument of science communication, decision support, and co-production of research for societal challenges more generally.

1 Introduction

Societal challenges arise in complex multi-level systems of human-environment interactions. Addressing such challenges requires understanding potential evolutions of the complex social – or rather socio-economic, socio-ecological and socio-technical – systems under consideration. In particular, potential consequences of alternative actions need to be investigated and evaluated. Therefore, all groups of actors who can contribute knowledge, perspectives, and values should be involved or represented in decision making, as pointed out by Renn and Schweizer (2009) in the context of risk governance. Similarly, in sustainability science there is a history of using participatory methods (Kasemir et al 2003); they are also referred to as stakeholder involvement (Mielke et al 2016), transdisciplinary research (Lang et al 2012), or co-creation of knowledge (Cornell et al 2013).

While a focus in dealing with risks is resilience, that is, maintaining structure and function of a system in the face of stresses or shocks (Anderies 2015), in contrast, sustainability transitions often require changing basic structures in the underlying system, so as to shift from a given status quo to a fundamentally different and more desirable future situation (Markard et al 2012). We consider the term "societal challenge" to include both of these basic settings.

Decision Theatres (DTs) provide a dialogue format supported by information technology (IT) for involving stakeholders and citizens in decision or research processes, using visualisations of empirical information as well as mathematical modelling and simulation of possible futures. DT participants can experiment with models, composing and interactively comparing scenarios. Through their combination of visualization and dialogue, and by allowing people with their creativity and intuitive insight to interact with data, models, and with each other, Decision Theatres stimulate co-production and active use of knowledge, facilitating common assessments and creation of solutions (Boukherroub et al 2016; John et al 2020).

As the name implies, the original focus of the Decision Theatre was decision support, in fact, a main aim was to give greater weight to quantitative data and modelling in complex decision processes (see Bush et al 2017, and references therein). Boukherroub et al (2016) provide an overview on DTs in this context. In a research context, the DT has been used to analyse decision processes themselves (see, e.g., White et al 2010; Bush et al 2017). Based on experience gathered with a mobile DT on sustainable mobility transitions, we will argue that the Decision Theatre is a useful instrument for science communication, decision support, and co-production of research on societal challenges. Further, we outline challenges in facilitating the set-up of DTs.

We refer to the instrument as the Decision Theatre Triangle (DTΔ) to emphasize the combination of three elements: empirical data and information, mathematical modelling and simulation, and a transdisciplinary dialogue format supported by visualisations of the former two. Previous works provide different categorisations of DT elements, such as decision entities, decision support component, organisational system, DT layout, and technologies (Boukherroub et al 2018), or purpose, process results, actors, process, visualisation, model, model results, library, and user interface (John et al 2020). Many of these elements appear in the DTΔ at one or several places – e.g. visualisation of both empirical information and modelled potential futures – however, the coarser triangle structure is more useful here.

Section 2 introduces our method along these three elements. Section 3 collects insights gathered from first DT events carried out with different kinds of audiences. Section 4 sketches resulting research challenges for turning this method into a more generally usable instrument for addressing societal challenges, with a focus on modelling and simulation. Section 5 concludes.

2 Method: The Decision Theatre Triangle for the example case of sustainable mobility

The Decision Theatre Triangle (DTΔ) builds on the Decision Theatre as established at Arizona State University. It was developed and tested for the example case of a sustainable mobility transition in Germany. We consider this a (rather drastic) change from the current German mobility system to one that would quickly reduce mobility emissions while increasing fairness, e.g. in terms of access to mobility for all or of mobility related burdens on health (see, e.g., Frey et al 2020, (in German)). In the following, we describe the stakeholder dialogue format (Section 2.1), the model (Section 2.2), and the empirical information used (Section 2.3) in this context.

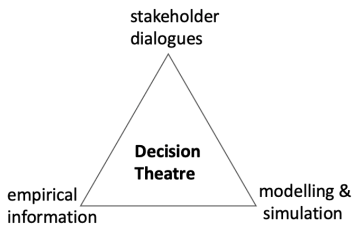


Fig. 1: Elements of the DTΔ.

2.1 A Decision Theatre event on sustainable mobility

The dialogue format, a DT event, is an IT-supported discussion that involves about 5 to 20 invited guests and a "DT-team". The team consists of an IT-expert, problem-expert, model-expert, visualisation-expert, and moderator, where several, but not all roles may be played by one person, and all team members need to be reasonably familiar with the other areas. Together, guests and team discuss possible strategies for sustainable mobility in Germany and experiment with model simulations. Additional guests can participate in the event as an audience with a less active role; they can take part in the discussion but do not immediately interact with the model.

When the DT takes place as a physical meeting, the room is equipped with several large screens. While the DT at ASU is a permanently installed facility[1], this version is mobile and hence flexible in the choice of location: it can be set up in any room that accommodates the screens. Hence, the DT event can "come to the stakeholders". Renting screens locally on each occasion reduces the necessity for transport, and allows choosing the number and size of screens adapted to the number of participants and size of the room. The team brings a portable workstation and a few tablet computers through which participants can interact with the model. The workstation is equipped with a visualization environment for interactively displaying empirical information as well as model simulation results on the screens. It can also run fast simulations on the fly and store large amounts of data from pre-calculated model simulation runs.

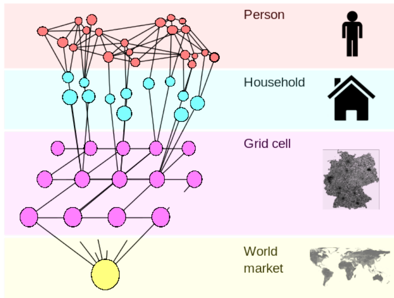
A DT event lasts between a few hours and a full day; the workshop is structured into several steps.

