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Lessons for model use in transition research: A survey and comparison with other research areas

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Abstract

The use of models to study the dynamics of transitions is challenging because of several aspects of transitions, notably complexity, multi-domain and multi-level interactions. These challenges are shared by other research areas that extensively make use of mod-els. In this article we survey experiences and methodological approaches developed in the research areas of social-ecological modeling, integrated assessment, and environmental modeling, and derive lessons to be learnt for model use in transition studies. In order to account for specific challenges associated with different kinds of model applications we classify models according to their uses: for understanding transitions, for providing case-specific policy advice, and for facilitating stakeholder processes. The assessment reveals promising research directions for transition modeling, such as model-to-model analysis, pattern-oriented modeling, advanced sensitivity analysis, development of a shared conceptual framework, and use of modeling protocols.

Keywords: Model design, Model uses, Model validation, Modeling protocols, Transition modeling

1. Introduction

Transition research involves the analysis of structural changes in society resulting from complex interactions in multiple domains (e.g., macro economy, politics and civil society) and at multiple levels (e.g., communities and national institutions). Transition research belongs to an integrated, normative and participatory type of science that aims to contribute to broader societal change (Loorbach, 2007). Several aspects of transitions challenge the use of models for studying the dynamics of transitions, such as their vast scope, complexity, and the involvement of multiple actors (Holtz, 2011). The research areas[1] of social-ecological modeling, integrated assessment and environmental modeling face similar challenges and frequently make use of models. Methods to deal with complexity, high uncertainties and stakeholder participation have been developed in these areas which might be also fruitful to the transition modeling community. A systematic review of these achievements and an assessment of their applicability in transition modeling are currently missing in the literature.

This article addresses the question what the relatively young field of transition modeling can learn from experiences made in these related research areas. An overview of challenges in transition modeling is provided and compared to challenges and potential solutions in the related research areas. Based upon a review of the literature on model uses, we distinguish between three model uses to facilitate the comparison: understanding transitions, providing case-specific policy advice, and facilitating stakeholder processes. These model uses have different modeling purposes (i.e., the goal of the modeling application), application contexts, and epistemological foundations that strongly influence core aspects of model building and application, notably the development of the model structure, the usage of empirical data, and validation. Making a distinction between modeling uses hence supports a more focused comparison of modeling applications and improvement of methodological knowledge.

The remainder of this article is organized as follows. An overview of characteristics of transition research is given in Section 2. These characteristics are utilized to demonstrate that the research areas of social-ecological modeling, integrated assessment and environmental modeling face similar challenges to those faced in modeling transitions. Based upon a review of the literature on model uses, we then describe the model uses that are relevant to the modeling of transitions. In Section 3, these model uses serve to structure a comparison between transition modeling and modeling in the three related fields. Lessons for transition modelers and potential directions for future research are discussed in Section 4.2.

2. Identification of model uses in transition research

In this section, the main characteristics of transition research are identified and compared to those of related research areas to substantiate the similarity between fields in terms of challenges for the usage of models. Then, different model uses relevant to transition modeling are defined that will structure the subsequent literature review and comparison of challenges and methods.

2.1. Characteristics of transition research

A variety of approaches and theoretical strands are used to conceptualize the phenomena and characteristics of transitions. These include the multi-level perspective (Geels, 2010; Smith et al., 2010), the multi-pattern approach (de Haan, 2010; de Haan and Rotmans, 2011; Haxeltine et al.,2008), transition contexts (Smith et al., 2005), technological innovation

[1] In this paper, a research area is understood as having a definable body of literature (e.g., existence of area specific reviewpapers) and being linked to scientific journals, societies and programs.

systems (Hekkert et al., 2007;Jacobsson and Bergek, 2011; Markard and Truffer, 2008), and evolutionary theory (van den Bergh et al., 2006; Safarzyńska and van den Bergh, 2010).

A major conceptual pillar of transition research is the existence of a regime and its replacement or fundamental restructuring. A regime consists of an overarching structure of elements such as technologies, rules and actors (Holtz et al., 2008; Smith et al., 2010). We draw upon the characterization of transitions provided by Holtz (2011) and focus on core characteristics of transitions:

(1) Multi-domain interactions: transitions cover multiple domains, such as production, consumption, regulation, and civil society, that are interconnected in co-evolutionary processes. This interconnectedness needs to be considered in order to understand and effectively influence transition processes (e.g., Yücel, 2010).

(2) Path-dependency: Regimes typically have developed over time and form a dynamically stable system. A regime's historical development is thus represented in the regime's structure. This tends to favor incremental change, rather than more radical change (e.g., Rip and Kemp, 1998).

(3) Drivers and self-reinforcement of change: There are also drivers of change and self-reinforcing mechanisms that can induce instability and make transitions possible. The interconnectedness of regime elements and non-linearity of processes within the regime provide the potential for self-reinforcement of change once it has been induced. According to the multi-level perspective, the regime may no longer fit with broader contextual developments (pressure from the landscape),and niches may challenge the regime (e.g., de Haan, 2008).

(4) Multi-level processes: A transition can be conceptualized as mutually dependent relationships between microscopic processes at the level of individuals and macroscopic processes related to conditions and institutions (Safarzyńska et al., 2012).

