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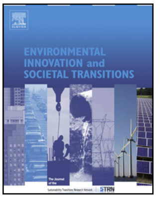


Survey

# Prospects of modelling societal transitions: Position paper of an emerging community☆

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ABSTRACT

Societal transitions involve multiple actors, changes in institutions, values and technologies, and interactions across multiple sectors and scales. Given this complexity, this paper takes on the view that the societal transitions research field would benefit from the further maturation and broader uptake of modelling approaches. This paper shows how modelling can enhance the understanding of and support stakeholders to steer societal transitions. It discusses the benefits modelling provides for studying large societal systems and elaborates on different ways models can be used for transitions studies. Two model applications are presented in some detail to illustrate the benefits. Then, limitations of modelling societal

☆ We, the authors, belong to a group of modellers who aim to make modelling of transitions a visible and fruitful sub-field of the societal transitions research field. We are related to the Sustainability Transitions Research Network (STRN, www.transitionsnetwork.org) and invite all interested researchers in the STRN and beyond to contact and join us.

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transitions are discussed, which leads to an agenda for future activities: (1) better cooperation in the development of dynamic models, (2) stronger interaction with other transition scholars and stakeholders, and (3) use of additional modelling approaches that we think are relevant to and largely unexplored in transitions studies.



## 1. Introduction

A societal transition is "a radical, structural change of a societal (sub)system that is the result of a coevolution of economic, cultural, technological, ecological, and institutional developments at different scale levels" (Rotmans and Loorbach, 2009). Societal (sub)systems as referred to in this definition cover key areas of human activity, including our transport, energy, agrifood, housing, manufacturing, leisure and other systems (STRN, 2010). For studying change of these systems societal transitions research adopts a broader perspective than other approaches to sustainable development, and highlights the multi-dimensional interactions between industry, technology, markets, policy, culture and civil society (STRN, 2010). Societal transitions are highly complex processes that unfold over time-spans of decades, rather than years, and involve "wicked" problems for societies that require a systems approach to policy (Rip and Kemp, 1998; Grin et al., 2010). The field of societal transitions studies has developed with two main interrelated agendas: (1) scientific progress: to better understand how structural change of large-scale complex societal systems comes about; and (2) impact: to make particular societal transitions happen and navigate developments towards sustainability.

The objective of this paper is to show how modelling can contribute to the agenda of societal transitions research – both for enhancing understanding and for increasing impact. Furthermore, we propose an agenda for future activities in our emerging (sub)community to increase the uptake and effect of modelling approaches in the societal transitions community and beyond. We start from the observation that there already has been modelling work in the field of societal transitions, as demonstrated by a special issue (Timmermans and de Haan, 2008), various conference sessions,[1] review papers (Holtz, 2011; Safarzynska et al., 2012; Zeppini et al., 2014; Halbe et al., 2014) and various PhD theses (Holtz, 2010; de Haan, 2010; Yücel, 2010; Chappin, 2011; Papachristos, 2012). Despite all these activities, model based studies to date have a smaller role in the field than we think they potentially could and should have, and we are of the opinion that the societal transitions research field would benefit from the further maturation and broader uptake of modelling approaches. We develop our argument as follows: Section 2 discusses fundamental characteristics of modelling and the associated benefits that arise for studying large societal systems. In Section 3 we then discuss specific challenges for model use that arise from the scope and perspective of societal transitions research, and outline typical ways how models have been and can be used in the societal transitions field, and how they make use of the previously discussed fundamental characteristics of modelling. In Section 4 we demonstrate the benefits by two examples, which we present at greater length. In Section 5 limitations for the use of models in societal transitions research are discussed. In Section 6 we identify promising avenues for using models to study societal transitions and to increase the impact of transitions studies through their use. In the final section we draw the conclusions from our discussions.

[1] There have been a week-long international workshop on "Computational and Mathematical Approaches to Societal Transitions" at the Lorentz Center at Leiden University in 2007 and sessions at several conferences: ESSA 2008 in Brescia, Italy; ESSA 2009 in Surrey, Guildford, UK; WCCS 2010 in Kassel, Germany; KSI Conference 2010 in Amsterdam, The Netherlands; EGU General Assembly 2013 in Vienna, Austria; IST Conference 2013 in Zürich, Switzerland; IST conference 2014 in Utrecht, The Netherlands.

## 2. Characteristics of models and benefits for transition research

A "model", as we use the term here, is a simplified, stylised and *formalised* representation of (a part of) reality. Models range from being specific for a particular real-world case, such as the Dutch electricity system, to being more general, such as generalised models of consumer-producer interactions. Modelling involves outlining a system boundary and selecting aspects of the studied system that are considered the most important with respect to a particular research objective. Then, a formal representation of these aspects and their interrelations is developed. Models can be formulated in many ways, for example conceptually, mathematically, graphically, or as computer programme code, and they can be used for a variety of purposes, most importantly to make forecasts, to improve the understanding about mechanisms that produce a certain observed phenomenon, to explore consequences of hypotheses, and to facilitate communication (Epstein, 2008). In the following sections we identify certain fundamental characteristics that models of a great variety of designs share, and discuss the benefits for transitions research that can be derived from these characteristics.