– *Briefings:* In the first step, participants are presented with two short briefings followed by equally short discussions. The briefings use the screens for showing data, images, and text elements. The first one outlines the problem, including visualizations of both uncontroversial facts and open questions. Alternative potential future developments may be presented in order to highlight the openness of the future in dealing with societal challenges. The initial discussion may be used to exchange prior views of participants on the basis of a few exemplary questions, focusing on expectations and visions, as well as on their plausibility and desirability.
  The second briefing explains the basic structure and key assumptions of the interactive simulation model participants will be experimenting with – an important feature being the fact that the model is not deterministic. The briefing also shows what kind of model output can be viewed and presents available choices for composing scenarios, including actions (like alternative policy measures or investment options) and events, that is, alternative assumptions about the evolution of specific factors of influence that are beyond reach of decision making in the given context (such as future world market developments). The second discussion clarifies potential questions about the model, e.g. on assumptions or data used.
– *Decision situation:* In the second step, participants form groups of about five people to simulate a decision situation. In particular, they discuss their goals and assumptions, and choose among the previously presented options in view of their goals. They can view the description of all options and implement their group's choice via a tablet computer.
– *Exploration of consequences:* In a subsequent joint discussion phase, the groups present their objectives and choices, and the consequences simulated by the model are interactively displayed on the screens and examined. The focus is on the comparison between different scenarios with respect to different aspects or objectives. It is made explicit that the model outputs are not predictions but tools for better understanding the underlying complex social system, e.g. by identifying mechanisms or being pointed to unexpected effects. Thus, the exploration phase also puts the model itself up for discussion: participants can criticize assumptions or suggest new ones, or indicate additional options that they would be interested in exploring with the help of the model. Step two and three may be iterated a few times.
– *Reflection:* In a concluding step, participants reflect together on what lessons they want to draw from their choices and the resulting outcomes. They also summarize which features of the model they found useful as well as where and how they would want the model to be modified. This kind of feedback from participants enters the DT-team's "post-processing" of each event and documentation of lessons learned.

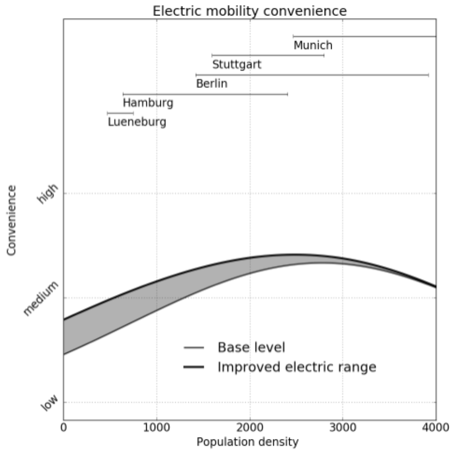
DTs can also be organised as online events. In that case, screen sharing replaces the large screens. To mimick the benefit of several screens, the shared screen can show a split view

[1] `https://dt.asu.edu/`

(a) Mobility choices of MoTMo persons



(b) MoTMo network structure



(c) Example convenience curve for electric vehicles: the base level is lower for sparsely populated areas (range anxiety), then increases with population density, but decreases for very dense areas (congestion, difficulty to find parking spots etc.). With improved electric range, the convenience increases, and more so in rural than in urban areas.

Fig. 2: MoTMo presentation in DT events

with several windows and zoom into one of these when helpful. The decision situation in this case makes use of break-out rooms for the subgroups; at this moment, the screen of the mobile device can be shared for choosing a scenario together.

2.2 The Mobility Transition Model (MoTMo)

The model used, called the Mobility Transition Model, in short MoTMo, is an agent-based model simulating private mobility demand in Germany with a time horizon of three decades, 2005–2035. In a nutshell, an agent-based model (ABM) represents a complex social system at the level of individual actors in the system with their features and their behaviour. Agents are software objects that encapsulate these actors. Their interactions define the temporal evolution of the system, which is computed by simulating a sequence of (usually very many) such interactions (e.g., Epstein and Axtell 1996).

MoTMo agents are a synthetic population of persons in households, that is, they statistically match distributions of the German population in terms of age, income, household type, and spatial location. In particular, population density is matched using a 5 by 5 km grid on the German map. Persons further have a mobility profile specifying monthly numbers of trips of given length categories, based on survey data from Lenz et al (2010). They satisfy their mobility demand using one of five mobility types: conventional combustion engine cars, public transport, and non-motorized mobility (bike and walking, also referred to as ‘active mobility’), electric vehicles as a technological innovation, and car sharing as a behavioural innovation (see Figure 2.a). Given the time frame of several decades and a monthly time step, MoTMo does not represent single trips made by individuals. Drawing on standard economic theory, persons aim to maximize expected utility by their mobility choice; however, the choice is taken at the household level as the budget constraint for mobility is a feature of the household. Utility is considered as consisting of four factors: costs, innovation, ecology, and convenience; agents weight these factors differently, represented by different exponents in a Cobb-Douglas utility function. In modelling each of these factors, costs are straightforward in that smaller costs are preferred; innovation is considered in relation to the choices of other agents; ecology depends on the emissions of the chosen mobility type, assessed also in comparison with other agents; convenience is modelled as follows. To aggregate many aspects (speed of travel, how comfortable it is, access and availability, security and safety, etc), but abstract from full spatial detail, convenience is modelled as a function over population density (see Figure 2.c). For each mobility type, assumptions are made about the form of the convenience function and how this form changes with the maturity or use of this mobility type. These assumptions are easy to modify and can be put up for discussion in a DT event. The second component of expected utility, namely expectation, departs from standard economic theory: MoTMo persons are not omniscient but form expectations via information exchange with their peers in a social network structure (see Figure 2.b).