Transition research is not only interested in understanding transition processes, but also shares an interest in processes that could influence ongoing and future transitions. This requires theories, concepts and methods for proactive and participatory management and governance of transition processes. Reflexive governance approaches (Voss et al., 2006), including transition management (Loorbach, 2007), address such methodological demands. Reflexive governance transcends the notion of policy makers steering a system in a desirable direction using command-and-control (Kemp and Loorbach, 2006). The concept provides five strategies to deal with problems, comprising integrated knowledge production, experiments and adaptivity of strategies and institutions, anticipation of long-term systemic effects, iterative and participatory goal formulation, and interactive strategy development (Voss and Kemp, 2005). Transition management is a specific reflexive governance approach that "aims at long-term transformation processes that offer sustainability benefits" (Kemp and Loorbach, 2006). Transition management considers the importance of network governance, long-term collective goals, innovation, and learning for transition processes. Use of strategic, tactical and operational activity clusters is advised for the active management of transitions (Loorbach, 2007). Thus, the involvement of actors, a future orientation and the consideration of normative goals are characteristics that are relevant for the use of models in transition research:

(5) Involvement of multiple actors: Transitions usually involve a variety of actors from multiple domains. These actors may stabilize current regimes (e.g., through established networks) or challenge them (e.g., grassroots initiatives). These actor groups can actively influence transition processes and need to be considered. This is reflected in the concept of reflexive governance, which puts emphasis on the importance of networks for public policy development (e.g., Loorbach, 2007).

(6) Future orientation: A main concern of many transition researchers is the transition to sustainability. Thus, transition research often takes a future-oriented approach by focusing on processes of change, and how they will unfold in the future (e.g., Köhler et al., 2009).

(7) Relevance of normative goals: Transition research also addresses normative elements through the consideration of desired system states (e.g., sustainability). When it comes to current transition processes (e.g., toward a sustainable energy system), the goals and visions of different actors, such as politicians and interest groups, influence the opportunities of the regime to change (e.g., Trutnevyte et al., 2011).

2.2. Related modeling research with similar characteristics

Social-ecological modeling, integrated assessment, and environmental modeling reveal characteristics similar to those in transition research. *Social-ecological modeling* is applied and developed indifferent fields, such as natural resource management, ecological economics and complex systems research (Schlüter et al., 2012). Glaser et al. (2012) define a social-ecological system as follows: “A social-ecological system is a complex, adaptive system consisting of a bio-geo-physical unit and its associated social actors and institutions”. Another definition of social-ecological systems highlights “a multi-scale pattern (both spatial and temporal) of resource use around which humans have organized themselves in a particular social structure” (Resilience Alliance, 2007). The similarities between social-ecological modeling and transition modeling are strong related to multi-domain and multi-level interactions (e.g., Christensen et al., 2011; Carpenter and Brock, 2004), path-dependency (e.g., Fletcher and Hilbert, 2007), and involvement of multiple actors (e.g., Becu et al., 2003) (see Table 1); all other characteristics of transitions are also shared, but to a lower extent.

Integrated assessment can be defined as “an interdisciplinary and participatory process of combining, interpreting and communicating knowledge from diverse scientific disciplines to allow a better understanding of complex phenomena” (Rotmans and van Asselt, 1996). Thus, integrated assessment has a strong focus on multi-domain interactions (e.g., Schneider et al., 2005) involvement of multiple actors (e.g., Kloprogge and van der Sluijs, 2006) and relevance of normative goals (e.g., Ravetz, 2000). Drivers and self-reinforcement of change (e.g., Valkering et al., 2009), multi-level processes (e.g., Rotmans, 2002) and future orientation (e.g., Berkhout et al., 2002) are also considered. Transition research builds upon an integrated assessment approach and, thus, is tightly linked to integrated assessment modeling methods and frameworks (Loorbach, 2007).

Environmental modeling covers a very broad range of research that aims to "understand the relevant processes and to be able to make predictions regarding the impact of human activities on the environment" (Schwarzenbach et al., 1993). Environmental modeling addresses multi-domain interactions (e.g., Liu et al., 2008), drivers and self-reinforcement of change (Hill et al., 2003), multi-level processes (e.g., Roetter et al., 2007), involvement of multiple actors (e.g., Lagabrielle et al., 2010), future orientation (e.g., Murray-Rust et al., 2013) and relevance of normative goals (e.g., Voinov et al., 2014).

Table 1 summarizes a comparison of the core characteristics of transition research with characteristics of the three other research areas.[2] These similar characteristics imply similar challenges and solution strategies, as discussed below in Section 3.

Table 1: Characteristics of transition modeling and related research areas (see definition of characteristics in Section 2.1).

	Transition modeling	Social-ecological modeling	Integrated assessment	Environmental modeling
Multi-domain interactions	F	F	F	C
Path-dependency	F	F	N	N
Drivers and self-reinforcement of change	F	C	C	C
Multi-level processes	F	F	C	C
Involvement of multiple actors	F	F	F	C
Future orientation	F	C	C	C
Relevance of normative goals	F	C	F	C

F, strong focus of this research field; C, considered in this research field but not focus; N, usually not considered.

2.3. Model uses

In the transition research community, only few researchers explicitly discuss different model purposes and uses, and the classifications developed by them are not congruent but partly complementary. Yücel (2010) distinguishes three uses of models in transition research:

[2] There is also some overlap among the areas of social-ecological modeling, integrated assessment, and environmental mod-eling (i.e., articles exist that are simultaneously related to more than one of these areas), as suggested by a review of keywordsrelated to these research areas using the database Scopus.