### *2.1. Models are explicit, clear, and systematic*

All theorising and conceptualisation requires making assumptions. The virtue of models is that these assumptions typically have to be very explicit (Epstein, 2008). Models have to be written down using some formal method in order to work with them. In the process of writing down, all the assumptions have to be explicated, and the variables and the relations between them have to be defined. Making it concrete like this – developing definitions and forcing choices between concepts – leads to discourse and can reveal differences in understanding between involved researchers and stakeholders that may remain unnoticed in less explicit approaches. The clarity of models helps to bridge disciplinary boundaries, as the formal description leaves little room for ambiguity[2] and can provides a common language to describe and discuss the analysed system. For this reason, models are also considered useful tools in participatory processes (cf., Vennix, 1996; van den Belt, 2004). Furthermore, models are systematic in the sense that they facilitate capturing a diversity of (previously isolated) pieces of knowledge in a single, logically coherent representation. During the process of knowledge integration, easy to overlook inconsistencies between partial pieces of knowledge and knowledge gaps can be revealed because of the need for logical consistency. Models with appropriate visualisation and data processing techniques can furthermore help to make the structure of complex systems more accessible, e.g., through visual representation of interaction networks, systematic representation of inputs, key system elements and outputs, identification of feedback-loops etc. This can assist researchers and stakeholders in getting an overview of the studied system. In sum, the process of modelling itself – irrespective of the modelling outcomes – facilitates learning about the analysed systems and can make our present understanding of transitions more explicit, less ambiguous, and more interlinked.

### *2.2. Models allow inferences of dynamics in complex systems*

Although some processes involved in societal transitions, such as increasing returns to scale and diffusion of innovations, are reasonably well understood in isolation, considering several of them simultaneously is a daunting challenge. The transition dynamics emerging from the interplay of these processes is difficult to oversee and comprehend, let alone foresee. This is rooted in a basic limitation of the human mind to imagine and comprehend dynamics in complex systems. It has been found that the mental models[3] which humans (consciously or unconsciously) use to deal with complex systems are typically event based, have an open loop view of causality, ignore feedback, fail to account for time

[2] However, the interpretation of the variables, i.e. the understanding of the relation between the formal description and the real world, may involve more ambiguity. Resolving these potential multiple understandings is an important aspect of participatory modelling, more on this later.

[3] The term mental model here refers to someone's thought process about how something works in the real world, i.e. her/his idea of the surrounding world, the relationships between its various parts, and about acts and their consequences. A more precise

delays, and are insensitive to non-linearity (Sterman, 1994). Hence, essential elements of dynamics in complex systems, namely feedback, time delays and non-linearity, cannot be appropriately dealt with. Consequently, mental simulations of complex systems are highly defective, as has been demonstrated empirically in various studies (Dörner, 1980; Sterman, 1989a,b; Brehmer, 1992; Kleinmutz, 1993; Diehl and Sterman, 1995; Atkins et al., 2002; Sastry, 1997). Dynamic models[4] that are cast mathematically or are implemented as software models are able to calculate or derive the dynamics that arise from multiple interacting (non-linear) processes and can hence help the researcher to infer system behaviour from assumptions with greater confidence than is possible with mental simulations (Sterman, 2002).

In particular, dynamic models are useful to understand and explore emergent phenomena. Emergent phenomena result from the *interactions* between various parts, and any explanation of the overall system behaviour depends upon both the properties of its parts and the characteristic way the parts are related (Elder-Vass, 2010). Emergent phenomena therefore "...are somehow constituted by, and generated from, underlying processes..." yet at the same time "somehow autonomous from underlying processes" (Bedau, 1997). Understanding emergent phenomena is highly relevant for transitions studies. To give some examples: the inertia of a regime (partly) arises from interdependencies of elements, niches arise, grow and merge, and different transition pathways unfold depending on particular relations between landscape, regime and niche levels (Geels and Schot, 2007). Dynamic models allow to represent the parts and the relations and to let their interactions "generate" the emergent phenomenon from the underlying processes (Epstein and Axtell, 1996). Since mental simulation is prone to failure when it comes to complex systems and dynamic models are the only other possibility to infer dynamics in complex systems, we argue that understanding emergent phenomena will strongly benefit from the use of dynamic models. Bedau (1997) even gives a philosophical argument that emergent phenomena can be understood *only* through using dynamic models.

### *2.3. Models facilitate systematic experiments*

It has been argued that model-based science is very much like experimental science (Bankes, 2009). In experimental science, the researcher creates an experiment in which various factors are carefully controlled. Models can be used in the same way, i.e. it is possible to fully control the various factors affecting the behaviour of a model. Consequently, one can use models to try out things and analyse their consequences, including experiments that would be impossible, impractical or unethical with a real system, or in system configurations that do not (yet) exist. For example, when studying energy systems, models can be used to experiment with alternative policy options for steering the system towards more sustainable functioning (Chappin and Dijkema, 2010). Such experimentation in the real world would be costly and could also have negative social effects and consequently such a comparison between alternative policy options is next to impossible to achieve (Kwakkel et al., 2012). Models can thus be used for systematic and controlled what-if analyses, similar to experimental science. It is relatively cheap to execute series of experiments in order to explore the effects of different policies, to assess the consequences of unresolved deep uncertainties, or to replicate an experiment a large number of times in order to study the consequences of the inherent stochasticity of the modelled system.

definition is given by (Doyle and Ford, 1999, p. 414) who define a mental model as 'a relatively enduring and accessible, but limited, internal conceptual representation of an external system (historical, existing or projected) whose structure is analogous to the perceived structure of that system'.

[4] We use the term "dynamic model" to refer to a sub-class of models that relate elements and their interactions and are able to infer dynamics that arise from this structure, e.g. computer simulation models or models cast in an analytical or numerical mathematical description. Dynamic models of complex systems do not have to be large and complicated per se (i.e., include many variables and relations), but in the transitions context there is a certain tendency towards this, as transitions happen in large complex systems.

## 3. Model uses in transitions studies

Models differ largely in terms of their formulation, level of abstraction, epistemological foundations, application context, data requirements, and purpose. These dimensions have to be carefully balanced in each model study to design a useful model that is fit for purpose. The specific benefits and limitations of a model depend on the particular design and its intended use. It is therefore not possible in the scope of this paper to provide a comprehensive discussion of model uses and associated benefits and limitations in the transitions field. Instead, we discuss some specific challenges that societal transitions modelling must cope with. We then present some rather generic classes of how models have been and can be used by transition scholars and discuss how these model uses draw on the characteristics presented in Section 2 and how they deal with the specific challenges. For the discussion of model uses, we adopt the classification developed by Halbe et al. (2014) and distinguish three classes: (1) understanding transitions; (2) providing case-specific policy advice; (3) facilitating stakeholder processes.