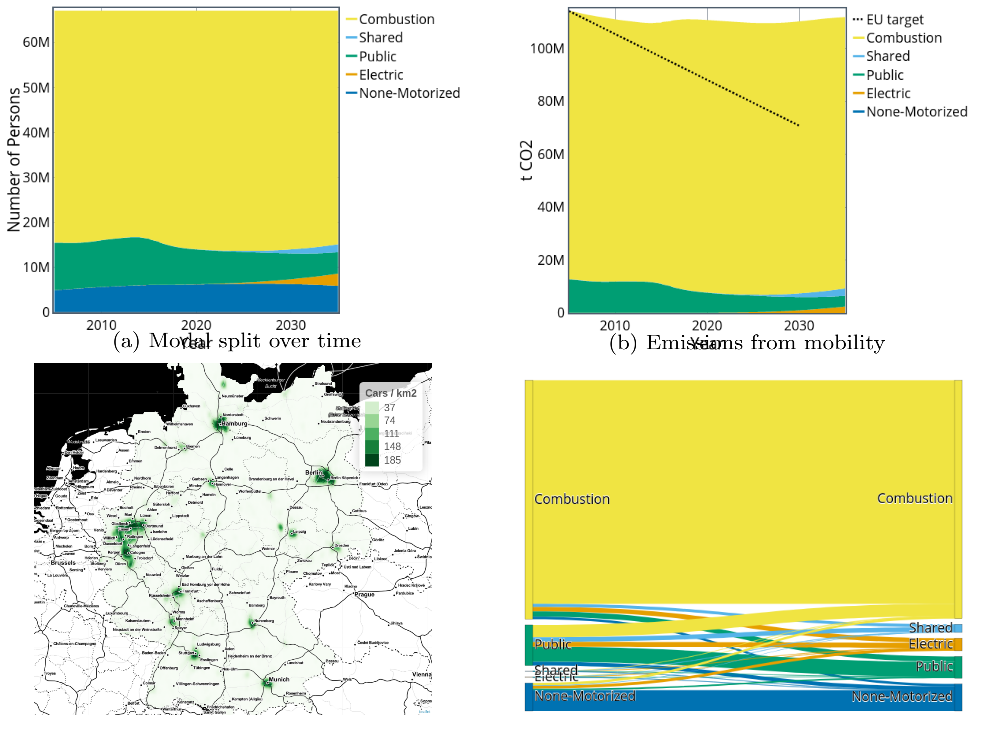
This peer network between persons is sampled based on similarity of features and spatial proximity. This means, the probability of two specific agents being connected is higher if their features are similar and their locations are close.

The 5 by 5 km grid already mentioned constitutes the spatial environment in MoTMo (Figure 2.b); for each cell, the convenience of each mobility type is determined from the population density using functions as illustrated in Figure 2.c. Further spatial elements, such as charging infrastructure deployment for electric vehicles, have an influence on agents’ utilities and hence on their choices. Moreover, a global level in MoTMo records technological change and prices that evolve based on external inputs and co-evolve with the agents’ actions. MoTMo thus combines technological with social change dynamics in a spatially differentiated environment.

Figure 3 illustrates a few representative model results and a selection of possible visualisations for a business as usual (BAU) scenario, which assumes that current trends will continue in the future. Many aspects of possible mobility futures can be explored, the most basic being the evolution of the modal split over time, that is the number of agents choosing each mobility type (Figure 3.a). Based on the modal split and the agents’ mobility profiles, resulting emissions or electricity demand are obtained, showing also how they compare with emission reduction goals (Figure 3.b). Due to the high model resolution, spatial distributions of mobility choices and their consequences can be investigated, e.g. in maps (Figure 3.c). Via aggregations at different levels, it is possible to zoom in on many details (an example is Figure 3.d). Results can be viewed for a specific Federal State in Germany or for a specific group of people, e.g., a household type (single household, couple, multi-person household).

The list of options that participants of a DT event can experiment with includes policy measures, investment strategies, and exogenous events. In the model, these options are implemented by inducing a change in convenience functions or other assumptions (e.g., price developments), see Table 1.

As MoTMo is too large for running simulations on the spot, for DT events, simulation results are saved on the portable workstation. Groups can choose up to two options within each category (policies, investment, events). Practically, this reduces the number of combinations to be pre-run; conceptually, it constrains the decision situation in that groups cannot simply activate all options but have to decide which ones to prioritize.



(a) Modal split over time

(b) Emissions from mobility

(c) Example map: electric vehicles

(d) Mobility type "migration"

Fig. 3: MoTMo result visualisations

2.3 Empirical information on mobility in Germany

Empirical data of different types and from different sources was used in developing the Mobility Transition Model, both as input and for calibration, so that for the time-frame corresponding to the past, the model adequately reproduces observed developments. For example, a population density map for Germany from SEDAC (2015), price developments for electric and conventional cars from Weiss et al (2012), and agents' mobility profiles from Lenz et al (2010) were used as model inputs; numbers of conventional and electric vehicles for the years 2012–2017 and survey data on mobility choice were used for calibrating the model (Wolf et al 2018).