(1) modeling for case-specific insight development, which aims to replicate reality in order to assess possible impacts of policies; (2) modeling for general insight development focuses on understanding specific mechanisms; such models are more abstract and tend to be independent of a particular context; and (3) modeling for theory development, which resembles the second use but aims to clarify assumptions and hypotheses of a theory and, thus, supports theory development. Due to the unpredictability of transition processes, the aforementioned model uses are not applied for the development of optimal policies, but predominantly for description and understanding of inherent system dynamics. Chappin (2011) distinguishes between four model purposes: (1) understanding existing systems, (2) improving the performance of existing systems, (3) predicting the future state of existing systems, and (4) designing new systems. An understanding of the system is required to predict consequences of alternative policies in order to improve performance of the system through the selection of appropriate policies. This process includes modeling the complex socio-technical system at hand, identifying intervention points, and proposing concrete actions for transition management. Loorbach (2007) proposes the application of participatory modeling for problem structuring and envisioning of transition paths as part of strategic activities in transition management. In addition, participatory modeling can be a helpful approach for reflexive governance, e.g., for integrated knowledge production, anticipation of long-term systemic effects, and interactive strategy development (Voss and Kemp, 2005; Sendzimir et al., 2006; Ruth et al., 2011).

An encompassing and agreed categorization of model uses and purposes in transition modeling is hence currently missing. A typology of model uses is presented in the following that integrate the classifications mentioned above. This typology distinguishes the different purposes, contexts and epistemological foundations of modeling and allows to extract unique challenges for each model use. Funtovicz's and Ravetz's (1993) philosophy of science form the basis for a systematic classification by revealing the epistemological foundations of model uses (i.e., whether it is related to core science, applied science or post-normal science). The different model uses identified above are sorted into three types: the use of models for understanding transitions, for providing case-specific policy advice, and for facilitating stakeholder processes. Given its general foundation in the philosophy of science, this typology is suitable to facilitate a comparison between various applied research areas. Each model use is presented in detail below.

Model use for *understanding transitions* is related to core science (Funtowicz and Ravetz, 1993); it aims at the generation of general knowledge and insight for the curiosity-driven process of fundamental research. Modeling is supposed to improve understanding of phenomena and processes. Due to the complex nature of problems, these models are not expected to forecast the system behavior. Lüdeke (2012) considers the use of quantitative modeling to be the testing of assumptions and deriving logical deductions. Models should be more "food for thought" rather than a tool that is expected to generate exact predictions of future development. Model use for understanding transitions covers the model uses generic insight and theory development described by Yücel (2010).

Model use for *providing case-specific policy advice* is problem-driven and refers to applied science (Funtowicz and Ravetz, 1993) that strives for case-specific results with practical application for external stakeholders (e.g., public authorities). The purpose of modeling in this case is of a practical nature (e.g., for policy advice) and, thus, models are adapted to a specific question and context. Models for exploratory analysis are frequently applied in this type of modeling to explore the range of possible future development trajectories of the system, e.g., depending on different assumptions on threshold effects (Brugnach and Pahl-Wostl, 2007). This allows the exploration of the influence of underlying model assumptions on system behavior. Local knowledge, values, or preferences may be included in the model but without engaging stakeholders in the model development process (Lynam et al., 2007).The model use for case-specific insight development (Yücel, 2010) and model purposes provided by Chappin (2011) fall in this category as they are related to real-world systems and aim at the analysis of case-specific interventions.

Finally, model use for *facilitating stakeholder processes* is based on post-normal science (Funtowicz and Ravetz, 1993). Post-normal science involves issues with high epistemological and ethical uncertainties. In such cases, the "hard" facts of core and applied science must be complemented by "soft" measures like public participation and ethical considerations. Models in this context can be tools to support stakeholder engagement and learning and to contribute to communication between researchers and stakeholders (Brugnach and Pahl-Wostl, 2007). Joint model development can reveal diverging perceptions and values of stakeholders and thereby support a constructive discussion process. This model use comprises participatory modeling applications that are highly relevant for transition management (Loorbach, 2007) and reflexive governance (e.g., Voss and Kemp, 2005).

Table 2 gives an overview of model purposes, contexts and epistemological foundations assigned to the three designated model uses.

Table 2: Model uses in transition research and their purposes, application contexts and epistemological foundations.

	Understanding transitions	**Providing case-specific policy advice**	**Facilitating stakeholder processes**
Model purposes	Development of general insights/ theory/understanding	Development of practical solutions to case-specific problems	Participatory modeling for strategic activities in transition management and reflexive governance
Application contexts	Curiosity-driven: tailored to a specific research question or phenomenon of interest	Problem-driven: tailored to specific problem in specific spatial/temporal context	Stakeholder-driven: process that engages with stakeholders
Epistemological foundations	Core science	Applied science	Post-normal science

3. A survey of challenges in transition modeling and relevant experiences in related areas

The following section reviews model uses in the transition research community and discusses experiences from the related research areas identified earlier. Based upon a thorough literature review, the state-of-the-art and promising future research directions are identified.[3] The lessons learned and a further discussion of promising methodological approaches are provided in Section 4.

3.1. Model use for understanding transitions

Models for understanding a phenomenon can help to unravel the complexity that characterizes transitions by relating a "micro-level" model structure (consisting of elements and processes) to emergent transition dynamics at a "macro-level". If the chosen micro-level structure is able to generate the observed macro phenomena, the model provides a potential explanation for these phenomena. Models should base upon a sound theoretical foundation and use empirical data and expert knowledge to substantiate the model's micro-foundation (Boero and Squazzoni, 2005; Windrum et al., 2007; Yilmaz, 2006).

