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Participatory modeling for transition governance: Linking methods to process phases

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Abstract

Participatory modeling – the involvement of stakeholders in the modeling process – can support various objectives, such as stimulating learning processes or promoting mutual understanding of stakeholders. Participatory modeling approaches could therefore be useful for the governance of transitions, but a systematic account of potential application areas of participatory modeling methods in transition governance is still lacking. This article addresses this gap by providing a review of participatory modeling methods and linking them to phases and objectives of transition governance. We reviewed participatory modeling studies in transition research and related fields of social-ecological modeling, integrated assessment and environmental management. We find that participatory modeling methods are mostly used for participatory visioning and goal setting as well as for interactive strategy development. The review shows the potential for extending the application of participatory modeling methods to additional phases of transition governance and for the exchange of experiences between research fields.

Keywords: Participatory Modeling; Transition Governance; Reflexive Governance; Transition Management; Adaptive Management

1. Introduction

Transition governance has the aim of actively supporting sustainability transitions by steering and aligning societal processes. It embraces the complexity of multi-actor processes in societal transformations towards sustainable development (Loorbach, 2010; Halbe, 2016), which arises from the distribution of relevant decision-making powers throughout society (see Ardoin et al., 2015) so that specific sustainability outcomes of the governance process cannot be controlled or pre-determined by a single authority (Voß and Kemp, 2006). Instead, transitions emerge through the interactions of multiple actors with different interests and perspectives and (changing) context conditions such as economic development, technological innovation and cultural changes. Transition governance requires the involvement of a diversity of stakeholders and an integration of their knowledge, perspectives and values. While various methods, tools and frameworks exist to support stakeholder engagement, Holtz et al. (2015) underline the particular relevance of modeling to deal with the complexity of sustainability transitions. Here, a model is understood as "a simplified, stylised and *formalised* representation of (a part of) reality" (Holtz et al., 2015, p. 43). Thereby, models have the benefit to be explicit, clear and systematic, allow for inferences about the dynamics of the system, and facilitate systematic experiments that might not be possible otherwise (Holtz et al., 2015).

Participatory modeling denotes the involvement of stakeholders in the development and application of models. We propose that participatory modeling might be particularly useful for the governance of transitions, as it promises to combine the necessity of intense stakeholder participation with the benefits of modeling methods mentioned above. Participatory modeling processes can be classified along various dimensions (see Halbe, 2019). An important dimension is the mode of knowledge capture and exchange between stakeholders that describes the level of involvement and impact of stakeholder participation. Lynam et al. (2010) defines three modes of knowledge capture and exchange: (1) a co-management mode (stakeholders are actively involved in knowledge synthesis and the decision-making process), (2) a co-learning mode (multiple stakeholders exchange and synthesize knowledge, but are not involved in decision-making) and (3) an extractive mode (i.e., researchers inquire knowledge, preferences or values from stakeholders; however, stakeholders neither directly exchange knowledge nor are they involved in decision-making). We argue that participatory modeling in the co-management and co-learning modes is particularly valuable for transition governance, as it allows for intense stakeholder involvement. Participatory modeling methods have been fruitfully applied for decades in various fields, including environmental management (e.g., Hedelin et al., 2017), social-ecological systems research (e.g., Metcalf et al., 2010), integrated assessment (e.g., Tàbara et al. 2008), foresight (e.g., Bishop et al. 2007) and operational research (e.g., Franco and Montibeller 2010), amongst others. Some studies have also made use of participatory modeling methods in the context of sustainability transitions research (e.g., Valkering et al. 2017). We perceive the latter to be a small but growing branch of transitions research that is yet mostly constituted of single works with little mutual exchange and no systematic link to transition governance approaches.[1]

Against this background, this article aims at the identification and classification of participatory modeling methods which have been applied in a co-learning or co-management mode and therefore are promising for the governance of transitions. We conduct a literature review of participatory modeling methods used in transitions research as well as research

[1] First steps to connect researchers have been made through sessions on participatory modelling at the International Sustainability Transitions Conferences 2016 in Wuppertal, 2017 in Gothenburg and 2019 in Ottawa.

fields that share core characteristics with transition research (see Halbe et al., 2015a) and have a longer tradition of participatory modeling, such as social-ecological modeling, environmental modeling and integrated assessment. For structuring the review, we derive a classification of the objectives of transition governance in different transition governance process phases. We derive this classification from a synthesis of process phases and associated objectives that reoccur in three approaches for the governance of complex socio-technical or socio-ecological systems (see Section 2). Participatory modeling methods are subsequently sorted to these process phases based upon shared objectives, which allows us to systematically link methods to their specific application areas in transition governance processes.

The added value of the article is therefore twofold: First, the systematic linkage of participatory modeling methods to governance process phases supports the identification of methods which are potentially applicable in transition governance. Second, we provide an overview of participatory modeling methods for transitions governance that takes stock of and – through widening the review to other fields – goes beyond current practice in socio-technical transitions research. This allows for the exchange and integration of methodical knowledge between research fields.

The article is structured as follows. First, we discuss and compare three transition governance approaches (Section 2). From this comparison we synthesize the process phases and associated objectives along which the review of participatory modeling methods is structured. For each process phase, we then present the results of our review (Section 3). We then go on to discuss our results (Section 4) and draw conclusions (Section 5).

2 Process phases and associated objectives of transition governance

In this article, we use the term "transition governance" as an umbrella term that includes governance approaches that aim at the purposeful facilitation of societal transition processes towards sustainable development. The term governance reflects that such a transition cannot be implemented by a central authority alone, but requires communication and action of various stakeholders, including civil society, businesses, NGOs and public authorities.

The current research agenda of the Sustainability Transitions Research Network (STRN) highlights three approaches for governing socio-technical transitions, namely reflexive governance, transition management, and strategic niche management (Köhler et al., 2019). *Reflexive governance* has been developed against the background of a rising disappointment about the limited practical success of sustainability strategies (Voß and Kemp, 2006). Reflexive governance transcends the notion of an external navigator of social change, but acknowledges the diversity of problem perspectives, expectations and strategies (Voß and Bornemann, 2011). The actions of various actors, such as state actors, interest groups and scientists, have to be coordinated to steer transition processes and to deal with the inherent complexity, uncertainty and ambiguity of social goals (Voß and Kemp, 2006). *Transition management* is a more specific reflexive governance approach that has explicitly been developed with the aim of pro-active facilitation of socio-technical sustainability transitions (Loorbach 2007, 2010, Voß and Bornemann, 2011). It includes a focus on experiments, which is shared by the related governance approach of *strategic niche management* (Schot and Geels, 2008). Strategic niche management is defined as “the creation, development and controlled phase-out of protected spaces for the development and use of promising technologies by means of experimentation […]” (Kemp et al., 1998). Strategic niche management focuses on a specific aspect of sustainability transitions, namely technological innovation. Due to this specific focus, strategic niche management was not included in the later development of an overall classification of transition governance phases.

In addition to the reflexive governance and transition management, Voß and Bornemann (2011) consider *adaptive management* as another specific design of reflexive governance (in addition to transition management), which particularly deals with managing change towards sustainability in social-ecological systems. Foxon et al. (2008, 2009) suggest the combination of adaptive management and transition management for the governance of transitions. They detect various opportunities for a fruitful dialogue between transition management and adaptive management and perceive them as complementary approaches to understand and handle the complexity of transition processes. While the reflexive governance and transition management approaches were developed in the 2000s, the proliferation of adaptive management approaches started already in the 1980s and 1990s. Adaptive management demands an integrated and multidisciplinary approach to reduce surprising side-effects and unintended outcomes of management actions, but also assumes that surprises are inevitable due to the adaptive behavior of the environment (Holling 1978). Thus, adaptive management builds upon carefully designed experiments that allows for continuous learning from past actions (Lee 1999; Berkes et al. 2002; Pahl-Wostl 2007).