Further, empirical information appears in a DT event in several forms. For credibility, the researchers involved have to bring empirical knowledge on the problem, in particular, the problem expert needs to be able to convey a "big picture" supported by a list of specific facts.[2] Visual presentation of empirical information occurs, in particular in the first briefing, through data in form of charts, tables, maps, networks, etc.; examples relating to the status quo include in particular recent trends and stated goals (and the gap between them) for mobility and transport, e.g. for emissions at the national level, or the modal split at city level. Images which illustrate this status quo, e.g., simply photographs of streets with traffic, are another form of empirical information that can be used. Pictures illustrating potential futures may not be considered empirical in a direct sense, however, they can provide empirical content at a meta-level: for example, an illustration of a green, car free future stemming from advertisement, while fictional on the direct level, provides empirical information on visions that are present in a society.

[2] We leave the question how the "post-truth era" and fake news or data may influence the position of experts in a DT event to future research.

Category	**Option**	**Description**
Policies	Car weight regulation	While in the BAU case the weight of cars continues to grow according to the current trend, this option assumes constant weight from 2018.
	Bike friendliness	The convenience curve for active mobility is higher than in the BAU case.
	Urban combustion restrictions	The convenience curve for cars with internal combustion engines falls more steeply with higher population density than in the BAU case.
Investment	Electric vehicle subsidy	The BAU case implements the 2016 environmental bonus. With this option, the amount per vehicle (and the total subsidy) doubles.
	Public transport subsidy	Public transport costs are cut in half compared to the BAU case.
	Charging infrastructure	With BAU, charging station deployment rises linearly to 200.000 in 2035; with this option, the deployment follows a sigmoid curve to 1 mio in 2035.
Events	Higher gas price	Operating costs for internal combustion engine cars are based on fuel price data for 2005-2017. In the BAU case, they increase by 1% per year from 2018, with this option, by 3% per year.
	Intermodal digitalisation	ICT applications improve the convenience of the modes electromobility, public transport, and car sharing, represented by improved convenience curves for these three modes.
	EV world market growth	For BAU, the market share of electric cars grows to 10% by 2015. This option assumes higher growth to 30%.
	Increased car sharing availability	In the BAU case, the supply of car sharing cars grows by 3% per year, with this option by 6% per year.

Table 1: List of options for composing a MoTMo scenario. Note that the option "higher gas price" which here represents, e.g., oil price increases, can also be viewed as a policy option, if a CO_2 tax is added to fuel costs.

3 Results: Insights from initial DT events

A list of DT events carried out with different kinds of audiences, including researchers and practitioners from the fields of business, administration and policy, as well as students (high school and university) and citizens, is provided in the Appendix. Insights gained mostly stem from the combination of two or even all three elements of the DTΔ, so that this section does not consider the three elements separately. Rather, we group insights according to three purposes that Decision Theatres can have,[3] illustrated by Figure 4.

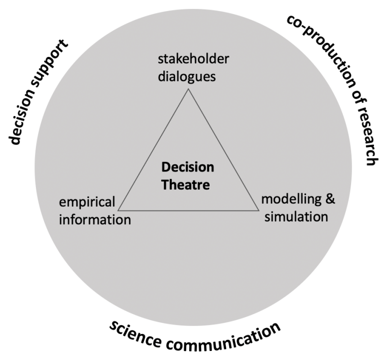


Fig. 4: DTΔ purposes.

3.1 Science communication

The Decision Theatre provides a means of communicating scientific work to a non-technical audience. This includes research objectives and questions, methods (e.g., modelling activities) and results. Choices made by researchers in applying methods, such as model type used or specific assumptions within the model, as well as uncertainties relating to results, can be communicated alongside the method and results themselves.

Here, agent-based modelling offers the advantage that the many individual actors of a complex system and their interactions are directly represented on a computer. Modellers have to explain their assumptions about these transparently – especially since, unlike for

[3] A fourth one, namely data collection on beliefs and norms entertained by different social groups, akin to focus groups, is not considered here.

example for molecules in a chemical system, there are no generally agreed assumptions and corresponding equations for interactions between people. However, the discussion participants do not need any theoretical knowledge of e.g. mathematical or economic modelling. Due to the model's similarity with the real world (Castro et al 2020), understanding of an important element in the research process, the computer simulation model, can be achieved comparatively easily with a non-technical audience.

In introducing MoTMo to various audiences, it proved valuable that DT-participants can identify with agents in the model; after all, most people experience the mobility system on a daily basis and they often have the same set of choices at hand as MoTMo agents do. They can hence relate to assumptions made on agents' mobility decisions and may suggest alternative assumptions or additional elements for inclusion in a model. A local focus further supports identification of participants with the issue under discussion, both for empirical information, such as local data or images in the briefings, and for the exploration of model results, for example by zooming in on a map.

Participants perceived the (fictitious) decision situation step in the DT event as beneficial to communication in several respects. The decision situation provides a framing that focuses discussions to specific aspects, so as not to discuss everything at once. With preferences voiced in the decision situation group work, e.g. for one policy option over another one, participants also explained their motives, making explicit what they consider desirable concerning sustainable mobility. The decision situation often revealed objectives, assumptions and values that might otherwise have remained implicit. Moreover, the need of making a decision in each group within a previously specified time frame, illustrated a constraint of real-world policy making, where it can be assumed that many decisions have to be taken within limited time and under insufficient information. Once scenarios are composed by the groups, their immediate comparison strongly conveys the idea of an open future in societal evolutions that is relevant to any societal challenge.

Finally, even when used mainly with the purpose of communicating from scientists to a broader audience, the dialogue situation always introduces also the reverse direction of communication, from the guests to the researchers. In particular for the interactive exploration of different scenarios in a DT event, this means that science communication occurs in a more demand-driven way than, e.g., a written report or a presentation, for which the author would define the order of topics, points of focus, and details emphasized. Here, the audience influences the flow of communication, allowing participants a closer look into those aspects of model and results they are most interested in. Again, there is an advantage of ABMs: the high level of detail in the model means that a large amount of different aspects can be investigated. In principle, for any feature and action of agents, averages, maxima, minima, and distributions throughout the synthetic population can be visualised, so that, for example, simulated effects of certain policies can be viewed by age group, income bracket, or household type. Particular agents can be followed through a simulation run, if this is of interest. Which pieces of information are of interest to participants is in turn interesting for the researchers (see Section 3.3).