3.1.1. Understanding transitions: approaches and challenges in transition research[4]

Transitions, with their broad scope, long time-horizon and intrinsic complexity, are difficult to grasp in a single simulation model. There are models aiming at a comprehensive explanation of transitions based on historical analyses (Bergman et al., 2008; Yücel, 2010) or in an abstract way (Papachristos, 2011). These approaches are challenged by the multiplicity of processes involved, which renders a detailed micro-foundation difficult to develop and impedes validation (cf., Holtz, 2011). Other modeling exercises focus on particular aspects of transitions and aim to enhance the understanding of transitions through integrated consideration of existing concepts. For example, Weisbuchet al. (2008) integrate increasing returns and heterogeneity of a consumer population into their analysis of socio-economic transitions. Validation of these complex system models faces several challenges, such as the under-determination problem (Beven, 2002; Sterman, 2000), the balance between analytical tractability and descriptive accuracy, and the selection of appropriate assumptions on actor behavior (see Windrum et al. (2007) for an overview of validation challenges). An additional challenge, particular to transition research, is the identification of appropriate emergent patterns to be generated by such models. The theoretical and empirical base for the identification of appropriate sub-patterns and their relation to the overall transition process is sparse albeit growing. The multi-pattern approach presented by de Haan (2010) provides possibilities for "dissecting" a transition into smaller partitions that are more appropriate for analysis with simulation models. Safarzyńska et al. (2012) discuss several concepts from evolutionary economics that are of importance for sustainability transitions and which can be studied through simulation models, such as technological co-evolution, demand-supply co-

[3] Besides undertaking a through literature review using literature databases, we asked members of the Sustainability Tran-sitions Research Network (STRN) to send us references to studies on particular model uses.
[4] See Holtz (2011) for a review of models for understanding transitions.

evolution and group selection. The absence of theories and formal descriptions of some transition phenomena or processes is a further challenge. Examples are the politics of transitions (Meadowcroft, 2011; Mayntz, 2004) and the role of civil society, social movements and grassroots innovations (Geels and Verhees, 2011; Seyfang et al., 2010).

Other research areas have gathered several experiences in dealing with complexity and identifying appropriate sub-patterns and variables at different abstraction levels, which are presented in the following section.

3.1.2. Understanding transitions: relevant experiences in other research areas

In their review on social-ecological system models, Schlüter et al. (2012) identified four core challenges which are also highly relevant in the transition model community: (1) identifying variables and an abstraction level appropriate for the model purpose, (2) addressing uncertainties, (3) addressing the role of co-evolutionary processes, and (4) understanding the links between micro-scale drivers and macro-scale outcomes. Pattern-oriented modeling (Grimm et al., 2005; Janssen et al., 2009) has been suggested in the social-ecological modeling community as an approach to develop more rigorous and comprehensive models. Janssen et al. (2009) define a pattern as "a characteristic, clearly identifiable structure in the data from the system of interest. [. . .] Such patterns can manifest themselves in spatial and temporal contexts".

Pattern-oriented modeling starts from multiple empirically observed patterns, at different scales and hierarchical levels, which are supposed to indicate essential underlying processes and structures of the system. It is argued that a higher degree of structural realism can be achieved if model development is guided by multiple patterns. Pattern-oriented modeling meets the challenge of choosing the abstraction level and model structure by providing a way to test the ability of alternative theories and mechanisms to reproduce empirical reality. The ultimate goal is to avoid both: simplistic models that neglect essential elements of a system as well as overly complex models that are cumbersome and incomprehensible. Pattern-oriented modeling can also support parameter calibration by finding values that can reproduce multiple patterns (Grimm et al., 2005).

Another approach to structured model development was proposed by Ostrom (2007, 2009) who proposes a common conceptual framework encompassing a set of important variables for the description of social-ecological systems. While still allowing a wide variety of model designs, such a framework can help to organize a multitude of key variables in social-ecological systems, which were identified in empirical studies. Ostrom (2007, 2009) developed a nested, multi-tier framework that defines interactions between attributes of resource systems (e.g., fishery lake), resource units generated by that system (e.g., fish), users (e.g., fishermen) and the governance system (e.g., fishing quota). These attributes are very simple and general at the highest-tier level, but become very specific and detailed at a lower tier level. Use of such a common framework supports a systematic approach for assessing the impact of a range of variables on system behavior. It also supports the comparison of different models and reduces uncertainty related to the definition of a model structure.

The social-ecological modeling community has found model-to-model analysis (Rouchier et al., 2008) helpful for choosing a model structure that can adequately capture a complex system. Robust conclusions can be reached and sensitive assumptions identified by comparing multiple models that address a similar research question but which are based on different assumptions or use different methods. Protocols for presenting and communicating complex social-ecological system models (see Schlüter et al., 2012), such as the ODD (Overview, Design concepts, and Details) protocol, standardize the description of individual-based and agent-based models. The ODD protocol encourages modelers to provide structured information about the model, such as the model purpose, state variables, scales involved, and initial system states (Grimm et al., 2006, 2010). Through this, similar and diverging assumptions of different models can easily be identified what supports model comparison and theory building.

3.2. Model use for providing case-specific policy advice

Model use in the context of providing case-specific policy advice aims at the analysis of barriers and drivers for a particular case in order to provide practical policy recommendations on how to influence a transition. Such models are problem-driven and their results go beyond general policy recommendations by considering the specific context of problems. The idiosyncrasies of transition processes require applying and adapting general understanding to the specific case at hand, for example to identify relevant mechanisms and parameterize the models based on data. Modeling for case-specific policy advice has to apply approaches for model validation and the handling of uncertainties to achieve robust conclusions. Empirical research, literature reviews, or interviews may be conducted to obtain relevant data for model implementation and validation.