### 3.1. Specific challenges

As outlined in the introduction, the perspective of transition studies is especially broad, covering multiple sectors. It also includes inter alia institutions, markets, various types of actors and actor networks, technologies and infrastructures. Given this broad perspective, models of transitions have to either include many elements and relations making them large and complicated, adopt a comparably high level of abstraction, or purposefully limit their scope of analysis. The modelling also requires the integration of knowledge from different disciplines such as sociology, (social-) psychology and economics, including their various sub-fields, as well as the natural sciences and engineering. Unlike in less formalised approaches this integration needs to be explicit, which often requires the making of choices and developing creative solutions where things do not readily combine.[5]

Furthermore, transition research adopts a highly dynamic perspective and conceives technologies, infrastructure, institutions, actors, behaviour and values as all being variable during the transition process (STRN, 2010), and this includes deep uncertainties (Lempert et al., 2003; Kwakkel et al., 2010; Walker et al., 2013), such as the potential emergence of a game-changing technology or crises. This characteristic of transitions requires attention when making assumptions about the ontology of dynamic models, as elements of this ontology might change during the simulated time period (Andersson et al., 2014), for example if completely new actor groups such as “prosumers” of solar energy appear during a transition of the energy system. In principle, modelling can cope with a changing ontology through choosing the level of abstraction such that the required change in the ontology becomes part of the dynamics of the model. This will be easier to realise for historic cases where the change in ontology can be established after the fact, while this is more difficult for prospective use.

A concomitant issue to ontology is the development of metrics and indicators for transition processes. The need for that is evident in studies that transfer theoretical work (e.g., Geels and Schot, 2007) to models (e.g., Bergman et al., 2008) where a conceptual framework conducive to modelling has to be developed before building the model (Haxeltine et al., 2008).

Finally, not all social processes involved in transitions can easily be captured in models. Mayntz (2004) distinguishes between processes that emerge from the uncoordinated actions of many actors (e.g., increasing returns to scale, diffusion of innovations, percolation effects in networks, etc.), and processes that result from coordinated actions or discussions of few actors (e.g., strategic actions, political processes). The latter are especially sensitive to agency of a single or a few actors, and moreover are often shaped by very specific sets of institutions, which influence the process and its outcomes. Therefore these types of processes are contingent on potentially very specific circumstances of the actors involved and the institutional setting. On the one hand, omitting these issues in models can lead to models that essentially ‘miss the point’ because their dynamics do not incorporate agency

[5] The need to be explicit can be a benefit if it stimulates discussions and makes unspoken assumptions visible (see Section 6.2.1).

where it would be appropriate. On the other hand, incorporating the processes may lead to very specific models that require hard to obtain data on specific rationales and motivations of single actors and which are difficult to generalise.

### 3.2. Models for understanding

All kinds of models can enhance understanding of transitions through making the structure of complex systems explicit and by doing so supporting the identification of the most relevant elements and processes.[6] Dynamic models can furthermore enhance understanding through linking overall dynamics and emergent phenomena to the underlying elements and processes. They can assist the evaluation of historical transition narratives by testing whether the proposed set of assumptions can actually generate the described dynamics (Bergman et al., 2008; Holtz & Pahl-Wostl, 2012; Yücel, 2010), and be used to test and refine proposed theories about the way transition processes unfold and how certain theorised mechanisms produce certain effects such as, e.g., lock-in or various transition pathways (see, e.g., Eising et al., 2014; de Haan, 2008; Papachristos, 2011; Safarzynska and van den Bergh, 2010; Schilperoord et al., 2008; van der Vooren and Alkemade, 2012). In all cases, benefits of model use result from the ability of dynamic models to systematically integrate the knowledge about variables and processes of the analysed system, and to let their interactions generate the phenomenon of interest. The assumptions are explicit to the analyst and the clarity of causal factors enables understanding of the operating mechanisms. Furthermore, the model can be varied in systematic experiments to reflect a variety of hypotheses about simulated circumstances. This allows identifying different sets of assumptions that do, or do not, qualify as potential explanations for the phenomenon of interest.

Some of the cited model exercises thereby adopt a high-level of abstraction to cover the scope of multiple sectors and to account for changes in the ontology (Bergman et al., 2008; Yücel, 2010; Schilperoord et al., 2008; de Haan, 2008; Papachristos, 2011), while others focus on specific subsystems to keep the size of the model manageable (Eising et al., 2014; Holtz and Pahl-Wostl, 2012; Safarzynska and van den Bergh, 2010; van der Vooren and Alkemade, 2012). The focus on historical cases and theoretical patterns allows accounting for deep uncertainties, strategic action and political processes as pre-defined boundary conditions for and parts of the model.

### 3.3. Models for case-specific policy advice

Models for case-specific policy advice aim to provide practical policy recommendations on how to influence a transition in a particular case. A precondition for this type of model use is that the modellers and stakeholders involved have sufficient confidence in the theory, hypotheses and assumptions behind the model. The dynamic model then may be used to produce forecasts, projections of future states of the analysed system given an initial state and a certain policy scenario that captures (the results of) strategic action and political processes. As outlined above, transition cases involve many deep uncertainties, and consequently the dangers of relying on model forecasts as accurate predictions are severe. Therefore, state-of-the-art model applications acknowledge uncertainty and incorporate it in the model study to assess its relevance and to analyse its consequences. In recent decades, scholars have been advocating an approach called Exploratory Modelling (Bankes, 1993), which involves acknowledging uncertainties through analysing model behaviour over ranges of parameter values, and variation of certain assumptions such as actor rationality. This approach does not result in a model that produces a prediction, but rather one that produces a portfolio of possible futures (see, e.g., Chappin and Dijkema, 2010; de Haan et al., 2013; Kwakkel et al., 2013). Exploratory Modelling is at the heart of decision support approaches like robust decision making (e.g., Lempert and Collins, 2007) and model-based adaptive policy making (Hamarat et al., 2013, 2014). These approaches aim at supporting the design of a plan that performs robustly in the face of the many uncertainties, rather than the identification of an optimal plan that only performs optimally under one narrowly defined future scenario. Exploratory Modelling is suggested to be a key way to incorporate modelling into strategic planning

[6] See Sections 2.1 and 6.3.1 on participatory modelling and Section 6.3.3 on structural modelling.