3.2 Decision support

The DT on sustainable mobility has not, so far, been employed with the purpose of supporting concrete decision situations. In the DT literature, this seems the rule rather than the exception (John et al 2020) and there have also been warnings about unrealistic expectations on the ability of science to inform policy decisions (White et al 2015). Nevertheless, we want to highlight one benefit to decision support that was pointed out by an event participant.

When a group of people from different backgrounds, with different knowledge bases, preferences, beliefs, and aims comes together – e.g. to work on a long-term transport strategy for a region in a European country[4] – they bring in expert knowledge on different parts of the system and different perspectives; they may make different assumptions about the systems' elements and mechanisms. Fixing a model, that is, defining relevant agents, other entities, their interactions, and their environments, can help provide common ground and establish some agreed assumptions before discussing those that do not find agreement.

In this capacity, models used in DTs are not so much tools for forecasting possible evolutions but rather helpers for making assumptions explicit and understanding mechanisms in how assumptions translate into outcomes, observed in simulations. In other words, rather than informing policy, their purpose is to provide a platform for common understanding in a decision process (as also described by Barreteau et al 2003); they function as an instrument that enables a group to think through a set of options or different courses of action. The possibility of "playing through" different scenarios is also available in other contexts, e.g. via websites that offer the possibility to experiment with models[5]. By embedding models in a dialogue, the DT adds the multi-directional conversation that can establish common assumptions or make explicit where ideas differ.

3.3 Co-production of research

As mentioned above, the dialogue situation is a helpful source of information also for the DT-team, in particular, the modellers involved; beyond the straightforward and generally applicable principle that stakeholders confronted with a particular challenge (be this an engineering problem or a societal challenge) can help direct research work towards addressing the most important questions and looking into the most relevant detail.

For societal challenges, from risk governance (Renn and Schweizer 2009) to global environmental change (Cornell et al 2013) and sustainability (Lang et al 2012), the necessity of including complementary, practical knowledge and expertise by stakeholders into research processes has been established and is being addressed under the labels of transdisciplinary research and co-production of knowledge. The experience made through the DT events on sustainable mobility indicates that agent-based modelling in combination with DT dialogues lends itself to some such co-production concerning both the development and the use of models. We refer to co-production of research, because the collaboration concerns not only research results (knowledge) but also its methods or instruments (models). In contrast to some earlier DT work, where the moderator of the discussions was a "professional facilitator, not associated with the scientific information presented or the development of the model" (White et al 2010, p225), in this case it is essential that modellers themselves are included in the dialogue.

The ABM MoTMo has always been presented as work in progress. In fact, due to the immense freedom of the agent-based modeller in choosing assumptions about elements in the model, at any point an ABM can be considered work in progress to some extent; one may always find a different representation of some element that improves the model. In the DTs carried out, participants provided feedback on aspects they considered relevant to mobility decisions of persons and households, and in particular local factors of influence. For example, public transport was not considered a viable alternative to individual cars by several participants in the Ruhrgebiet, an urban area consisting of several large cities, where commuters between cities often face travel times 3-4 times as long as by car. This could be rather easily included in MoTMo by shifting the convenience curve of public transport down. In general, as agent-based models are defined via interactions of many individuals, changes of assumptions at the individual level are easier to implement than in aggregate models. This allows putting not only simulation results and scenarios but also the model itself and the defensibility of its assumptions up for discussion in a DT. Given that these assumptions are not a priori fixed (e.g., by experiments or convention), stakeholders

[4] In fact, this was the example case this participant was interested in.

[5] One example relating to the current pandemic can be found at `https://covid-sim.info/`

can hence contribute directly to the modelling activity, suggesting desirable refinements or extensions of the model or the visualisation.

The combination of models and dialogue further advances the research process on another level, in that it brings together quantitatively outlined descriptions of possible futures and potential consequences of alternative actions, in the form of simulated scenarios, with a narrative element in the discussion. As Mielke and Geiges (2018) point out, this opens a space for common production of visionary stories about the future with a quantitative core, the plausibility and desirability of which can be assessed and negotiated in the DT.

Last but not least, combining models and dialogue provides a source of creativity. Models, especially agent-based models, may produce unexpected results; that macro-level consequences of micro-level behaviours can be surprising is well-known since Schelling's (1969) segregation model, where weak individual preferences for living with similar neighbours and simple rules for moving homes can lead to harsh segregation at the city level. In the case of a large-scale empirically grounded ABM such surprises imply a check of the model for artefacts – or an enlargement of the space of potential consequences in the discussion. This stimulates thinking about why a specific consequence might occur in the real world. In particular, if an observed consequence from some measure taken is not desirable, the question arises how such a measure may need to be complemented to avoid the undesired effects. Such impulses for discussions encouraged thinking about the possibility of fundamental changes in a system in the some of the events carried out. Ideally, this can lead to the production of transformative solutions, or so called positive tipping points (Tàbara et al 2018).

4 Discussion: Research needs

The above suggests the Decision Theatre Triangle as a useful instrument for communication, decision support, and co-creation of research on societal challenges. However, developing the present example required several years of work by a research group consisting of several people. A main effort was the development of the ABM to be used in DT events. In the following, we therefore outline research directions for facilitating such model development (Section 4.3). Before, we very briefly touch upon research needs also for the other two vertices of the DTΔ. The main challenge in all three cases is enabling cumulative development of DTΔs, meaning that researchers can build on each others' work instead of starting from scratch for each further challenge or specific context investigated.