3.2.1. Providing case-specific policy advice: approaches and challenges in transition research

Exploratory modeling is widely used in transition research to address concrete problem situations, for example by assisting in the delineation of multiple future development trajectories and discussion of their potential consequences. Exploratory transition models give policy advice for diverse topics such as plausible system trajectories of the Dutch electricity system (Yücel, 2010), transition toward a low-carbon power supply and low-electricity consumer lighting in the Netherlands (Chappin, 2011), or transition toward a hydrogen economy in Germany (Schwoon, 2006), the Netherlands (Huétink et al., 2010), and the UK (Köhler et al., 2009). Case-specific empirical data is applied in each of these studies to parameterize the models. Köhler et al. (2009) also uses historical data for model calibration by using data for the strength of the mobility regime and niches in 2000 and 2010.

A shared conceptual framework or even a shared theoretical basis for transition modeling is currently missing. Some models base upon a general conceptual framework such as the actor-option framework (e.g., Yücel, 2010) or the multi-level perspective (e.g., Köhler et al., 2009), while others do not refer to a general transition framework (e.g., Huétink et al., 2010). Different methods are used to model transitions, such as agent-based models (e.g., Chappin, 2011; Schwoon, 2006) or a combination of a system dynamics model and an agent-based model (Köhler et al., 2009; Yücel, 2010).

There are currently no standard approaches for model validation in the transition modeling community. Due to limited availability of historical data for model validation, Yücel (2010) benchmarks the conceptual coverage of the ElectTrans model with other models of the Dutch electricity system that have similar objectives (but are not classified as transition models). Huétink et al. (2010) uses a benchmark model to compare hydrogen diffusion scenarios. Chappin (2011) draws upon model testing methods from system dynamics modeling which include direct structure tests (e.g., dimension analysis) and structure-oriented behavior tests (e.g., extreme conditions and sensitivity analyses).

Sensitivity analysis is a critical step in all modeling studies and involves the variation of key parameters within realistic bounds to test the robustness of model results in the face of high uncertainties (e.g., Schwoon, 2006; Huétink et al., 2010). A structured approach for uncertainty analysis is provided by Kwakkel and Yücel (2012) who extended the analysis of the Dutch electricity system by Yücel (2010) by explicitly exploring the implications of uncertainty pertaining to investment costs, operational costs, demand development, planning horizon, desired return on investment, and future carbon prices. For each of these uncertain factors, bandwidths of plausible values are specified. The resulting uncertainty space is explored systematically by generating an experimental design containing 50.000 experiments. The results are analyzed using data mining methods (i.e., Patient Rule Induction Method) to reveal typical system trajectories and their conditions for occurring (cf., Friedman and Fisher, 1999; Bryant and Lempert, 2010).

Given the lack of a common conceptual framework and theoretical basis, transition model applications differ widely in terms of chosen model structures. Sensitivity analysis is a widely applied approach to address uncertainties related to model structure and parameters. In the following section, we review experiences in related research areas in providing specific policy advice despite high complexity.

3.2.2. Providing case-specific policy advice: relevant experiences in other research areas

The integrated assessment modeling area also faces the challenge of providing concrete policy advice on complex issues. For instance, climate change mitigation requires the integration of several aspects, such as emissions from economic activities, the atmosphere system, climate change, and resulting impacts and damages (e.g., Schneider et al., 2005). Climate mitigation models are slowly maturing, and model comparisons and discussions of differing findings are quite common (e.g., Edenhofer et al., 2010). Publications in this research area are in a phase of critically reflecting on the use of integrated assessment modeling, finding that policy advice derived from such modeling exercises clearly depends on the underlying choice of uncertain parameters, most importantly the discount rate and, related to this choice, ethical questions of intergenerational equity (Schneider et al., 2005; Vecchione, 2012). Integrated assessment modeling has helped to identify critical factors that affect decisions on climate mitigation, through comparison and critical reflection on numerous modeling applications.

Jakeman et al. (2011) highlight the importance of transparently handling uncertainties throughout the modeling and decision-making process and propose the development of databases that gather modeling experiences and their evaluation for the continuous evolution of best practice guidelines (cf., Jakeman et al., 2006). Serious model quality assurance is required for ensuring reliability of results and enabling model reuse and comparison. Walker et al. (2003) propose an uncertainty matrix to communicate uncertainties to policy-makers. The uncertainty matrix bases upon a coherent terminology and includes different types of uncertainties with respect to locations of uncertainties (i.e., related to context, model, inputs and parameters), uncertainty levels (i.e., statistic uncertainty, scenario uncertainty and recognized ignorance) and nature of uncertainties (i.e., epistemic and variability uncertainty). Refsgaard et al. (2007) provide an overview of qualitative and quantitative model testing methods to address the various types of uncertainties identified by Walker et al. (2003). Uncertainty assessment should start right at the beginning of any modeling study, as uncertainties can already be addressed in model design and development (Refsgaard et al., 2007).

Sensitivity analysis is applied in all reviewed research areas for model validation, uncertainty quantification, model reduction (i.e., model simplification), and policy identification (cf., Bennett et al.,2010; Refsgaard et al., 2007; Schlüter et al., 2012). Local sensitivity analysis methods (e.g., ceteris paribus sensitivity analysis) vary individual parameters while all other parameters are kept fixed. Global sensitivity analysis methods (e.g., Monte Carlo sensitivity analysis) vary multiple parameters simultaneously and assess the influence on model output (Saltelli et al., 2008; Schouten et al., 2014). Global sensitivity analysis encompasses many simulation runs, and hence can require substantial computing time. To address this challenge, emulation techniques have been developed to reduce model complexity (Ratto et al., 2012). For instance, Parry et al. (2013) present a Bayesian Analysis of Computer Code Outputs (BACCO) methodology to identify sensitive parameters in a complex agent-based model. In this methodology, a simplified version of the original model is constructed by using a Gaussian process model (O'Hagan, 2006) that allows for rapid and thorough sensitivity analysis. Sensitivity analysis can also help to identify policy leverages that are critical intervention points for the steering the system toward a desirable path (e.g., Brown et al., 2005; Schouten et al., 2014).