(Malekpour et al., 2013). Through doing systematic modelling experiments and mapping the space of possible futures, dynamic models can hence be used to test policies or approaches for governance and indicate how they affect the set of likely future paths for a particular system. Furthermore, through the clarity of causal factors and the ability to scrutinise the mechanisms that produce results, models provide insight into the conditions under which a given type of future will occur. In sum, dynamic models can support the identification of robust transition policies, of thresholds whose crossing leads to unwanted future developments with high probability, and facilitate discussions about possible and necessary interventions to steer a system in the desired direction.

### *3.4. Models to facilitate stakeholder processes*

Models to facilitate stakeholder processes have so far received limited attention of transition modellers (Halbe et al., 2014), but we see big potential for this model use. All kinds of models can be developed in a participatory way and there are various ways to include stakeholders in modelling processes (see Renger et al., 2008; Voinov and Bousquet, 2010; Hare, 2011), therefore there is a certain overlap of this category with the other model uses. In front- and back-end participatory modelling processes, stakeholders are consulted at early and at late stages of the model building process to provide input on definitions and validity, without extensive participation in model construction (Hare, 2011). Such processes are common for decision-support and communication of scientific findings, and existing models can be applied. We give an example that falls into this class in Section 4.1. In co-construction participatory modelling, the very process of modelling itself becomes a participatory activity (Hare, 2011). By jointly building a model, stakeholders explicitly discuss assumptions and learn about each other's perspectives. The developed models may then be used in a second step to derive forecasts and discuss policies. Also different kinds of games can serve multiple purposes in stakeholder processes. For example they allow the testing of policies and strategies and to experience the role of another actor in a conflict situation. We discuss co-construction participatory modelling as well as gaming approaches as promising future avenues in Section 5.

## 4. Examples

In this section we present two examples of modelling studies to demonstrate that the benefits of modelling discussed above can be realised in practical terms. We first present a study that applies well-established models developed outside the (core) transitions community for the exploration of transition pathways towards a sustainable electricity system. Models that range from statistical data techniques to more advanced models from the disciplines of economics, econometrics, engineering, environmental and other natural sciences, or models that cross-cut through several disciplines, such as energy–economy–environment models, are readily available or can be easily adapted to be used in the transitions field. While such models are well established and widely used for research and policy making in general, the transitions community has barely used them to date, despite the arguments given in Section 2 suggesting it might be beneficial to do so.

The second example complements the first one and describes a dynamic model that has been specifically developed to use (formalised) transition concepts for exploring transition dynamics towards sustainable mobility.

### *4.1. Using existing models to scrutinise narratives*

An example that demonstrates the benefits of using already existing models for transitions research comes from the Realising Transition Pathways project (Realising Transition Pathways, 2013). This project explores the UK electricity system transition in 2010–2050. In this project, transition scholars in stakeholder workshops and through desk research developed three governance narratives for this transition: market-led, government-led and civic society-led governance narratives (Foxon, 2013; Foxon et al., 2010). These narratives consisted of 4–5 pages of text about governance patterns, choices of the key actors and the co-evolution of these aspects and electricity demand and supply (Transition Pathways, 2012). In a semi-structured process, these narratives were initially quantified into the so-called transition pathways to enable communication with the key stakeholders and further detailed assessment of the narratives and pathways (Foxon, 2013). Yet, when these pathways became used for wider audiences and purposes, they were continuously challenged and could not always withstand critical feedback. For example, no economic considerations were taken into account when developing the pathways. This raised concerns over how realistic the pathways were.

To address the concerns and criticisms, a multi-model analysis of the narrative and pathway of the government-led transition was initiated (Trutnevyte et al., 2014). The narrative was linked with eight already existing models. These models included (1) an energy demand model, (2–4) three supply–demand models, (5) an energy–economic model, (6) an energy–behaviour model, (7) an economic appraisal model, and (8) an energy and environmental appraisal model. These eight models were used with harmonised assumptions to tailor them to the government-led narrative and were then applied to assess and flesh out the narrative and its quantification in a systematic way. As a result of this process, several limitations in the narrative and its underlying assumptions were identified (Trutnevyte et al., 2014). For example, the narrative wishfully overestimated the electricity demand reduction levels and this was inconsistent with the results of the energy–behaviour model and energy–economic model. The uptake of costly marine renewables, envisioned in the narratives, was also questioned by the energy–economic model and the economic appraisal model. The narrative also depicted an irreplaceable role of carbon capture and storage (CCS) for meeting long-term stringent greenhouse gas emissions targets. In contrast to that assumed irreplaceability, all models, except the energy demand model that did not analyse electricity supply options, showed that transition pathways without CCS can also meet the emission targets. In fact, the energy and environmental appraisal showed that if energy requirements for extraction, processing/refining, transport, and fabrication, as well as methane leakage that occurs in coal mining activities are also considered, CCS is likely to deliver only 70% reduction in greenhouse gas emissions instead of the commonly assumed 90% (Hammond et al., 2013).