In the following sections, we succinctly describe the different process phases and associated objectives that are conceptualized in each of the governance approaches. As all governance approaches deal with complex systems, the three approaches agree that process phases do not proceed linearly. Instead, different phases and related activities usually proceed in cyclical and iterative terms. They often operate simultaneously and are hardly distinguishable one from another (cf., Loorbach 2007, 2010). A process phase is thus a more interpretative concept that comprises a set of activities that belong together, due to a common objective and a particular timing in the process.

2.1 Reflexive governance

Voss and Kemp (2006) describe five reflexive governance strategies to deal with the challenges of complexity, ambiguity and distributed control, which can be sorted to three dimensions of problem solving: the first dimension called “problem analysis” comprises the strategies (1) *integrated knowledge production,* (2) *experiments and adaptivity of strategies and institutions*, and (3) *anticipation of long-term systemic effects.* Integrated knowledge production refers to inter- and transdisciplinary research that integrates knowledge from different disciplines and stakeholders. Solution strategies and related institutions have to be considered as experiments which have to be monitored continuously. Long-term systemic effects of actions need to be anticipated to reveal undesired side-effects. The second dimension, "goal formulation", requires (4) *iterative and participatory goal formulation*. Sustainability goals must base upon a broad societal or political discourse in order to consider alternative values and goals in society. It might be necessary to revise sustainability goals during the process, as values or perceptions can change during transformation processes. Third, the dimension of "strategy implementation" requires (5) *interactive strategy development* that draws upon resources and influence of various stakeholders. A collective action strategy has to be developed that *coordinates actions of actors* who might have diverse interests.

2.2 Transition management

Transition management comprises different activity clusters that form a transition management cycle: strategic, tactical, operational, and evaluation. The "strategic activities" usually start with a group of innovative individuals who are thinking and acting outside of conventional boxes. This includes 1) *participatory problem structuring* to find a common language between actors and a shared conceptualization of the system at hand. This allows for 2) the *development of sustainability visions,* which are inspiring pictures of the future. The "tactical activity cluster" involves organizations, businesses, NGOs and others who are able to further promote and specify sustainability visions. This involves 3) the *development of transition images* (e.g., for public transport or solar energy) that fit into the overall sustainability vision but are more specific. Then, 4) *transition paths* are specified, which are a series of process steps that lead to these transition images. Finally, the broader public is addressed in the "operational activity cluster" to embed transformation processes within society. This can be achieved through 5) *concrete projects* or *communication of the sustainability vision* (e.g., in the media or public debates). The activity clusters are followed by a "monitoring and evaluation" phase to 6) continuously *assess and adapt actions* (Loorbach 2007, 2010).

2.3 Adaptive management

Various adaptive management approaches are available that usually share many commonalities, but use different terminology (Plummer, 2009). Pahl-Wostl (2008) provides an adaptive management approach that distinguishes between five steps in an iterative adaptive management cycle, which all require strong stakeholder participation and transparent decision-making: (1) The *problem definition and goal setting* phases need to take multiple perspectives into account. The problem definition phase can also include the setting of alternative issue-specific hypotheses that are later tested through management actions (Allen and Gunderson, 2011); (2) *Policy design* should consider different scenarios to assess policy performance under different possible futures. Models are frequently used in this step for understanding consequences and associated uncertainties of management actions or policy designs; (3) Correctability of decisions is a major guideline to be considered in *policy implementation* (e.g., by considering the costs of reversing decisions); (4) *Monitoring and* *evaluation* should include different kinds of knowledge (such as expert and local knowledge); Finally, (5) *policy assessment* should be accomplished in a transparent way.

2.4 Synthesis of process phases and associated objectives of transition governance

The three governance approaches described above share similar process steps that only differ slightly with respect to the chosen emphasis on a particular phase in the overall process and terminology used. Thus, their comparison shows some form of conceptual consolidation with respect to process phases useful for a pro-active facilitation of sustainability transitions. We synthesize the following sequence of six process phases:

Process phase 1: Integrated knowledge production and problem definition: In this phase, the problem is framed by integrating knowledge from different sources, including science, experts, as well as perceptions from further stakeholders, such as affected citizens or interest groups. The development of a shared language is also an important aspect that allows communication between stakeholders and development of a shared understanding.

Process phase 2: Stakeholder analysis and selection: Transition processes usually require broad stakeholder participation that can take different forms ranging from close cooperation to coordination and consultation. Different stakeholders can become important at different steps of a transition process so that an active and continuous reflection on stakeholder involvement is required.

Process phase 3: Participatory visioning and goal formulation: The objective of this process phase is to bring different interests together, and to develop a vision and shared goals that motivate stakeholders and function as a reference point for action. Wiek and Iwaniec (2014) describe visions (desirable future states) as a subgroup of scenarios (possible future states) clearly different to predictions (likely future state). Visions have a normative component that requires the consolidation of interests and perspectives from various stakeholders, as well as an assessment component to analyze potential consequences of visions. Common goals must be discussed that make the vision tangible and integrate various perspectives and interests of stakeholders.

Process phase 4: Interactive strategy development that anticipates long-term systemic effects: In this process step, different strategies are developed and their expected outcomes assessed with respect to the achievement of the future vision, including possible side-effects and trade-offs. The decision for a particular strategy has to consider the spatial-temporal context as well as uncertainties that can influence the effectiveness of actions.

Process phase 5: Coordination of the implementation of experimental actions: Multiple experiments are implemented that aim at the gradual achievement of the future vision. The design of experiments should consider the possibility of failure, i.e., the experiment should be reversible and leave sufficient resources for follow-up actions. Societal transitions usually require multiple experiments and actions that are implemented by various actors. Thus, experiments need to be coordinated in order to foster synergies and avoid negative interplays.

Process phase 6: Systematic monitoring and assessment of actions: The effectiveness of actions needs to be systematically monitored with regard to process goals and potential negative side-effects. A careful identification of indicators should be accomplished to systematically describe the various consequences of actions. The actual outcomes of actions need to be compared to previous assumptions to reveal misperceptions. The assessment process should be transparent and involve all participants in order to account for different appraisals of a situation. The assessment phase should furthermore allow for learning of participants, which can lead to a revision of problem definition, stakeholder selection, goal formulation, strategy development and implementation of experiments.

3 Review of participatory modeling methods

This section describes the results of the literature review of participatory modeling methods. To identify relevant journal articles, a literature query using the Scopus database was complemented by expert knowledge on participatory modeling of the authors. Four queries were used to identify participatory modeling studies[2] which resulted in a total of 112 articles (a time limitation was not applied; search date: September 7, 2019). In addition, we added literature identified by a recent review article on the various dimensions of participatory modeling in transition research (Halbe, 2019; 15 articles). The full texts of these articles were read to initially check their relevance for the review's topic. Studies were found to be relevant, if (1) an actual participatory modeling application is provided (i.e., we excluded all conceptual studies without a practical application), (2) the studies' topic addresses a transition governance issue (i.e., studies that do not address a sustainability issue with a broader societal relevance were excluded) and (3) the involvement of stakeholders is organized in a co-learning or a co-management mode (i.e., studies applying an extractive mode were excluded). In total, we identified 56 relevant journal articles (i.e., 56 articles were excluded as they did not fit into the scope of this review). These relevant articles stem from the transition research field (in total 9 articles included in the review), and related fields including social-ecological modeling (19 articles), integrated assessment (6 articles), environmental management (16 articles) and other fields (6 articles). The authors added further journal articles using a snowball approach, i.e. checking references of articles already included in the sample, and according to their own expert knowledge (26 articles). We mark articles that were included using the snowball approach or expert assessment by an asterisk, as an expert-based selection

[2] The following search string was used to identify participatory modeling articles in the field of transition research: TITLE-ABS-KEY (transition AND participat* AND model*). The query yielded 4,943 documents. This was narrowed by manually selecting journals (in particular strictly natural science journals dedicated to e.g. molecular biology, physics and medicine journals were removed from the list). The remaining 218 articles were checked manually by title, leading to a subset of 28 articles. The other queries combined "participatory modeling" OR "participatory modelling" with (1) "social-ecological" OR "socio-ecological" (36 articles), (2) "integrated assessment" (9 articles) and (3) "environmental management" (24 articles). The Scopus database applied these queries to the title, abstract and key words of research articles.

can involve some bias (see also our discussion of this aspect in Section 4.3). In total, we were identified 79 relevant journal articles.