An interesting and innovative modeling approach to deal with high uncertainty and complexity is offered by Haasnoot et al. (2012, 2014) for the identification of sustainable water management strategies. Here, models are used to assess the efficacy of policy actions sequentially over time. In a case where specified objectives are no longer achieved, an adaptation tipping point (Kwadijk et al., 2010) is reached. After a tipping point is reached, additional actions are needed to achieve the objectives, and, as a result, an adaptation pathway emerges. Adaptation pathways support decision-making under uncertainty by providing insight into policy options, potential lock-ins, and path dependencies.

Good modeling practice to generate case-specific policy advice is also a topic in social-ecological modeling. Evaluation of the model applications as such and the modeling process for providing case-specific policy advice must ensure that model users and decision-makers will understand modeling results (see also Jakeman et al., 2006, 2011). The TRACE (TRAnsparent and Comprehensive Ecological modeling) protocol addresses this requirement by considering all steps of the modeling cycle, i.e., model development, testing, analysis and application (Schmolke et al., 2010). The TRACE documentation framework defines important elements that need to be considered for good modeling practice, including the context of the model application and the audience addressed.

The choice of indicators is a further important aspect of policy advice in which transition modeling can learn from experience in other research areas (see Niemeijer and de Groot, 2008). Indicators may highlight relevant relationships and help to communicate and evaluate them with policy-makers and other stakeholders (Stosius et al., 2012; Tscherning et al., 2012). Environmental modeling has a long experience with indicator selection, and thus could support transition research to find appropriate indicators. Indicator selection involves the analysis of the most relevant pressures on the environment, the former states of the system, and resulting transition dynamics. Indicators cannot reduce existing system complexity, but they "may serve to make the complex reality more transparent, thus enabling decision makers to better deal with it" (Jesinghaus, 1999).

3.3. Model use for facilitating stakeholder processes

Reflexive governance processes, with their involvement of multiple actors and the relevance of normative goals, can be assisted through participatory modeling to support communication and learning. Models can reveal diverging stakeholders' perceptions and values and thereby support a constructive discussion process. This kind of modeling activity is rooted in social learning theory and collaborative management (Pahl-Wost, 2007). Social learning processes are perceived as a central means to improve relationships and cooperation between stakeholders. Tools like role playing games and group model building can aim to initiate reframing processes that can lead to revision of current mental models. The abstraction level and model scope are usually adjusted to stakeholders' needs and interests.

3.3.1. Facilitating stakeholder processes: approaches and challenges in transition research

Modeling can play a vital role in each of the activity clusters of transition management (see Section 2.1 for details). For instance, conceptual modeling can be used for problem structuring and envisioning of transition paths as part of strategic activities (see Loorbach, 2007). In the same way, modeling can support most of the strategies of reflexive governance (e.g., integrated knowledge production, anticipation of long-term systemic effects, and iterative, participatory goals formulation). For instance, conceptual models can support the integrated analysis of issues across scales and disciplinary boundaries, and can help with the anticipation of long-term systemic effects (Sendzimir et al., 2006; Ruth et al., 2011). Modeling can thereby be applied for opening up discussions as well as for helping them reaching a conclusion by reducing complexity (cf., Voss and Kemp, 2005). However, concrete modeling applications that explicitly refer to the transition studies literature are rare.

Sendzimir et al. (2006) describe an adaptive management process for the renaturalization of the Tisza River Basin in Hungary that includes participatory modeling to discuss and analyze alternative system perspectives of stakeholders. Sendzimir et al. (2006) conclude that the use of models in reflexive governance processes can facilitate visualization and analysis of alternative assumptions and perspectives.

Trutnevyte et al. (2011, 2012) present a methodology that combines qualitative visioning exercises with quantitative modeling to support energy transitions. Stakeholders are asked, in a group or individually, to express their visions of a future energy system. These visions are tested through quantitative resource allocation scenarios in order to define options for their realization (e.g., different configurations of the energy system, including supply and efficiency aspects). In a third step, stakeholder-based multi-criteria assessment is conducted to assess potential consequences of the scenarios. After the presentation of results, stakeholders are asked to reconsider their preferred vision. In the work by Trutnevyte et al. (2011, 2012), the majority of stakeholders changed their preferences based upon the analytical results. Trutnevyte et al. (2011, 2012) consider the development of such informed preferences and capacity-building through stakeholder processes as necessary requisites of future energy transitions.

The identification of specific challenges in the transition community with respect to this model use was not possible, due to the low number of modeling studies with an explicit linkage to the transition literature. Therefore, we reviewed the literature in related modeling areas to provide an overview of transition-relevant approaches and experiences.