The divergence between narratives and models observed in this case is not surprising because narratives, envisioned by stakeholders and even experts, often tend to be overly optimistic and overlook complex interdependencies in the systems (Baron, 1998; Trutnevyte et al., 2011, 2012a). The models helped to identify the resulting questionable assumptions in the narratives. Furthermore, the models also helped to identify issues that were not considered in the narratives at all. The narratives barely touched on the important challenges of supply–demand balancing. When transition pathways, as envisioned in the narratives were modelled, the results of seven models showed that balancing supply and demand will be challenging due to the simultaneous deployment of large-scale inflexible power plants, such as nuclear power, and substantial deployment of intermittent renewable energy sources. To ensure that the supply–demand challenge would be met in the envisioned pathways, deployment of flexible back-up capacity and interconnectors with Europe would be needed. The modelling results drew attention to these issues and thus increased the inferential power of the study overall. Such findings will be used in the up-coming revision of the narratives (Trutnevyte et al., 2014).

This example illustrates that models can be useful to support conceptual and narrative based transition approaches, increase their robustness, enhance confidence in them, and improve their policy relevance. In particular, the usage of existing models from outside the core transition community can help to consider factors that typically remain out of scope (Hansen and Coenen, 2013; Trutnevyte et al., 2012b).

### *4.2. Explore transition dynamics with a dynamic model*

Dynamic models which integrate multiple non-linear processes can be developed specifically to analyse transitions or relevant sub-processes thereof as phenomena that emerge from a selection of underlying elements and processes. To demonstrate the potential of such dynamic models for analysing possible futures we report on a model for assessing transitions to sustainable mobility, more precisely personal (inland) transportation behaviour (Köhler et al., 2009). The model implements an (extended) multi-level perspective with two classes of agents.[7] There are eight "constellation agents", which have an internal structure and represent subsystems within society: (1) the regime agent represents the internal combustion engine (ICE). There are three car-based niches: (2) ICE/electric hybrid cars, (3) biofuel cars and (4) hydrogen fuel cell vehicles. Other niches following changes in ownership patterns are: (5) increased use of public transport, and (6) product to service shift (from car ownership to car sharing). Niches with decreased mobility demand are: (7) adoption of slow modes (walking and cycling) and 8) urban information and communication tools (ICT) for home working. A (much) larger number (1000 in the reported results) of simple agents represent consumers.

All agents are located in a "practice space," a multi-dimensional characterisation of the functionality of a societal subsystem and the preferences of consumers. The chosen practice dimensions are: $CO_2$ emissions of vehicles ($gCO_2$/km), cost of transport (€/year), ICT use, structure of the built environment (mixed use of zones affecting mobility decisions) and private and public demand split (measured in person km/year). Each type of constellation agents (regime, niche, niche–regime) has a different behavioural algorithm for its movement in the practice space based on policy driven party dynamics (Laver, 2005). Constellation agents may interact, for example the regime might absorb a niche and niches may merge into a stronger niche.

Consumers support the constellation agent they consider most attractive and provide resources to this constellation agent. In turn, the constellation agent uses these resources for movement in the practice space or increase of strength. The attractiveness of a niche or the regime for consumers depends on its strength and the match between its practices, expressed by its location in the practice space, and the consumers' preferences. The consumer agents in the practices space change their position depending on landscape signals, which are exogenous inputs to the model. Landscape signals include: (1) climate change that shifts preferences towards lower $CO_2$ emissions, (2) change in consumers price acceptance, (3) ICT usage among consumers, (4) public transport investments, and (5) planning of built environment as weak but steadily decreasing transport requirement over time. The model defines a transition as a significant shift in the system's dominant practices. The first way in which a transition can happen is through regime change, which occurs when an incumbent regime loses support and strength and another constellation agent with different practices takes its place. The second way in which a transition can happen is when the regime significantly changes its practices through adaptation and/or absorption of niches, moving to a significantly different location in the practice space (cf. Geels and Schot, 2007).

The model represents a very complex system with feedback between the consumers on the one hand and the niches and regime on the other hand. Also, there are mutual interactions between the regime and the emergent niches, and between the niches themselves. In addition, the system is influenced by a set of exogenous landscape factors. The model links these processes in a systematic way and provides an integrated and logically coherent perspective on the large system and its many interdependencies. Simulation experiments can be used to infer the dynamic consequences, including particular possible emergent properties: the disappearance of the regime and the emergence of a new regime. The model can be used to investigate the conditions of a regime shift, making these conditions explicit and discussable since the model formulates the various elements and processes clearly and assumptions have been made explicit. Through this, the model can be used to test hypothesis about necessary and sufficient conditions for transitions, and to explore future developments given certain initial conditions and assumptions.

The model was parameterised using UK data (Whitmarsh and Nykvist, 2008) and calibrated to provide plausible strengths of the regime and niches in 2000 as well as 2010. Simulation results for the time period until 2050 show that hydrogen fuel cell vehicles come to dominate, but only in the very long run (after 2030), while biofuels and ICE-electric hybrids are the main alternatives to the regime in the next 10–30 years, because (a) they are already developed and (b) they fit better into current infrastructures. The model shows that transitions through the adoption of new technologies are most likely, whereas lifestyle change transitions require sustained pressure from the environment on society and behavioural change from consumers.

[7] Bergman et al. (2008) provides a detailed description of the mechanisms in the model.

Although the results from the model are preliminary, there are three policy implications: (1) a large-scale change in consumer attitudes together with strong and sustained policy support are required for a transition to sustainable mobility; (2) the best alternative in the short and medium term may not be the best option in the long run; and finally (3) directing radical institutional and behavioural change is more difficult than achieving technological change.