Table 1 provides an overview of the participatory modeling methods we have identified. A detailed assessment of each method is beyond of the scope of this article; in the following section, we instead outline their purpose and sort them to the process phases identified in Section 2. The sorting process bases upon the information provided in the respective article. In case that a study addresses multiple phases, the article is sorted to the phase that represents the focus of the study. If this was not possible, articles were sorted to multiple phases. In addition, we state the research field based upon the query in which the article was detected (if the article was included in multiple queries, all fields are indicated), including transition research (abbreviation: TR in Table 1, bold font), social-ecological modeling (SE), integrated assessment (IA), environmental management (EM) and other fields (OTH).

Table 1: Overview of participatory modeling methods

Method	**Objective(s)**	**References and field of study** (transition research := **TR**; social-ecological modeling := SE; integrated assessment := IA; environmental management EM; other := OTH; *:= selection based upon snowball approach or expert assessment)
Phase 1: Integrated knowledge production and problem definition		
Conceptual modeling / Causal Loop Diagrams	Visualization of multi-causal relationships and identification of feedbacks	Magnuszewski et al. 2005 (SE); Videira et al., 2012 (IA); Leenhardt et al., 2017 (SE); Kopainsky et al. 2017 (SE); Ingram et al., 2018 (SE)
Participatory Rapid Appraisal	Creative process to express point of view in an integrated way	Chambers, 1994 (OTH)*; Lara et al., 2018 (OTH)*
Companion modeling	Analyze perceptions and practices of stakeholders; education for sustainable development	Gourmelon et al., 2011 (EM); d'Aquino and Bah, 2013a,b, 2014 (EM); Bodonirina et al., 2018 (EM)
Phase 2: Stakeholder analysis and selection		
Social network analysis / Net Maps	Map and describe relations between stakeholders as well as stakeholders' roles and positions in the network	Schiffer and Hauck, 2010 (OTH)*; Scott, 2012 (OTH)*; Hauck et al., 2015 (EM)*; Stein et al., 2018 (EM)*
Phase 3: Participatory visioning and goal formulation		

Visual methods, such as collages, rich pictures or animations	Visualization of desirable future visions and storylines	Robinson et al., 2011 (OTH)*; Tàbara et al. 2008 (IA); Vervoort et al., 2012 (SE); Amazonas et al., 2019 (SE)
Conceptual modeling / causal loop diagrams	Envision innovative system designs	Iwaniec et al., 2014 (OTH); Halbe et al. 2015b (**TR**)*
Consistency analysis / Cross impact analysis	Develop consistent future scenarios based on expert judgment about systemic interactions	Weimer-Jehle, 2006 (OTH)*; Truffer et al., 2008 (**TR**)*; Withycombe Keeler et al. 2015 (EM);
Fuzzy cognitive mapping	Analyze plausibility of sustainability visions based upon expert and local knowledge	Penn et al., 2013 (OTH); Halbe and Adamowski, 2019 (IA)
System dynamics modeling	Assess trade-offs and plausibility of visions	Schmitt Olabisi et al., 2010 (SE); Iwaniec et al., 2014 (OTH);
Diverse quantitative models	Analyze specific aspects and consequences of visions	Krumdieck and Hamm, 2009 (OTH); Trutnevyte et al., 2011, 2012 (**TR**)*; Möller et al. 2012 (OTH); Fortes et al. 2015 (OTH)*; Delmotte et al. 2017 (OTH)
Multi-Criteria Decision Analysis	Assess options along predefined criteria; Prioritization of actions, construction of portfolios of actions	Wang et al., 2009 (OTH)*; Addison et al. 2015 (EM); Moraine et al., 2016 (OTH); Cohen et al. (2018) (OTH)*
Phase 4: Interactive strategy development that anticipates long-term systemic effects		
Conceptual modeling / Causal loop diagrams	Identify suitable intervention points	Burks-Copes and Kiker, 2014 (EM); Videira et al. 2014 (**TR**); Auvinen et al. 2015 (**TR**)*; Halbe et al. 2015b (**TR**)*; Valkering et al. 2017 (**TR**)
	Identification of sources of policy resistance and designing ways to overcome it.	de Gooyert et al. (2016) (**TR**)*
Causal loop diagrams / generic simulation model	Stimulate discussions and learning across cases; assess the effects and trade-offs of various actions with regard to their impacts on well-being	Daw et al., 2015 (SE/EM); Galafassi et al., 2017 (SE); Ulli-Beer et al., 2017 (**TR**)*
Fuzzy cognitive mapping	Capture expert knowledge and perspectives; testing different strategies	Kok, 2009 (OTH)*; van Vliet et al., 2010 (OTH)*; Nyaki et al., 2014 (SE); Gray et al., 2015 (SE); Henly-Shepard et al.. 2015 (SE); Olazabal and Pascual, 2015 (**TR**)*; Tiller et al., 2016 (SE); Firmansyah et al., 2019 (SE)
Companion modeling (conceptual modeling, agent-based modeling and role playing game)	Foster dialogue between stakeholders, investigate management scenarios and produce effective management plans.	Barnaud et al., 2008 (SE); Garcia-Barrios et al., 2008 (EM); Tàbara et al. 2008 (IA); Dupont et al., 2016 (SE); Perrotton et al., 2017 (SE)
Bayesian networks	Probabilistic analysis of management scenarios; of different types of data and models	Carmona et al., 2013 (IA); Martinez-Santos et al., 2010 (IA); Molina et al., 2011 (IA)

System dynamics	Assess options for action and potential side effects to a achieve a future vision	Videira et al., 2003 (EM); Metcalf et al., 2010 (EM); Collier et al., 2011 (SE); Koenigstein et al., 2016 (SE); Ulli-Beer et al., 2017 (**TR**)*
Participatory exploratory modeling	Assess strategies, policies and pathways under (numerous) future scenarios	Wiese et al., 2014 (**TR**); Daw et al., 2015 (SE/EM); Ruth et al., 2015 (**TR**)*; Withycombe Keeler et al. 2015(EM); Holman et al., 2016 (IA); Jorda-Capdevila et al., 2016 (EM); Galafassi et al., 2017 (SE); Moallemi and Malekpour, 2018 (**TR**); Schinko et al, 2019 (OTH); Simoes et al. (2019) (OTH); van Hardeveld et al. 2019 (EM); Venturini et al., 2019 (**TR**)
Participatory anticipatory modeling	Let stakeholders explore pathways and the effectiveness of policies	Carmichael et al., 2004 (OTH)*; Robinson and Tansey, 2006 (OTH); Lechtenböhmer et al., 2015 (OTH)*; Zivkovic et al., 2016 (**TR**)
Phase 5: Coordinate the implementation of experimental actions of multiple actors		
Management and Transition Framework	Map a sequence of social interaction processes, involved actors and outcomes (ex-ante planning)	Pahl-Wostl et al., 2010 (EM)*; Halbe, 2016 (**TR**)*; Halbe and Pahl-Wostl, 2019 (**TR**)
Analytical-evaluative framework	Map a sequence of events that leads to a particular outcome (ex-ante planning)	Forrest and Wieck, 2014 (**TR**)*
Phase 6: Systematic monitoring and assessment of actions		
Simulation models, e.g. System Dynamics	Define suitable indicators through identification of critical variables	Metcalf et al., 2010 (EM); Collier et al., 2011 (SE); Koenigstein et al., 2016 (SE)
Development of sustainability indicators	Define indicators to measure systemic interactions	Bossel, 2001 (OTH)*; Reed et al., 2006 (EM)*
Management and Transition Framework	Map a sequence of social interaction processes, involved actors and outcomes (retrospective analysis)	Pahl-Wostl et al., 2010 (EM)*; Halbe, 2016 (**TR**)*
Analytical-evaluative framework	Reconstruct community transition processes through analysis of intervention outputs and tracking back the sequence of events that led there (retrospective analysis)	Forrest and Wieck, 2014 (**TR**)*