3.3.2. Facilitating stakeholder processes: relevant experiences in other research areas

Participatory modeling approaches in which stakeholders jointly develop and discuss models and researchers act as facilitators have frequently been applied in the area of environmental modeling to support stakeholder processes (for an overview, see Voinov and Bousquet, 2010). There are several purposes according to which such participatory modeling processes can be designed, for instance, development of a shared problem understanding (Pahl-Wost, 2007), consciousness-raising (e.g., Mathevet et al., 2007), improving local and experts' knowledge (e.g., Campo et al., 2010), mediation (e.g., Gurung et al., 2006; van den Belt, 2004) and negotiation (e.g., Barreteau, 2003). Modeling methods that are particularly suitable for participatory modeling include systems thinking and system dynamics modeling (Vennix, 1996; van den Belt, 2004), Bayesian networks (e.g., Castelletti and Soncini-Sessa, 2007), companion modeling (Barreteau et al., 2003) and fuzzy cognitive mapping (e.g., van Vliet et al., 2009).

Scenario analysis based on models developed by researchers is also frequently applied for facilitating stakeholder processes. For instance, Schlüter and Rüger (2007) developed a quantitative simulation model for generating scenarios regarding the future water availability in the Amudarya river delta in Uzbekistan and Turkmenistan. They analyzed the applicability of the simulation tool to make uncertainties visible, for discussion with stakeholders. They conclude that such a tool can facilitate analysis and decision-making processes among stakeholders to define a future water management strategy, while pointing out uncertainties and specifying future research and data needs. Cairns et al. (2013) discuss the application of scenario analysis in a case study in Australia and conclude that various contextual factors influence the success of scenario exercises in catalyzing change. Multiple agencies, interests and agendas and contingent factors can slow down momentum in scenario exercises.

Exploratory modeling is also used in the SCENES Project (water SCenarios for Europe and NEighboring States). The project aims at the combination of exploratory and backcasting approaches to develop scenarios on a Europe-wide level. Kok et al. (2011) found that this approach is methodologically feasible and can produce narratives that are complex, integrated, and rich in detail. Several lessons have been learned from past participatory modeling efforts in environmental modeling and integrated assessment. Siebenhüner and Barth (2005) proposes the use of simple models for stimulating stakeholder discussions and awareness-raising (see also Kraker and Wal, 2012) because overly complex models are not comprehensible for stakeholders and therefore their results may be not accepted. In addition, uncertainty needs to be addressed explicitly in modeling with stakeholders. Brugnach et al. (2006) propose an uncertainty agent who communicates uncertainties between scientific experts, policy-makers and other stakeholders. A major challenge relates to the design of participatory processes in which model use is embedded. This comprises problem and stakeholder analysis, choice of appropriate methods and specific organization of stakeholder involvement (e.g., workshops or permanent engagement) (Voinov and Bousquet, 2010). Research has mainly focused on the "doing" of participatory processes rather than the theoretical and methodological foundations (cf., Jakku and Thorburn, 2010; Cerf et al., 2012). Methodologies are needed that provide sound guidelines for the organization, implementation and evaluation of participatory processes. Transition management could fill this methodological gap in other research fields.

Evaluation methods are needed that are able to assess the model development process, the resulting model, and the context in which the process is embedded. The "Protocol of Canberra" represents such a framework for the evaluation of participatory model building processes (Jones et al., 2009). The quality of decision-making processes that involve participatory model building methods is assessed after consideration of their context, process, and underlying theory. The framework consists of two components, the "Designer Questionnaire", and the "Participants Evaluation Guide". The "Designer Questionnaire" outlines the theoretical assumptions and objectives of the research team. This involves the socio-political and physical context and the project design. The "Participants Evaluation Guide" analyses the experiences that participants made during the process. The content of the guide is similar to the designer questionnaire in order to allow for comparison of assessments stemming from researchers and participants.

4. Lessons for transition modeling and future research directions

The review of challenges in transition modeling and comparison to experiences in related research areas make it possible to identify several methodological approaches from which transition modeling could potentially benefit.

Model-to-model analysis is a promising approach that comprises a number of different aspects, such as model comparison, replication and reimplementation (Rouchier et al., 2008).

Similar to the principle of replicability in empirical science, the replication of models and the comparison of findings across various modeling studies is seen as an essential practice to develop robust conclusion sand identify critical assumptions. It can be applied to improve applications of models for understanding transitions and providing case-specific policy advice. Currently, model comparison is impeded by the low number and high variety of transition models that differ with respect to topic (e.g., water management, mobility, energy), the transition dynamics considered (e.g., consumer-producer interactions or diffusion in networks) and model use (i.e., model use to understand transitions, or to provide case-specific policy advice). Therefore, opportunities to identify key variables through comparison of assumptions, structure and resulting dynamic behavior of models are currently limited. Thus, the development of several models on similar transition (sub-) cases and research questions is proposed as a fruitful future activity. The use of benchmarking models for model validation (e.g., Huétink et al., 2010) can be considered as initial efforts in this direction by the transition modeling community.

Another important future research direction would be the development, compilation and application of a shared conceptual transition framework. Such a shared framework would provide a well-founded base for the design of model structures, facilitate model comparison, and constitute a step toward refined theory-building in the transition area. Indeed, widely shared conceptual frame-works (such as the multi-level perspective) do exist, but transition modeling exercises often do not explicitly make use of them. These heuristic frameworks only provide few details so that model implementation requires many additional assumptions (c.f. Bergman et al., 2008; Papachristos, 2011). Ostrom (2007, 2009) presents a framework for the study of socio-ecological systems, which encompasses general and specific key variables in a nested, multi-tier structure. Its general structure could probably be adopted in a multi-tier transition framework to be developed in a joint effort of the transition research community. While frameworks such as the multi-level perspective could constitute an upper tier, the transition community has not yet developed a shared understanding of the most relevant micro-level processes that could define a lower tier. A first collection of micro-level processes used in different transition models has been made by Holtz (2011). These include market-based interactions, heterogeneous demand, demand and supply-side network effects, learning and experience, increasing returns to scale, the accumulation of stocks, policies and (exogenous) technological change. This list should be validated and extended in future work, and could serve as a starting point to define lower tiers of a shared transition framework. Bridging different levels of abstraction through a multi-tier framework allows to "ground" high-level frameworks, and to embed the wealth of knowledge eabout particular sub-processes in the wider transition picture (cf. Holtz, 2012).