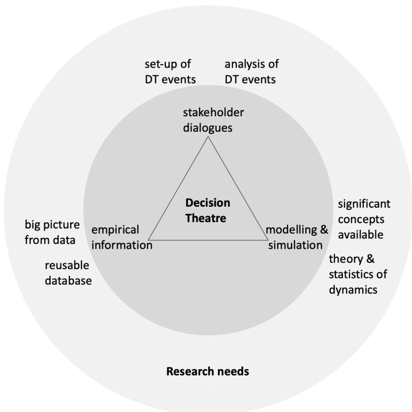


Fig. 5: DTΔ research needs.

4.1 Set-up and analysis of stakeholder dialogues

Future research needs for the dialogue element of the DTΔ have been discussed in previous literature. John et al (2020) point out a lack of transferable design principles for Decision Visualisation Environments, Boukherroub et al (2016; 2018) miss clear guidelines and a systematic approach for designing and implementing DTs. These authors then propose frameworks for DTs geared towards decision support.

For the purposes of communication and co-production of research, that can but need not immediately lead to concrete decision support activities, guidelines are similarly needed. On the one hand, setting up DT events should be facilitated; one important point among many others is how to communicate uncertainties and sensitivities related to data and models, such as, how reliable a given dataset is or what the main drivers of a model's outputs are. On the other hand, a systematic method for distilling information from DT events carried out is needed to iteratively improve empirical information, models, the dialogue format, and the guidelines themselves. Experience from social sciences and participatory methods should play the leading role in this endeavour.

4.2 Empirical information for a "big picture"

The empirical challenge may include both extremes of a wide spectrum: scarcity of data relevant for specific questions on the one hand, and an overflow of (big) data on the other hand. While with the digital transformation underway, data is being collected at ever-increasing speed, it needs to be processed, analysed, and turned into insights and knowledge to actually be of use. For an overview on a societal challenge, empirical data further needs to be accompanied by knowledge on previous scientific work, relevant actors, and specificities of an issue in a given (e.g. local) context.

A conceptual challenge therefore is to turn data into a "big picture", that is, to distill a coherent impression of the status quo, or what led to it, for a given societal challenge. It can be much harder than expected to arrive at such an overview from large scientific literatures and disparate sources of data, even if one just concentrates on relevant orders of magnitude for a given challenge. Comparing and connecting numerous details, as it were to see the forest from the trees, is a prerequisite for selecting those pieces of information that one wants to have at hand for a DT event.

Software-wise, empirical information to be shown in a DT needs to interface in an appropriate way with the visualisation environment used. Here, a main challenge may be to organise and document empirical information (data, products from it, images, etc.) in an open source data base in such a way that relevant parts can be reused from one case to another one, to systematically enable building on previous work. The data structures needed will include geographical data, population data, e.g. for reusing or extending existing synthetic populations (see, e.g., Gallagher et al 2018), time series of data as well as combinations of these (timeseries of maps etc.) but we will not go further into this challenge here.

4.3 Model building and simulation analysis

As argued above, ABMs are useful for simulating and discussing social, socio-economic, socio-ecological, and socio-technical systems; referred to as socio+ systems in the following. Challenges in ABM development – usually an iterative process of definition or specification, ideally careful documentation, programming, observation, and adaptation – relate to model building, that is, specification and implementation of a computer programme for running simulations (4.3.1), and analysing these (4.3.2).

4.3.1 Common building blocks

Model building can be facilitated by re-using existing models and parts thereof[6] or employing ready-to-use building blocks. The latter result from identifying common elements and structures among socio+ systems.

The mathematical structure of a dynamical system helps fix terminology. The situation of a system at a given point in time is referred to as its state ($x_t \in X$, where X, the state space, is the set of all possible states and the index $t \in T$ denotes time, e.g. $T = \{0, 1, 2, \ldots\}$).

[6] See, e.g., the CoMSES Network model library `https://www.comses.net/`.

State changes, in the simplest case, are described by a transition function ($f : X \to X$) that, applied to a state outputs the next state ($f(x_t) = x_{t+1}$); dynamics result from repeatedly applying this function. In less simple cases, the transition function will, e.g., involve randomness; in a simulation, a random number generator may draw the next state according to a given probability distribution.

Agent-based models are of interest when it is impossible to define the overall system state and its transition function in a concise form; as is often the case for a socio+ system. Its evolution is shaped by a multitude of individuals, groups, and organisations as well as their common natural, built, economic, legal, cultural, etc. environments, no central entity exerts control. In particular, the micro-level elements of socio+ systems by definition go beyond a set of interacting agents; co-evolution with other elements of different kinds, such as production technologies in an economic, or ecosystems in an ecological dimension, is essential.