## 5. Limitations of model use in transitions research

We have discussed benefits of models and advocated and illustrated their use in transitions research. However, as all methods, modelling also has limitations. The specific limitations of a model depend on a range of model dimensions: model purpose, method applied, level of abstraction, epistemological foundations, application context, and data requirements and availability (Boero and Squazzoni, 2005; Brugnach and Pahl-Wostl, 2008; Brugnach et al., 2008; Janssen and Ostrom, 2006). The following identifies some typical limitations of transitions models. These limitations are similar to those discussed for models in other fields (e.g., Cressie et al., 2009; Modarres, 2006; Aughenbaugh and Paredis, 2004), but sometimes go beyond the limitations of modelling in general as transitions are complex, multi-faceted processes involving social dynamics in big systems evolving over large timescales (see Section 3.1).

### *5.1. Conceptualisation and implementation issues*

Modelling transitions includes creating explicit links between pieces of knowledge from different fields, using some formal language for doing so. This includes combining conceptual elements that were developed with different background assumptions and world-views, and their integration often requires creative solutions. Transition theories that provide an already integrated perspective, such as the multi-level perspective, usually have the form of heuristics that do not readily translate into the formal descriptions needed for models, but require additional assumptions to make them operational for modelling. These issues may lead to models that have a weak theoretical and conceptual foundation (Holtz, 2011).

Furthermore, modelling involves conceptual choices that have to be made. A model employs a certain conceptual frame to explain a specific phenomenon, and that typically means other explanatory avenues are not explored – there is always more that could be included or model parts that could be designed differently. Whereas the whole point of modelling is exactly to focus on specific processes and abstract away from others, the relevance of co-evolution across the different sectors (markets, politics, culture, etc.) makes it especially difficult to select the processes that need to be included in transition models, and to identify those which may be neglected. The systems analysed being large creates a tendency for transitions models to be also large, i.e. to include many variables and parameters, what makes validation more difficult (see below). A single model therefore can hardly achieve the goals of completeness and detailedness at the same (cf. Bollinger et al., 2014).

Finally, many types of models, especially large and complicated ones, necessarily include small, ad hoc assumptions to make the model operational. These assumptions are typically considered not to influence the modelling results and therefore often left unmentioned in publications and receive limited attention during testing the model. But, they might in some cases influence results in some unnoticed way and lead to wrong conclusions regarding the causes for the observed effects (Galán et al., 2009). The inclusion of unmentioned small assumptions also seems to go against the claim that modelling makes assumptions explicit. However, on the proviso that the model is made fully available,[8] all assumptions can at least in principle be checked and tested.

[8] E.g., through publication of source code.

### 5.2. Validation issues

The conceptualisation issues sketched above directly lead to issues with validation, understood as testing whether the model captures reality sufficiently well (Windrum et al., 2007; Ormerod and Rosewell, 2009). The conceptual diversity included in the model and the uncertainties associated with formalisation and integration may yield a large number of free parameters[9] which can lead to: (1) over determination of the model. A model with enough parameters can reproduce almost any empirically observed behaviour with an appropriate choice of parameter values. This diminishes the validity of the model and can be detrimental to the trust of stakeholders in the model; (2) a high dependency on data to “fit” the model behaviour. This makes the model highly specific to a certain case from which the data is taken, with limited possibilities to draw general insights from it; and (3) if not fixed against data, the model may have wide ranges of, in principle, equally valid parameter values, potentially yielding many regimes of qualitatively different model behaviours. This can diminish explanatory power and reduce trust in a similar way to point (1).

The availability of data can be another severe problem for validation, even more so because some of these data are qualitative which means that they need to be mapped or translated in a quantitative format for comparison with, or use in, the model. Furthermore, for prospective model uses, there is an issue of unpredictability that cannot be resolved even with huge amounts of data. Validation of a model against historic data may increase confidence in the model but does not necessarily say much about the validity of forecasts of the future. This is simply because one cannot expect that the (historic) circumstances under which the model produced accurate results will be quite the same in the future (see Section 3.1). In fact historical transitions and future transitions to sustainability pose considerably different demands on transitions modelling (Papachristos, 2014).

### 5.3. Agency and contingency

As outlined in Section 3.1, transitions are influenced by strategic actions of core actors and political processes, which are hard to capture in prospective model uses. They can be captured as (policy) scenarios under which diverse futures unfold differently, but the creativity of real actors when endogenously responding to changing circumstances cannot be fully be represented by predefined policies.

### 5.4. Issues related to expectations, results and communication

Models, due to their systematic nature, include a lot of knowledge and many different assumptions, all of which are (to various degrees) relevant for the model results. A model can therefore not easily be reduced to something simpler, without neglecting at least part of the story. But, fully explaining a (somewhat large and complex) model and how it generates certain emergent effects often would require more space than is available in policy briefs or even research articles, and truly understanding a model requires devoting a considerable amount of time to it (even for other modellers). Limited engagement with and understanding of the model may reduce the trust of stakeholders in the model, especially if the results do not match their intuitive expectations. On the contrary, the fact that models often produce numbers or graphs can convey a false sense of precision and results may be interpreted too “literal” or as unshakable truths. In order to deal with these issues, modellers should make sure to convey the complexity of the model and the uncertainty associated with its results, especially if they are used as input for decision support (Stirling, 2010).

## 6. Avenues to pursue

Despite the high potential we have discussed and demonstrated by examples, the uptake of transitions modelling studies in the wider transitions community and beyond and their contribution

[9] Free parameters are those which are not (sufficiently well) specified through theory or empirical data. Large numbers of parameters can slip into models through other routes as well obviously. Many thanks to Professor Ana Deletic for pointing out the risk of over determination of models which can be easily overlooked.

to impact of transitions studies has been comparably small. This section therefore discusses several avenues along which transitions modelling can develop and increase both, its contribution to understanding transitions and its impact.