In the following sections, we provide a summary of the identified studies, including the chosen methods, topics and process designs as well as exemplary results. Each family of methods is covered in a separate paragraph; we underline the name of the respective method to help readers finding a specific method of interest.

3.1 Phase 1: Integrated knowledge production and problem definition

Modeling can support the objectives of this phase to integrate knowledge and to develop a shared language because models are clear, explicit and systematic (Holtz et al. 2015). Conceptual modeling is a method that is useful to develop a common holistic understanding of a problem situation, and thus supports communication and learning between modelers, decision makers and other stakeholders (see Liu et al., 2008; Argent et al., 2016). For example, Ingram et al. (2018) used conceptual modeling to identify and quantify the strength of interactions between socio-economic and ecological system elements in Hawai'i. In this study, the Driver-Pressure-State-Impact-Response (DPSIR) framework was used as a guiding concept (see Bowen and Riley, 2003, on the development of the framework; Leenhardt et al., 2017, and Burks-Copes and Kiker, 2014, serve as further examples of the use of the DPSIR-framework for conceptual modeling).
Systems thinking is a specific conceptual modeling approach that visualizes multi-causal relationships and feedback processes through the development of causal loop diagrams (cf., Vennix 1996; Sterman 2000; Senge 2006). The development of causal loop diagrams by a group of stakeholders starts with the identification of key variables of a system and causal relationships between them (Vennix 1996). In this process, participants explain the concepts and rationales underlying variables, which reduces linguistic uncertainty (Brugnach and Dewulf, 2008) and supports the development of a shared problem understanding. Magnuszewski et al. (2005), Videria et al. (2012) and Kopainsky et al. (2017) serve as good examples that show how causal loop diagrams can support communication, knowledge integration and indicator identification. In these studies, causal loop diagrams were built in the scope of workshops on complex sustainability issues including the topic of sustainable Regional Development in Poland (Magnuszewski et al., 2005), maritime problems in Portugal (Videria et al., 2012) and farming in Zambia (Kopainsky et al., 2017).

Participatory mapping methods focus on spatial relationships between objects and animate participants to draw maps of a particular problem situation. Participatory Rapid Appraisal is such a mapping approach in which stakeholders draw maps, diagrams and timelines in a creative process to express their point of view in an integrated way (Chambers, 1994). Conceptual modeling and mapping methods can also be combined by a diagnostic scoring procedure, which allows stakeholders to prioritize aspects of a problem by using simple voting techniques (cf., Sheil and Liswanti, 2006). Besides knowledge integration, participatory rural approach can also be used as an educational tool to empower marginalized groups and developing integrated strategies (see Lara et al., 2018, for an example of an indigenous community in the Mexican humid tropics).

Companion modeling combines conceptual modeling, quantitative modeling (usually an agent-based model) with a role playing game to support dialogue and decision–making of stakeholders. For example, Bodonirina et al. (2018) developed a conceptual model using visual methods, in particular photography, within individual and group interviews. Based upon the conceptual model, a role playing game was design to inquire stakeholders' perceptions and practices in different resource management regimes. Finally, the results of the participatory process were compared to empirical data, such as land-cover maps. d'Aquino and Bah (2013a,b, 2014) present a "self-design" approach for role playing games and agent based models that has been applied in several participatory processes in Senegal. Their approach stresses the importance of providing stakeholders the freedom to develop their own conceptual framework, including the definition of issues and goals, upon which the design of the role playing game and the agent based model can build. Besides its application in specific case studies, companion modeling can also be applied as an educational approach by providing young people a learning environment for social-ecological dynamics (Gourmelon et al., 2011).

3.2 Phase 2: Stakeholder analysis and selection

Methods and approaches for stakeholder analysis can be differentiated between methods for (1) identifying stakeholders, (2) differentiating between and categorizing stakeholders, and (3) investigating relationships between stakeholders (Reed et al., 2009). While various flexible and tested methods for stakeholder identification and analysis exist, the study of relational aspects can be challenging (cf. Scott 2012). Understanding the relations between stakeholders is however very relevant for transition governance processes, e.g., for the purposeful selection of participants in a participatory process.

<u>Social network analysis</u> is a widely used approach for the empirical investigation of relations between actors (Scott, 2012). Social network analysis can be used to analyze several network aspects, such as the strength of ties between stakeholders, their centrality and the density of networks which can support the stakeholder selection process (cf. Prell et al., 2009, 2011). For example, stakeholders with strong ties in a network are likely to exchange information widely and to have a durable presence in the network. But also actors with weaker relationship can become important if they have a broker role between different networks, and thus, might introduce new ideas and a support a more holistic view (Prell et al., 2009).

<u>Net-Map</u> is a low-tech, low-cost, interview-based mapping method that allows qualitative and quantitative analysis of social networks. Schiffer and Hauck (2010) describe the application of Net-Maps in detail. Net-Maps are constructed in a step-wise way on a sheet of paper, using post-its for noting actor names, checker pieces (or similar tokens) to build influence towers, and colored pens to draw linkages that represent relationships, such as information exchange or funding flows. Net-Maps may be built in individual or group exercises that aim at knowledge extraction as well as learning of participants. The resulting network can be analyzed using graph-theoretical indices, such as centrality or density (Schiffer and Hauck, 2010). Net-Maps have been applied in several case studies and for diverse topics, such as biodiversity knowledge flows in Europe (Hauck et al., 2016), conservation and economic development in Southeast Asia (Hauck et al., 2015), and governance challenges linked to the water-energy-food nexus in the Upper Blue Nile region of Ethiopia (Stein et al., 2018).

Hermans et al. (2013 a,b) have used social network analysis to study the role of networks for innovation in agricultural niches through the development of databases and their analysis with statistical software programs. Although the network analysis did not involve stakeholders (i.e., strictly speaking it is not a participatory modeling exercise, as thus the reference is not included in Table 1) it illustrates the potential of social network analysis supported by formal methods for understanding the role of particular actors in a transition process.

3.3 Phase 3: Participatory visioning and goal formulation

The participatory development of visions usually requires non-technical and holistic methods to tap into the creative potential of stakeholders. Examples are written storylines (e.g., Vervoort et al., 2012; Delmotte et al. 2017), collages (Tàbara et al. 2008) and visual methods, such as rich pictures (e.g., Amazonas et al., 2019) or 3D computer-generated visualizations (Robinson et al., 2011).

Qualitative modeling methods can be applied to develop vision in a systematic way. For instance, conceptual modeling (see also Section 3.1) can be used for envisioning innovative system designs (e.g., Iwaniec et al., 2014). Halbe et al. (2015b) apply causal loop diagrams and the concept of Viability Loops (Hjorth and Bagheri 2006) to link innovations as part of a solution strategy to a particular problem perspective.