Pattern-oriented modeling is another interesting modeling strategy that could support modeling exercises in transition research and the development of a shared conceptual framework by identifying key variables. In particular, the use of models for understanding transitions and for providing case-specific modeling advice could benefit from this modeling strategy. However, as discussed above, the knowledge base with regards to the identification of appropriate (sub-) patterns for pattern-oriented modeling is still limited in transition research – especially on levels "below" the overall S-curve pattern. Experience in developing appropriate indicators in the area of environmental modeling could be helpful in filling this gap as indicators may help to make patterns visible by concentrating on the pressures on a system's state and their impacts.

The development of protocols for good modeling practices and documentation has been shown to be important for each model use. Approaches for the transparent description, assessment and evaluation of model performance, model development processes and application contexts have matured in the areas of social-ecological modeling, environmental modeling, and integrated assessment (e.g., Jakeman et al., 2006; Jones et al., 2009; Grimm et al., 2006, 2010; Schmolke et al., 2010). These approaches can be adapted and further developed by the transition modeling community. Consideration of the context of the modeling process (see Protocol of Canberra, Jones et al., 2009) may be of interest in transition management, in relation to contextual changes that emerge from stakeholder processes. Protocols can also foster the definition of theoretical and conceptual underpinnings of modeling projects.

Sensitivity analysis is a central method for uncertainty assessment, model reduction and policy identification in all reviewed research areas. Recent findings on the context-dependence of sensitivity analysis (i.e., the list of sensitive parameters changes between different policy scenarios) and merits of a joint application of local and global sensitivity analysis approaches (Schouten et al., 2014) exemplify a high potential for knowledge exchange. Sensitivity analysis is relevant for all model uses, in particular for the use of providing case-specific policy advice.

Regarding the use of models for facilitating stakeholder processes, there are still challenges in participatory modeling to support transitions toward sustainability. The application of participatory methods alone is not sufficient to initiate or support transitions (see Cairns et al., 2013). The various actor networks and their relations and the current phase of transition dynamics are arguably crucial elements to be considered in an effective stakeholder involvement strategy. We suggest that transition management and similar reflexive governance approaches develop by transition scholars can hence support the effective application of participatory modeling methods through providing an overall structure for the organization and implementation of participatory processes. Transition management defines different steps toward the initiation of broad societal change toward sustainable development that imply a specific selection of stakeholders and types of activities. The different activity clusters of transition management can thus guide the selection of combination of different participatory modeling methods. For instance, conceptual modeling can support the development of a shared problem understanding in the strategic activity cluster, while quantitative participatory modeling methods can be more suitable for tactical activity cluster. Despite this high potential, we could only find one concrete participatory modeling application that explicitly refers to these governance approaches (see Sendzimir et al., 2006). We therefore propose that there is an untapped potential for fruitful integration of participatory modeling and transition management.

The findings from the literature review suggest strong synergies that could emerge from a close cooperation between the areas of transition research, social-ecological modeling, integrated assessment, and environmental modeling. While some forms of knowledge exchange already exist, more target-oriented collaboration on certain aspects of transition modeling would be fruitful. The classification of model uses developed in this paper proved to be useful for an integrated consideration of modeling applications from different research areas and identification of potential areas for mutual exchange of experience and knowledge.

5. Conclusions

The literature review reveals several lessons that transition research can learn from related research areas for the different model uses of understanding transitions, providing case-specific policy advice, and facilitating stakeholder processes.

(1) Comparison of alternative models that deal with a similar problem situation has proven valuable in the integrated assessment and social-ecological modeling areas. Such comparisons help to develop robust results and identify critical assumptions for the use of models for understanding transitions and providing case-specific policy advice.

(2) Shared conceptual frameworks exist in transition research (e.g., the multi-level perspective), but remain on a high level of abstraction. The translation of such frameworks into lower level tiers (i.e., a framework that bridge different levels of abstraction) would be worthwhile to guide modeling processes and to make them comparable.

(3) Pattern-oriented modeling supports the handling of complexity and facilitates the development of structurally realistic models for understanding transitions. In addition, this approach could support the development of a joint conceptual framework by defining key variables at different levels.

(4) The design and use of protocols for documentation, uncertainty handling and quality assurance are further important approaches to ensure high quality of models and the development of best-practice guidelines. Transition modelers can build on different tools, protocols and frameworks that exist in other areas, such as the uncertainty matrix, ODD protocol, TRACE framework and the protocol of Canberra.

(5) Sensitivity analysis is applied for uncertainty assessment, model reduction and policy identification in all reviewed research areas. Transition modeling can draw upon these experiences, such as usage of an emulator approach to analyze uncertainties in model inputs.

(6) Although there is an extensive body of literature on the application of models to facilitate stakeholder processes in the reviewed research areas, a theoretical and methodological foundation is missing for guiding the design of participatory processes to support a sustainability transition. We propose that the transition management approach has the potential to fill this theoretical and methodological gap and support the design of effective participatory modeling processes in transition studies.

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