### 6.1. Stronger cooperation in the development of dynamic models

We have discussed dynamic models as tools to foster theory building and as means to make projections of future developments. The existing set of dynamic models in our (sub)community for doing so is highly diverse in terms of scope, level of abstraction, conceptual approach and method applied. This diversity can be seen as a result of different attempts to address the specific challenges outlined in Section 3.1, and also attributed to the juvenileness of the field. Due to the conceptual and validation issues discussed in the previous section, there is often scope to increase the robustness of conclusions derived from these models, especially if they are large and complicated. In order to promote the further maturation of dynamic models of transitions we intend to establish a stronger cooperation in their development so that it is done in a cumulative way, and learning from existing exercises is transferred. Several methods for this have been identified by Halbe et al. (2014). Among these are: (1) the comparison of alternative models that deal with a similar problem situation. This helps to develop robust results and to identify critical assumptions. A corollary would be to develop (more) models of the same or similar transition cases in order to facilitate comparison. A specific activity could be to address an open policy issue relating to transitions to test and showcase the usefulness of a variety of models; (2) the development of existing frameworks such as the multi-level perspective into more precise versions that are conducive to modelling exercises and reduce the ambiguity involved in the necessary specification for usage in models (cf. de Haan and Rotmans, 2011); (3) the development of a shared understanding and toolbox of elements and processes operating on lower levels of abstraction (e.g., increasing returns to scale, diffusion of innovations) to guide model design processes and to make models comparable (cf. Ostrom, 2007; Holtz, 2011, 2012). The identification of a set of important lower level mechanisms and their relation to higher level structures and processes would also be a contribution to theory development in the transition field; (4) to design and use protocols and tools for documentation, uncertainty handling and quality assurance. This serves to ensure high quality of models and the following of best-practices. Transition modellers can build on existing tools, protocols, platforms and frameworks that have been developed in other fields (cf. Halbe et al., 2014).

Such an intensified cooperation in the development of dynamic models can address limitations related to conceptualization and eventually lead to the development of a few core transition models,[10] which would facilitate accumulation of knowledge and experience and improve the validity of models (Frenken, 2006). A step towards such a better cooperation is the identification of one or more clear niches for dynamic transition models in relation to the broader context of existing modelling streams, and to identify a set of characteristics a “dynamic transitions model” should have to be able to contribute to cumulative insights in this niche.

### 6.2. Interaction with other transition scholars and stakeholders

Models can increase the impact of transitions studies through sharpening discussions, enhancing mutual understanding, and reducing uncertainties about potential future developments–or making uncertainties and their consequences explicit where they cannot be reduced. Although Section 4.1 provides an example of how impact can be achieved, the potential of a closer collaboration between modellers, other transition scholars, and especially stakeholders from practice such as policy makers is currently mostly untapped. We therefore intend to discuss the role of models for reflexive

[10] To illustrate the idea of core models: Frenken (2006) identifies three core models of technological innovation: fitness landscape models, complex network models and percolation models. These can be recombined, adapted and extended for specific cases and research questions, but provide a widely shared reference that captures certain important characteristics of the analysed system. Transitions are broader and different from technological innovation, therefore different core models should be developed.

governance[11] and policy making in general more deeply with transition scholars who are active in these fields. Moreover, transdisciplinary research involving practitioners directly affected by the transition processes and integrating their problem perspective as well as quantitative and qualitative knowledge is a promising avenue to increase the societal relevance of research (e.g., Jahn et al., 2012; Lang et al., 2012; Mobjörk, 2010).

However, due to the limitations outlined in Section 5, the complex numerical simulation models which have up to now mostly been developed to study the dynamics of transitions often are not mature enough to be readily applied to practical questions and decision making. Other modelling approaches exist which are more parsimonious regarding theory and data needs, and which may be more useful if the development and use of complex numerical simulation models is not advisable. An example is the usage of approved existing models from outside the core transition community as presented in Section 4.1. There are other approaches which we consider promising to make use of in future projects that intend to achieve impact through inter- and transdisciplinary research. We introduce them in the following section.

### 6.3. *Exploring and applying other promising modelling approaches*

#### 6.3.1. *Participatory modelling*

As mentioned in Section 2, modelling forces one to be very explicit about one's assumptions. Amongst these assumptions are the problem framing and world view themselves. Participatory modelling[12] can assist in making the fundamental and often unspoken assumptions of stakeholders visible and discussable through involving them in a modelling exercise. Through jointly developing a formal representation of the target system assumptions held by the various participants become explicit and can be more easily shared. The definition of variables in a group discussion reveals if stakeholders use different words for the same concept, refer to different concepts with the same words, or use concepts that overlap but do not match exactly, and the discussion of relationships between variables reveals different views and background knowledge. Discussing assumptions can help stakeholder groups to reach consensus or at least identification of underlying causes of disagreement and thus supports communication and learning between modellers, decision makers and other stakeholders (cf., Liu et al., 2008; Serrat-Capdevila et al., 2011). Such exercises can furthermore support the integrated analysis of issues across scales and disciplinary boundaries and the development of a shared language that supports communication (Sendzimir et al., 2006; Ruth et al., 2011). Participatory modelling, apart from serving the creation of shared understanding, is also held to increase legitimacy and acceptance of the resulting model and its outcomes (Jones et al., 2009). We argue that participatory modelling has much to offer to reflexive governance approaches. For example, it fits very well within the "strategic activity cluster" of transition management, which includes participatory problem structuring to find a common language between actors and a shared conceptualization of the system at hand (Loorbach, 2010). Auvinen et al. (2014) provide a framework and case study in which participatory modelling is integrated into a wider participatory process that includes foresight, impact assessment, and societal embedding. The case study illustrates the ability of such a process to support hands-on decision making and policy planning for transitions in passenger transport in Finland.

#### 6.3.2. *Gaming approaches*

A "game" here refers to a setting in which one or several actors interact(s) with a (simulated) environment (including other players) according to specific rules. Since games in this sense are formal representations of a particular system of interest we consider them to be a particular kind of models.

[11] We use the term reflexive governance to refer to various governance approaches that aim at inducing and navigating complex processes of socio-technical change by means of deliberation, probing and learning (Voß et al., 2009). Important examples in the transition field are transition management and strategic niche management.