Consistency analysis aims at the analysis of consistent future scenarios based upon expert judgments about systemic interactions between descriptors of a future system state (e.g., Meylan and Spoerri, 2014). Truffer et al. (2008) used cross-impact analysis (see Weimer-Jehle et al., 2016) in a stakeholder workshop to build alternative future visions of the future of utility services in Germany and assess their internal consistency. Participants of the workshop were initially irritated by some results of the cross-impact analysis, but accepted the results after a process of discussion and reflection. The visions finally served as different context conditions for innovation strategies that were developed by stakeholders in a subsequent two-day workshop (Truffer et al., 2018). Withycombe Keeler et al. (2015) use a related method, namely formative scenario analysis (Tietje, 2005) that calculates consistency scores for alternative system designs. The method was applied during a participatory process to analyze different configurations of water systems in Phoenix, Arizona. A large number of consistent scenarios were identified, which was later reduced by different techniques, such as a stakeholder survey and a sustainability appraisal.

Fuzzy cognitive mapping is another semi-quantitative method that can be applied to analyze the plausibility of sustainability visions. Penn et al. (2013) used fuzzy cognitive mapping to analyze visions[3] of a bio-based economy in the Humber region, UK, hold by stakeholders. They found the method very successful to engage stakeholders, but recommend analyzing the sensitivity of model outputs with regard alternative system structures, variable values and functional relationships. As another example, Halbe and Adamowski (2019) used

[3] Penn et al. (2013) do not use the term "vision", but clearly focus on the analysis of opportunities to establish a future system, i.e. a bi-based economy. As this corresponds to the objective of phase 3, this study was sorted to this phase.

the fuzzy cognitive mapping method to identify multiple visions of a sustainable food system in Southwestern Ontario, Canada. Fuzzy cognitive mapping was found to be able to assess complex food system visions as well as their synergies and trade-offs.

A variety of quantitative modeling approaches can be applied to support the development of visions. System dynamics modeling is a flexible approach to address technical, socio-economic and ecological elements of a vision (Iwaniec et al., 2014). For example, Schmitt-Olabisi et al. (2010) used system dynamics modeling to model different sustainability visions for the region of Minnesota in the year 2050. The model was able to reveal several side-effects and trade-offs that were not considered in the preceding process of developing qualitative future visions.

Fortes et al. (2015) used another quantitative modeling approach namely the technology-based energy system model to scrutinize for the energy sector the technical feasibility and cost-effectiveness of two distinct qualitative socio-economic scenarios of Portugal's development that were designed by national stakeholders. Möller et al. (2012) included local knowledge in the design of simplified energy models for five North Sea Islands. The models were then applied interactively in a SWOT[4] analysis of technological options and strategies. Delmotte et al. (2017) provide another example of quantitative vision modeling from the agriculture sector. They used a bio-economic optimization model to analyse the effects of various scenarios, which were developed before based upon narrative storylines, on land use, socio-economic and environmental indicators. In addition to a single expert model, multiple, more detailed models can be applied to test specific aspects and consequences of sustainability visions. For instance, Trutnevyte et al. (2011, 2012) combine a qualitative visioning approach to develop a holistic vision statement with a quantitative modeling approach to analyze technically feasible ways to implement the vision (resource allocation scenarios) and potential consequences. Krumdieck and Hamm (2009) performed a strategic analysis of a community's optimal level of energy service for the isolated Pacific Island Rotuma. They surveyed the social values about the energy supply and environmental impacts, and the shared cultural vision about domestic activities. They then used engineering models to identify feasible development options as well as to conduct a comparative risk assessment for socio-economic viability, environmental impacts and fuel supply sustainability.

Multi-criteria decision analysis (MCDA) methods are also supportive for evaluating a set of alternative options (e.g., technologies, strategies) in multiple dimensions (e.g., economic, ecologic, social properties) in a structured way (see Uhde et al., 2015). MCDA involves formulation of a set of selected criteria according to which the options are evaluated, to determine weights for the criteria to show their relative importance, and then to rank the alternatives based on the criteria weights. Multiple specific methods are available for each step (see Wang et al., 2009, Cohen et al., 2018). As an example for a participatory MCDA, Brand and Missaoui (2014) have calculated and evaluated different power system scenarios for Tunisia. The scenarios have been defined by key stakeholders, for which performance criteria were calculated using an electricity generation system model. A scenario was then

4 SWOT analysis is an established method to identify strengths, weaknesses, opportunities and threats of options in a qualitative fashion.

selected using MCDA based on weights for the performance criteria defined in an expert workshop. Moraine et al. (2016) provide an example from the agricultural sector. They applied MCDA to assess the sustainability of integrated crop-livestock systems at the regional level. A group of farmers and technical advisors designed alternative cropping systems and, by using a MCDA, assessed their impact on various sustainability indicators, such as ecosystem services, profitability and self-sufficiency. They found that the assessments were not completely tangible for stakeholders and suggest that more concrete evidence of innovative cropping systems might be needed, for example through field trials. As an example from water management, Addison et al. (2015) combine various methods in a participatory process, in particular conceptual modeling and the calculation of MCDA, to set conservation management thresholds for a marine national park in Victoria, Australia. They found it as an accessible and effective approach to deal with competing objectives and value judgements, while drawing upon scientific understanding of the system.

3.4 Phase 4: Interactive strategy development that anticipates long-term systemic effects

After a joint vision is developed, the process can proceed towards developing a strategy for its implementation. Qualitative modeling methods can be used to identify suitable intervention points. Videira et al. (2014) apply conceptual modeling in a participatory process with researchers and degrowth activists. Causal loop diagrams were applied in this study to analyze feedback processes in current social, ecological and economic systems in order to define leverage points that allow societies to enter degrowth pathways. Similarly, Valkering et al. (2017) used causal loop diagrams to capture the dynamics of transition initiatives and to identify activities that are suitable to accelerate transition dynamics. Auvinen et al. (2015) combine qualitative modeling (i.e., causal loop diagrams) with the use of a conceptual transition framework (the multi-level perspective) to design system transition roadmaps from a current socio-technical system to a future vision. System transition roadmaps are considered as a graphical tool that helps to visualize the interaction of various dimensions in transition processes. Halbe et al. (2015b) present a qualitative modeling approach that helps to analyze the various roles of actors in sustainability transitions. De Gooyert et al. (2016) have demonstrated how causal loop diagrams can illustrate balancing feedback loops that may cause "policy resistance" in an energy transition, i.e. effects that undermine the efficacy of actions to improve system behavior. Once potential sources of policy resistance are identified, it can be overcome by designing appropriate combinations of interventions.

Fuzzy cognitive mapping is a semi-quantitative method that can function as a bridge between qualitative and quantitative scenario development (Kok, 2009; van Vliet et al., 2010). Fuzzy cognitive maps can capture expert knowledge and different perspectives on sustainability issues, and allow for testing different strategies to achieve sustainability objectives (Olazabal and Pascual, 2015). Various applications of fuzzy cognitive mapping in stakeholder processes could be identified in social-ecological systems research. Gray et al. (2015) apply the method to analyze resilience in social-ecological systems. Firmansyah et al. (2019) use fuzzy cognitive mapping to define the concept of smart cities and explores what-if scenarios. Tiller et al. (2016) explore the perception of stakeholders on the link between environmental change on fisheries and aquaculture in the region of Troms in Norway. Further applications address the promotion social learning in community disaster planning (Henly-Shepard et al., 2015) and analysis of perception on local drivers of bushmeat trade (Nyaki et al., 2014).