Agent-based modelling frameworks[7] provide building blocks at a general level: they offer functionalities for implementing different types of agents, a geographical environment, etc. A domain specific language (DSL) would further narrow the scope to socio+ systems. It is an instrument from computational science that allows expressing the significant concepts of a domain directly in computer code, making model code easy to write and read and avoiding unnecessary clutter (Warnke et al 2015). Societal challenges or the socio+ systems underlying them are a vast field rather than a concise domain; nevertheless, as a first step, we collect elements and structures that different socio+ systems have in common. Significant concepts for describing the state of a socio+ system include:

– A synthetic population of agents. As mentioned in the case of MoTMo, this is a set of virtual agents that statistically matches the real-world population it represents for relevant features. Synthetic populations have been described as the “social coordinate system” in which empirical data, often from different sources, is attached to agents (Barrett et al 2009). Individuals in such a population may, for example, be people with demographic attributes or firms with attributes like sector, number of employees, etc. As the term “synthetic population” is often used for individuals of the same type, that is, a population of people or one of firms, the set of agents in a system can also consist of several populations.
– Other entities and groups of agents. Both of these are not necessarily captured in a synthetic population. They may or may not be considered ”agents” in their own right, while like agents, they may be present in large numbers and have features that change through interactions. An example in MoTMo are households, consisting of persons, with additional features and actions of their own.
– A geographical environment. Most, if not all societal challenges to be discussed in a DT will relate to some spatial unit in a geographical sense: a city, a region, a nation, etc. The respective models need to be able to intuitively represent this aspect, e.g. via spatial coordinates for elements of the model and maps in visualisation. The geographical environment may itself be composed of elements. It may be a natural anchor for other elements, such as transport networks and other infrastructures, and can help express vicinity between agents.
– Immaterial environments of agents. These include rules, institutions, norms, and narratives, and may vary with language, cultural contexts, and social groups.
– Relationships between all of the above. Relationships constitute links for interactions of various kinds. They represent membership (e.g., of a person in a household) or other affiliations (worker at a firm, teacher at a school, etc.), social connections (friend- or kinship, professional relations), various kinds of exchange (e.g., information, goods, money), spreading processes (opinions, viruses, etc.), inheritance (resources, features, habits), and more. Relationsships may have features of their own, such as an intensity or direction.

[7] See, e.g., Abar et al (2017) for a review.

These domain specific significant concepts suggest another mathematical structure for describing a socio+ system's state: a multilayer network, consisting of nodes and edges between them (Caldarelli and Catanzaro 2012). Nodes represent agents, groups of agents, other entities, e.g., environment elements, edges denote the relationships between them; both nodes (persons, firms, etc.) and edges (kinship, goods exchange, etc.) can be of different types. The geographical environment then is a layer in this network structure, with e.g., grid cells or administrative units like NUTS-regions[8] as nodes. How immaterial environments relate to this network structure or whether it needs to be further extended for representing them, is a question for future research.

Next, a graph dynamical system is a natural candidate for representing a socio+ system's dynamics: its transition function relates the state of nodes and edges at a given point in time to those at a next point. Again, it will hardly be possible to describe this function in concise form. Common concepts for a piece-wise description of transitions "on the micro-level" include:

- a notion of time. In computing a next state from a previous one, steps may represent regular time intervals (a day, a year, etc), or any (random) time intervals after which the next change occurs.
- transition functions for nodes in the network represent various kinds of processes in the socio+ system, that relate to agents, groups, other entities, e.g., elements of an environment. Examples include information or goods exchange, choices, production, etc. From a formal point of view, transitions may range from simple deterministic changes depending only on an agent's state (such as aging) via changes of a single agent's state that require inputs from other elements (like information from another agent) to transitions that change the state of more than one agent at a time (like an exchange of goods for money between two persons).
- transition functions for edges represent the dynamic evolution of relationships.
- the network structure itself may evolve through addition or removal of nodes and/or edges.

A DSL could provide such elements for model building, of course without requiring the inclusion of any particular element in any particular model. It would further facilitate model documentation. While the basics of an ABM can be rather easily communicated to non-specialists, in intradisciplinary communication, for example in economics, a different perspective arises. Often, agent-based models are seen as a way to escape the necessity of making unrealistic assumptions for reasons of analytical tractability in mathematically formulated models. While infinitely many, infinitesimally small and indistinguishable agents are not realistic (Borrill and Tesfatsion 2011), they are part of a convention that eases communication in groups of economists trained in using it. In a sense, the agent-based modeller's freedom in representing agents and their interactions at the micro level is blessing and curse at the same time because it drastically reduces the number of assumptions taken for granted in comparison with other approaches. Efforts for careful documentation of ABMs (Grimm et al 2020; Wolf et al 2013) need to make up for this lack in standards; by using significant concepts from the domain, a DSL would reduce the distance between a model's code and its description. Along with an ABM, data used (Laatabi et al 2018) and simulation runs (Warnke et al 2017) need to be documented.

4.3.2 Analysis of empirically grounded large scale ABMs

Two related perspectives can be taken on the analysis of simulations from complex large-scale agent-based models. On the one hand, one can run (a large number of) simulations and analyse the resulting timeseries of data using statistical means. One challenge here is

[8] Hierarchy of divisions of the European Union territory enabling statistical comparisons at various regional levels (Nomenclature des Unités territoriales statistiques).

to efficiently run and explore such simulations, in particular when even a single model run comes with high computational costs. On the other hand, one can ask what can be known about modelled dynamics from a theoretical point of view.

While it is often pointed out that ABM simulation analysis is given comparatively little focus in the ABM literature, there are, by now, a list of works addressing issues such as sensitivity analysis (finding out how changes in model inputs influence model outputs), model verification (does the code do what it is supposed to do?), validation (does the model represent those real-world aspects it is supposed to?), and parameter estimation or calibration (finding the parameters that produce the best fit between model simulations and real-world data). These works facilitate applying established methods to ABMs (Thiele et al 2014), summarize the state-of-the-art and challenges (Lee et al 2015), present methods geared to ABMs with their spatial and temporal dimensions (Ligmann-Zielinska et al 2020), or apply a theoretical perspective to simulation output data (Grazzini et al 2018).