[12] We focus on "co-construction participatory modeling" in which the very process of modelling itself becomes a participatory activity (cf., Hare, 2011).

There are different kinds of games that we consider useful for transitions studies that aim at making impact through the involvement of stakeholders and the general public.

Role playing games are behavioural simulations that allow stakeholder groups to explore actor dynamics and their outcomes on the economy, society or environment (Barreteau, 2003). Role playing games provide a model of actor preferences and relationships that can be included in board or card games, or in role descriptions that stakeholders can adopt in a creative way (cf., Pahl-Wostl and Hare, 2004). By playing these games, stakeholders can constructively interact with each other and explore and understand the mechanisms that lead to specific problem situations. Role playing games can also be an opportunity to experience the role of another actor in a conflict situation (for instance, a farmer could play the role of a water manager), and through this increase mutual understanding.

Serious games (Michael and Chen, 2005) can serve multiple purposes, such as educational purpose (Gosen and Washbush, 2004), or support of communication about a complex topic (Kelly et al., 2007). Chappin (2011) developed a serious game based upon a transition simulation model on $CO_2$ policies and electricity markets. The game was successfully tested by students and young professionals and resulted in a deepened understanding of participants in terms of the functioning of electricity and $CO_2$ markets as well as related decision-making processes. Such games can be widely distributed or offered online (e.g., Poplin, 2012) so that a high number of actors can gain experience in a particular problem area and learn about potential solutions.

Companion modelling integrates role playing games and agent based models (e.g., Barreteau et al., 2003) for consciousness-raising (e.g., Mathevet et al., 2007), for improving local and experts' knowledge (e.g., Campo et al., 2010), as well as in mediation (e.g., Gurung et al., 2006) and negotiation (e.g., Barreteau, 2003). The role playing game can reveal decision-rules or other behavioural elements applied by stakeholders which are later implemented in the agent-based model. The effects of these behaviours can be tested through the agent-based model which can reveal impacts. These results can be discussed with and reflected upon by stakeholders.

### 6.3.3. Structural modelling

Structural modelling is a method that uses qualitative structural (geometric, topological, etc.) aspects of the system being modelled to derive conclusions, without simulating the dynamics of the system. It is rooted in engineering and purely technological contexts (Alexander, 1964; Harary et al., 1965; Warfield, 1976; Lendaris, 1980) but is nowadays also used for the analysis of ecological (e.g., Berlow et al., 2009) and socio-ecological systems (Luthe and Wyss, in revision; Luthe et al., 2012).

Structural modelling can build upon participatory, qualitative-conceptual modelling (such as causal loop diagrams) and extend such approaches by representing the system as an ordered network with elements such as people, cars or trees being the nodes and the interactions between them being the links, and by analysing its network structure. The potential of structural modelling to produce insights arises from the fact that topologies of various types of complex systems share universal characteristics such as scale-freeness, small-world properties, community structure, and degree correlations which can influence the dynamics of the respective system (Cohen and Havlin, 2010; Watts and Strogatz, 1998; Barabási and Albert, 1999; Girvan and Newman, 2002). Examples for structural elements that influence the dynamics of a complex system are highly central hubs with leverage, controlling a system and its properties by their many connections (Liu et al., 2012), and 'asymmetric hubs' with few incoming but many outgoing links which are comparably easy to control but have considerable impact. The most recent advance in that field has been made by Barzel and Barabási (2013) who propose a theory on the universal interplay between network topology (structure) and network dynamics and find that "a complex system's response to perturbations is driven by a small number of universal characteristics." (p. 7). This suggests that measuring certain network metrics can provide crucial insights in the system's dynamics and facilitates the identification of intervention points.

We propose that structural modelling has potential for transitions studies in various ways. Regarding theory building, it can for example be useful to make the concepts of regime and niche more tangible through precisely and systematically mapping them as areas of dense interaction, and to analyse the linkages that bond them. Similarly the kind of interactions between regime and niches can be analysed more precisely. Furthermore, important actors who bridge and control existing subgroups can be identified, and those actors can then be specifically addressed. Structural modelling has as well value for communicating complex topics and aspects to stakeholders and especially practitioners by graphically structuring interdependencies in societal systems (Luthe et al., 2012).

## 7. Conclusions

Models provide some particular advantages for studying societal transitions: (1) they provide explicit, clear and systematic system representations that induce learning and facilitate communication about the target system, (2) they allow making inferences about dynamics in complex systems and generating emergent phenomena from underlying elements and processes, and (3) they facilitate systematic experiments. We have argued that due to these characteristics transitions modelling can contribute to theory building and support transitions studies to achieve more impact.

Theory building is relevant for the scientific maturation of the field, and in the long term also beneficial for more targeted policy development. Transition theory must relate certain circumstances to resulting transition dynamics, and be able to explain why and how these dynamics result. We have shown that dynamic models are useful to study such relations in complex systems and to make the dynamics traceable and understandable. Furthermore, models facilitate experiments in which various hypotheses can be tested and confirmed or rejected as candidates for explanatory theory. However, societal transitions pose severe challenges to model building and development and maturation of theory will require intense collaboration between modellers and empirical researchers, a better cooperation in the development of dynamic models, usage of advanced modelling techniques and supportive methods such as protocols – and a considerable amount of time.

From the perspective of pressing (environmental) issues the time for action is now, and sound and broadly agreed theory is not yet always available to support this action. Hence, as complements to dynamic models of transitions, less theory and data dependent approaches, which are readily available to be integrated in transitions studies should be used to support policy development and stakeholder processes. We have identified as promising candidates the usage of existent models from various disciplines, participatory modelling, gaming approaches and structural modelling. We invite transition scholars to engage into discussions with modellers, who are keen to adapt existing and develop new approaches to fit the needs of transitions studies.

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