Besides the application for knowledge integration and problem framing (see Section 3.1), companion modeling can also be applied for strategic purposes. We found different combinations of qualitative and quantitative modeling in companion modeling studies, i.e., combining conceptual modeling, role-playing games, agent-based modeling (see Barreteau et al., 2003; Tàbara et al. 2008; Etienne, 2014; Barnaud et al., 2008) or other types of simulation models, such as MCDA (e.g., Garcia-Barrios et al., 2008). For example, Perrotton et al. (2017) applied companion modeling to bring together local communities and protected area managers to negotiate effective management plans for protected area in Zimbabwe. Before the actual model was built, about 1.5 years were invested in ethnographic fieldwork to understand social–ecological context. Dupont et al. (2016) use companion modeling for the participatory construction of management scenarios and their assessment through their effects on various ecological indicators in a Natura 2000 site in France.

Bayesian networks can also be a suitable tool to actively involve stakeholders in model development. Bayesian networks are probabilistic models that consist of nodes, which are connected through causal links, which together form an acyclic network (i.e., feedback processes are not considered) (Uusitalo, 2007). Each node can have different states, while relationships between nodes are expressed as probabilities, which can be set through conditional probability tables (see e.g., Uusitalo, 2007). As an example for an application of the method, Martinez-Santos et al. (2010) tested the use of a groundwater flow model and a Bayesian network in the scope of a participatory process to support the management of the Mancha Occidental aquifer, Spain. While stakeholders were actively involved in the development of the Bayesian network (data from the groundwater model was used as an input to the Bayesian model), the involvement of stakeholders was limited to the design and discussion of scenarios for the groundwater model. They conclude that Bayesian network is a powerful method for supporting spontaneous multi-stakeholder dialogues. However, the groundwater model also provided important input to the stakeholder discussion process, due to the active request by stakeholders for a vulnerability analysis of the hydrological system. In another study, Carmona et al. (2013) developed a Bayesian network of water management issues in the middle Guadiana river basin, Spain, in the course of a participatory process. A crop model and an economic model were dynamically coupled to the Bayesian network, which shows the capability of the method to integrate various types of data (see also Molina et al., 2011; Mäntyniemi et al., 2013). The Bayesian network was applied to simulate the effects of management options under different climate change and economical scenarios.

While system dynamics for assessing visions (see Section 3.3) is a rare application area, the method's use for strategy development is more common. Quantitative system dynamics models can be built by stakeholders themselves, for instance by using a group model building approach (Vennix, 1996). However, the modeling process is usually a time-intensive process that requires advanced facilitation and modeling skills. The system dynamics method however allows flexibility to tailor the degree of participation and the scope of the model boundary to the problem and context at hand (Stave, 2010). Mediated modeling is modeling framework from environmental management that guides such a tailored development of a quantitative system dynamics model through a stepwise process design (van den Belt, 2004). Metcalf et al. (2010) applies mediated modeling to environmental conflicts in the Upper Mississippi River. During a three day modeling workshop, two groups of diverse stakeholder built two system dynamics models, which were quantified with the help of modeling experts. The model was considered as a scoping model, which requires further iterative development in the future. Such models aim at explaining critical dynamics in social-ecological systems without having the ambition to predict future developments. Collier et al. (2011) provides another example of the use of a system dynamics scoping model to investigate trade-offs and synergies between conservation and development in four diverse case studies. Videira et al. (2003) applied mediated modeling to support the development of a management plan for a protected coastal wetland in the South of Portugal. Four workshops were organized (in total about 48 hours) with diverse stakeholder groups to gradually develop a management model that allows for scenario analysis. The process resulted in the formulation of guidelines for the management plan as well as further positive outcomes, such as shared learning and commitment towards results. Koenigstein et al. (2016) also went beyond a scoping model by developing an integrated system dynamics model that links climate change scenarios with effects on relevant species. Stakeholders provided input to the modeling process through interviews and workshops. The model supported a discussion of adaptation options for different stakeholder groups and the role of uncertainties due to climate change. In the context of the Swiss federal energy strategy 2050, Ulli-Beer et al. (2017) used causal loop diagrams and system dynamics modeling to support stakeholders in the development and evaluation of adequate strategies for an energy transition. It is particular about their work that they test and emphasize the usage of more generic models to stimulate discussion and learning across cases.

Scenarios help to analyze and design implementation processes that comprise several intermediate steps towards a long-term vision (e.g., Schneider and Rist, 2014). Exploratory scenarios (also called forecasting scenarios) start from the current condition and describe different plausible futures depending upon uncertain processes and events (Börjeson et al. 2006; Millennium Ecosystem Assessment 2005). Through this, they facilitate discussions about possible and necessary interventions to steer a system in the desired direction. Simulation models of different types can be used for exploratory scenario studies. Daw et al. (2015) and Galafassi et al., 2017 combine causal loop diagrams and the use of integrated models built by scientists to explore trade-offs between various interventions and the well-being of community near Mombasa, Kenya. An interactive "toy model" was developed within Microsoft Excel using fuzzy logic rules, which are simple social-ecological models that support a dynamic understanding of trade-offs. In addition, the toy model was complemented by a fisheries ecosystem model and artistic representations of future scenarios of the social-ecological system. Schinko et al (2019) also demonstrate that simplified energy system models can provide helpful insights to stakeholder discussions. In their study, a spreadsheet version of an energy system model was developed to investigate opportunities of renewable energy in Morocco. Ruth et al. (2015) applied an interactive simulation model to analyse interdependencies and trajectories of the energy and agriculture sectors of the Bremen/Oldenburg Metropolitan Region in Northwest Germany. Three scenarios of external influences on the region were defined by stakeholders and each was combined with two scenarios of the region's future demand. Hardeveld et al. (2019) present another interactive simulation system, a kind of serious game that was applied in for peatland management in the course of 10 stakeholder workshops. Stakeholders can take several roles in the simulation and explore the effected of actions on various sustainability indicators as well as a 3D representation of the system. The workshops were systematically monitored and evaluated, which helped to show positive effects of the simulation on the cooperative attitude and understanding of the system. As another example for an exploratory scenario study, Moallemi and Malekpour (2018) introduce a participatory exploratory modeling[5] approach to assess policies under numerous future scenarios and illustrate it with examples from energy transitions. A participatory process supported model design and validation, the definition of potential policies and the identification of coping strategies to remove, circumvent or ameliorate vulnerabilities. As an example for another comprehensive model, Holman et al. (2016) present the CLIMSAVE Integrated Assessment Platform, which is freely available online. By combining various models, the platform allows for the analysis of climate change scenarios and their impact on different sectors, resources and ecosystems. Four scenarios were developed in a participatory process using the Story-and-Simulation approach (Alcamo, 2008), which iteratively combines the crafting of narratives and computer models (e.g., Kok et al., 2014). Venturini et al. (2019) also built upon the Story-and-Simulation approach to investigate multiple future pathways of the Danish transport sector. In particular, their study focused on the systematic identification and application of driving forces (i.e., trends and patterns, which can influence the outcome of events) and how to involve stakeholders in the iterative revisions of scenarios. Simoes et al (2019) show another approach for using an energy system model in a participatory process. In this study, a MCDA was conducted to systematically consider quantitative and qualitative criteria in the participatory assessment of scenarios. Wiese et al. (2014) also develop an open source techno-economic simulation model of the future development of the German and European electricity system. Users can explore different pathways and configurations of a future energy system and their effects on output variables, such as total system costs. We found also several studies of participatory explorative scenario applications in the water sector, such Jorda-Capdevila et al. (2016) who coupled a water allocation model and an ecosystem service provision model, or Withycombe Keeler et al. (2015) who used an integrated water system model.