There is a multitude of ABMs developed for studying mechanisms in social systems, such as opinion dynamics, in abstract populations of (often not further differentiated) agents (e.g., Sîrbu et al 2017). For such models, parallels can be drawn to similar models from other contexts, for example molecules in chemical systems. When an ABM can be expressed in the same form as such existing models, results from these contexts can be transferred or translated to the social system context. This provides insights on systems switching between different patterns from time to time, or on quantifying probabilities of rare events in the long run, and it helps approximate an ABM by much simpler models, allowing a reduction of computation times (Niemann et al 2021). Approximations of an original complex agent-based model can also be obtained by fitting a simpler model to the ABM's output (Wulkow et al 2020), in turn relating back to questions of parameter estimation.

To facilitate ABM development for DTs, an important question therefore is how, and how far, mathematical concepts, methods and tools for the analysis of complex systems consisting of many (often rather simple) interacting elements carry over to or can be further developed for complex socio+ systems. Patterns identified may then correspond to significant concepts concerning meso- or macro-level dynamics of socio+ systems. How this helps analyse, e.g., the presence and evolution of niches and regulatory networks in these systems (Laubichler and Renn 2015), is another topic for further research.

5 Conclusion and Outlook

Based on experience gathered through a set of Decision Theatre events on sustainable mobility, this paper presented the Decision Theatre Triangle as a method for communication, decision support, and co-production of research on societal challenges. The tripartition into the elements empirical information, modelling and simulation, and dialogue format complements other frameworks which put more focus on the dialogue processes but do not necessarily consider an empirical component, which goes beyond data alone, and the modelling and simulation of potential future evolutions as distinct elements.

We envision a research process in which Decision Theatre events are interleaved with empirical research and modelling activities (Mielke and Geiges 2018) in order to address a societal challenge. In such a process, an initial model and its simulations would be adapted, extended, and improved according to questions and suggestions from participants. In following events, effects of such model changes would be analysed together. This would enable the creation of a community between researchers and stakeholders, where lines between "producers" and "users" of research are blurred, and both scientific and practical expertise are drawn upon so as to explore possible future evolutions that are

– plausible: based on the best available scientific evidence, combining empirical, theoretical, and practical insight on the complex social system underlying the challenge and its potential dynamics associated with alternative courses of action,

- socially desirable: involving all relevant stakeholders, including citizens, business, administration, and policy makers, who would be well informed about the scientific evidence without needing to become scientific experts themselves and who would contribute their practical expertise as well as different preferences, values, interests, and knowledge bases,
- creative: in the sense of being able to contemplate parts of the decision space that involve fundamental changes from current patterns, e.g., in terms of technological solutions or behavioural innovation,
- and adaptive: taking into account that each decision not only generates consequences, but also influences which decisions are possible in the future.

Turning the DTΔ into an easily usable instrument requires research on "all three vertices" that would facilitate building on previous work with each new application case. While the focus here was on modelling and simulation, structures for organising empirical information and guidelines for DT-event preparation as well as methods for their analysis are equally important points that we leave for future research.

As a longer-term outlook beyond the research challenges sketched above, an easy-to-set-up DTΔ could be of interest in terms of providing consultancy services. Returning to our example case, many urban areas in the world are facing the challenge of re-organizing mobility in ways that benefit people's well-being (better health due to less noise and air pollution) and inclusion (available and accessible to all), the environment (no carbon emissions), and the regional economy (e.g., jobs in the automobile and related industries, logistics in the city, etc.). The DTΔ could provide the opportunity of giving local authorities a possibility to combine scientific evidence with participation of their stakeholders (citizens, businesses, etc.) in decision processes.

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Appendix: List of events

when	where	event	participants
June 2018	Talent Garden, Turin	preparatory workshop "Cosa succede se ...? Immaginando la mobilità del futuro con il MoTMo" (What if...? Imagining mobility futures with the Mobility Transition Model, event in Italian)	researchers, stakeholders (administration, business)
November 2018	Haus der Kulturen der Welt, Berlin	DT "Transforming the Mobility Sector – Between Digitalisation and Sustainability" `https://globalclimateforum.org/2018/12/14/decision-theater-on-sustainable-mobility/`	researchers, stakeholders (policy, business)
February 2019	Leuphana Universität, Lüneburg	interactive sessions as part of the conference "Leverage points for sustainability" `https://globalclimateforum.org/2019/02/21/leverage-points-for-sustainable-mobility/`	conference participants
Summer 2019	GCF, Berlin	several "mini-DTs" with 2-4 participants to present the DT as an instrument	researchers at policy organisations
June 2019	IASS Potsdam	DT "Between Digitalisation and Sustainability – Exploring a Transition of the Mobility Sector" `https://globalclimateforum.org/2019/06/04/decision-theater-enavi-summer-school-2019/`	early career researchers
September 2019	UN, Geneva	interactive sessions at UNECE Sustainability Energy Week, Geneva `https://globalclimateforum.org/2019/10/15/unece-sustainability-energy-week-geneva-25-27-09-2019/`	members of the UN committee
December 2019	IASS Potsdam	DT "Wege zu nachhaltiger Mobilität" (Paths towards sustainable mobility, event in German)	highschool students, teacher
December 2019	Halle Münsterlar Münster	interactive sessions as part of the conference "Zukunftsstadt" (future city, sessions in German and English)	conference participants: researchers, city stakeholders
March 2020	Zuse Institute Berlin	DT "Mobility and Social Cohesion – What Future for Berlin?"	researchers, stakeholders (business)
September 2020	Zollverein, Essen	Klimafreundliche Mobilität für alle (Climate-friendly mobility for everyone. 2 events, in German) `https://globalclimateforum.org/2020/10/21/dtnamo-in-essen/`	citizens and local mobility experts
Autumn 2020	online	several online DTs, for testing and research purposes	researchers

Further events have been carried out that were not considered in the writing of this paper, others are planned.