Anticipatory scenarios (also called backcasting) are more normative by starting with a desired or feared vision and define intermediate system states that connect the current condition with the future to identify effective policies (Mahmoud et al. 2009; Robinson et al., 2011). Backcasting approaches are suitable to analyze pathways for implementing a particular sustainability vision. QUEST is an example of a modeling tool for regional sustainability scenarios applying a backcasting approach which provides a user-friendly interface that allows stakeholders to run simulations in order to explore the effectiveness of policies

[5] Exploratory Modeling (Bankes 1993; Kwakkel and Pruyt, 2013) is an approach that uses ensembles of models to deal with uncertainties in the model formulations themselves. It produces a portfolio of possible futures and supports the design of a strategy that performs robustly in the face of many uncertainties.

(Carmichael et al., 2004; Robinson and Tansey, 2006). Users of this integrated assessment model are first asked to rank their priories, and specify external conditions and developmental factors. Second, users make choices at different levels of detail for achieving their future vision. Third, the results of these choices are presented and evaluated against the user's priorities (Carmichael et al., 2004). Lechtenböhmer et al. (2015) describe the development of long-term strategies for carbon emission reductions in energy-intensive industries in the context of the climate protection plan of the German state of North Rhine Westphalia. In a series of six workshops with key stakeholders, a scenario for economic development was defined and the assumptions and parameters of a bottom-up energy system model (that was operated by the researchers) were discussed and refined. The results of two scenarios that include different assumptions about availability of low-carbon breakthrough technologies were discussed regarding their feasibility and required policies and measures. Zivkovic et al. (2016) used an urban energy system model to analyze backcasting scenarios developed by stakeholders for a sustainability transformation of the heating sector in the city of Nîs, Serbia. Various stages of the stakeholder process provided data for setting up the model. The results of the model supported the design of a final combined scenario for implementation.

3.5 Phase 5: Coordinate the implementation of experimental actions of multiple actors

To proceed from integrated strategy development in phase 4 towards more detailed implementation plans in phase 5, actions of various actors in the actual implementation phase need to be coordinated. In particular, methodologies are needed that help to depict key elements of strategies, including events, responsibilities and expected outputs, and how they finally reach sustainability outcomes. This might require a translation of general modeling results into context-specific, operationalizable implementation strategies. The Management and Transition Framework (MTF) is a conceptual and methodological framework that allows for such a description, analysis and assessment of transition processes (Pahl-Wostl et al., 2010). The conceptual pillars of the MTF are adaptive management, social learning, regime transitions and the Institutional Analysis and Development Framework (cf. Ostrom, 2005). The framework consists of a static and a process-related representation of transition processes. The static representation defines important elements of transition processes, including elements from ecosystems and social systems as well as action situations (i.e., social interaction processes) and their outcomes, such as knowledge, institutions or operational outcomes. The process-related representation allows for the analysis of transition processes by reconstructing their sequence, i.e., how action situations are connected by outcomes (i.e., the outcome from one action situation can be an input to other action situations). Up to now, the MTF has been mainly applied to understand processes of change in water resource issues in an ex-post analysis (e.g., Sendzimir et al., 2010; Schlüter et al., 2010; Knueppe and Pahl-Wostl, 2012). However, the same framework can be applied in an ex-ante planning exercise that defines the action situations, participating actors, and aspired outcomes. The application of the framework for such a prospective design of transition paths has already been explored (Halbe et al., 2013, 2018; Halbe and Pahl-Wostl, 2019).

Another analytical-evaluative framework is presented by Forrest and Wieck (2014). Their framework allows for the structured analysis and evaluation of community transition processes. It helps to reconstruct transition processes starting from the intervention outputs and tracking back the sequence of events that led there (Forrest and Wieck, 2014). The following elements are used to reconstruct transition paths: outputs (e.g., infrastructures, products, institutions), activities (networking, mobilizing, planning), actor types (e.g., NGOs, businesses, community groups), and barriers (e.g., infrastructures, institutional, economic). Even though the framework has been only applied in an ex-post analysis yet (Forrest and Wiek, 2015), the same framework could be applied in an ex-ante planning exercise, similar to the MTF mentioned above. Future research is needed to test the applicability of these frameworks for the coordination of the implementation of experimental actions in the context of transition governance processes.

The two process design and analysis approaches mentioned before can greatly benefit from evaluation schemes, which guide ex-ante evaluation of experiments. Luederitz et al. (2017) developed an evaluation scheme for transition experiments that considers four evaluative dimensions, namely inputs, processes, outputs and outcomes. Process design idealtypically follows the sequence of defining desired outputs and outcomes first, before processes are designed and inputs are identified. For each evaluative element, Luederitz et al. (2017) specify various features, indicators and evaluative questions that help organizers of transition experiments to reflect and improve their process design. Adaptive planning is another important approach to operationalize implementation strategies and to find practical ways to deal with the tremendous uncertainties of transition governance. The term of transition experiments already underlines that designing optimal transition governance strategies is not possible, but each step has to be treated as an experiment that allows for learning and iterative adaptation (see also Pahl-Wostl et al., 2007). Explorative modeling (see Section 3.4) and other modeling approaches can be used for the development of robust and adaptive strategies (Kwakkel et al., 2010; Walker et al., 2013; Haasnoot et al., 2019)[6].

3.6 Phase 6: Systematic monitoring and assessment of actions

Systematic monitoring and assessment requires measures to take stock of the changes in the target system over time and a clear understanding of the aspired outcomes (i.e., goals). Furthermore, understanding the co-evolutionary processes in the socio-technical system that have led to the observed changes is important for learning and adaptation of future actions. Simulation models can support all of these aspects: the definition of appropriate indicators (e.g., Magnuszewski et al., 2005), the stock taking of changes in the system according to these indicators, and the analysis of the underlying socio-technical or social-ecological processes (e.g., van den Belt, 2004).

[6] The importance of stakeholder involvement is mentioned in these studies, but an actual participatory modeling process is not presented. Therefore, the references are not included in Table 1, but mentioned here due to their particular importance.

Reed et al. (2006) provide an overview of expert-based and participatory approaches for developing sustainability indicators, and highlight their synergies. While expert-led indicators imply scientific rigor and some form of objectivity, stakeholder-led indicators are likely to be more relevant and useable in a specific local context. According to Reed et al. (2006), models can be used for identifying suitable indicators for the evaluation of strategies. For instance, system dynamics models can be used to identify sensitive parameters and tipping points, as well as the influence of uncertainties on model results (Sterman, 2000). Thus, modeling can guide the selection of indicators by identifying critical variables.

The measurement of system change includes indicators for which data can directly be collected, such as for example CO_2 emissions. Besides that, more complex indicators of a system's state might be required to grasp systemic characteristics, whose assessment requires the use of formal models. Bossel (2003) proposes seven basic orientors, such as adaptability, security and effectiveness, pointing to key aspects that must be considered in the assessment of a system's viability and sustainability. The performance of these indicators needs to be assessed in qualitative or quantitative terms by defining specific viability and performance measures that are appropriate for the target system. Bossel (2003) also stresses that the development of these indicators should be embedded in a participatory process to draw upon several knowledge sources.

As part of the adaptive policymaking approach, contingency planning is conducted through the identification of signposts and triggers (Walker et al., 2001; Kwakkel et al., 2010; Raso et al., 2019)[6]. Based upon the prior identification of vulnerabilities and opportunities, signposts specify the information that need to be traced in order to make sure that the strategy is on track. Triggers are critical values of signposts at which corrective action become necessary in the course of the strategy's implementation. Hermans et al. (2017) also highlights that the monitoring system should support collaborative learning between various actors, which needs to be considered in its design (e.g., by explicitly addressing the roles and responsibilities of actors).

The MTF (Pahl-Wostl et al., 2010) and the analytical-evaluative framework of Forrest and Wieck (2014) introduced above in Section 3.5 can be used in ex-post analyses of the socio-technical processes that have led to the current system state (by comparing the planned process to the actual process). Perpetuating the analysis over time supports an understanding of (transition governance) actions and their impacts on the system.

4 Discussion

4.1 Structure of the results

The methods and exemplary applications we have identified are distributed unevenly over the six phases of transition governance (see Table 1). There is a considerable amount of modeling methods available for "participatory visioning and goal formulation" (phase 3) and for “interactive strategy development” (phase 4). In these process phases, methods are used and combined in a variety of creative ways with various types of stakeholder involvement.

We could identify fewer methods that are used for the other phases. For “integrated knowledge production and problem definition” (phase 1), a set of well-established modeling methods exist. However, to our knowledge those have not yet been used for the governance of socio-technical transitions (i.e., all studies stem from related research fields). For “stakeholder analysis and selection” (phase 2) social network analysis is a widely applied method in the fields of environmental management and social-ecological modeling, while its application for transitions studies seems to be limited, up to now. For “Interactive strategy development that anticipates long-term systemic effects” (phase 4), fuzzy cognitive mapping shows many applications in social-ecological modeling to capture stakeholder knowledge and assess strategies. Transition research could build upon these experiences with this semi-quantitative modeling method. In addition, companion modeling could be an interesting approach for transition governance. Combining agent-based modeling with participatory methods, such as role playing games, seems particularly promising as agent-based modeling is argued to be among the modeling methods which are best able to capture core characteristics of transition dynamics (see Holtz et al., 2015; Köhler et al., 2018; Hansen et al., 2019), while the involvement of stakeholders in the development of such agent-based transition models is – to our knowledge – limited, up to now. Transition researchers could hence make use of the established methodology of companion modeling for the involvement of stakeholders in the development, testing and application of agent-based models. For the “coordination of the implementation of experimental actions” (phase 5) and “systematic monitoring and assessment of actions” (phase 6), we could identify potential candidates and plausible contributions of modeling methods. But further research is needed to test and assess the suitability of the identified methods for transition governance.

4.2 Transferability of methods to transitions governance

We were able to detect a diverse set of methods to fulfill the different objectives of transition governance process phases. Some of the methods have a long legacy of application in other research fields (e.g., conceptual modeling) while others turned out to be more recent and tailored to the sustainability transitions field (e.g., participatory exploratory modeling). The similarity of process phases and associated objectives in the reflexive governance, transition management and adaptive management approaches is a favorable condition for transferring long-standing findings and experiences on the use of participatory methods from other, more mature research fields. Foxon et al. (2008) point to the various similarities of transition and adaptive management as iterative, learning-based approaches that draw upon repeated experiments and broad stakeholder participation. In addition, both approaches integrate bottom-up and top-down approaches and focus on learning and adaptation in the face of crises and long-term pressures (Foxon et al., 2009). It is therefore to be expected that methods that have been fruitfully used for adaptive management are also useful for transition governance.

4.3 Design of the review and its limitations

By combining a systematic literature review using search queries and an expert-based review, we indented to utilize the strengths of both approaches, i.e., a systematic search through the literature as well as the inclusion of relevant publications from an expert perspective that might have been overlooked otherwise. Some of the identified participatory modeling methods are only backed by expert-selected studies (e.g., Participatory Rapid Appraisal in Phase 1), which can involve some selection bias. Also the methods identified in Phase 2 (Stakeholder analysis and selection), Phase 5 (Coordinate the implementation of experimental actions of multiple actors) and Phase 6 (Systematic monitoring and assessment of actions) solely base or heavily rely upon expert-selected articles. The relevance of most methods is, however, substantiated by studies found in the search queries as well as selected articles by experts (e.g., Multi-Criteria Decision Analysis in Phase 3), which points to solid findings of the review. To allow for a differentiated account of the two review approaches, articles added based upon expert assessment are marked with an asterisk in Table 1. By making the source of the selection explicit (query-based or expert-based), our findings are presented in a transparent way. In our opinion, the combined review approach allowed us to not only highlight gaps in the literature, but suggest potential methods to close this gap.

Although the review covers a broad range of literature, we cannot guarantee that all relevant studies and methods have been identified. A limitation of this article is the restriction of the literature review to peer-reviewed academic articles. There is also a breadth of grey literature from practitioners (e.g., civil society groups or consultancies) that provides insights into the constraints and opportunities of participatory modeling methods. However, by manually checking the full text of 109 articles in the review, we think that we included a wide range of modeling applications that reflects also the diversity in practice. In addition, we only included studies with a practical application of the method in co-learning and co-management processes, which also indicates the practical applicability and relevance of the used methods. It is however not always possible from reading the articles to clearly see the level of stakeholder involvement and distinguish between “extractive mode” and “co-management / co-learning”. Some studies might have been included which do not strictly follow a “co-management / co-learning” approach while others might have been omitted due to lack of knowledge about the wider context of the study (e.g. when articles focus on the model and model results, and not the application).

5. Conclusions

This article has identified various participatory modeling methods and their links to transition governance practice. For the six phases and associated objectives of transition governance processes, the key findings are as follows:

- For integrated knowledge production and problem definition (phase 1) specific application of modeling methods seems to be the exception in transitions studies, up to now. But modeling methods have been developed in other research fields that seem promising for usage for transition governance: causal loop diagrams, participatory mapping methods and companion modeling.

- For Stakeholder analysis and selection (phase 2) we found that social network analysis is applied to understand the relations of stakeholders in environmental management and social-ecological modeling, and that formal methods are available that can contribute to conducting such network analyses. However, we could identify only one application of social network analysis in transition research.
- Participatory visioning and goal formulation (phase 3) requires the use of non-formal methods to tap into the creative potential of stakeholders, but a broad range of modeling approaches can be and are used to test the plausibility of visions, and to analyze their consequences with greater rigor: causal loop diagrams, the cross-impact balance method, system dynamics modeling, energy system models, multi-criteria analysis, and specific quantitative models to scrutinize particular aspects of a vision (e.g., engineering models).
- For interactive strategy development that anticipates long-term systemic effects (phase 4), qualitative modeling methods such as causal loop diagrams can be used to identify intervention points. Fuzzy cognitive mapping is a semi-quantitative method that allows for testing different strategies. Companion modeling combines conceptual modeling, agent-based modeling and role playing game, and therefore constitutes an multifaceted approach for participatory modeling. Furthermore, Bayesian networks show a high capability to integrate different types of data and deal with high uncertainty in complex systems. The development of exploratory and anticipatory scenarios can be supported by simulation and optimization models of different types.
- The coordination of the implementation of experimental actions (phase 5) is yet challenging. Methods are needed that clarify the sequence of actions, responsibilities and potential barriers. There are some promising conceptual frameworks available that have been mostly applied in an ex-post analysis yet. The application of these frameworks for ex-ante process design appears to be doable, but requires further research.
- For systematic monitoring and assessment of actions (phase 6), we found no specific applications of modeling methods in the transitions field that were used for monitoring real-world change. But work in other fields demonstrates that simulation models can support the identification of critical variables that require monitoring, and can be used to indicate the current state of systemic characteristics that cannot be directly measured. The MTF and the evaluative framework by Forrest and Wieck (2015) are suitable approaches for monitoring and evaluation as well as ex-post analyses of the socio-technical processes.

In sum, our review shows that participatory modeling methods are currently used in particular for phases 3 and 4. For several other phases we have identified participatory methods for which extensive experiences exist in other research fields that can be useful for transition governance. Methods are readily available in particular for phase 1, while in particular for phases 5 and 6 there is greater need for further research on the suitability and transferability of methods that are in principle available to support these phases. Since the specific context, stakeholder constellation and other factors are most important for successful participatory modeling, future research should also investigate more closely the specific contexts and process designs within which the identified methods are most promising for application in transition governance processes.

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