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Governance of Transformations towards Sustainable Water, Food and Energy Supply Systems

Facilitating Sustainability Innovations through Multi-Level Learning Processes

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Dissertation

GOVERNANCE OF TRANSFORMATIONS TOWARDS SUSTAINABLE WATER, FOOD AND ENERGY SUPPLY SYSTEMS
-
FACILITATING SUSTAINABILITY INNOVATIONS THROUGH MULTI-LEVEL LEARNING PROCESSES

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Summary

A fundamental change in societal values and economic structures is required to address increasing pressures on ecosystems and natural resources. Transition research has developed in the last decades to analyze the co-dynamics of technological, institutional, social and economic elements in the provision of key functions such as energy, water and food supply (van den Bergh et al., 2011). This doctoral dissertation provides conceptual and methodological contributions to the pro-active governance of sustainability transitions. The term 'transition governance' is understood to embrace the full complexity of multi-actor processes in societal transformations towards sustainable development. The specific sustainability outcomes of the governance process cannot be controlled or pre-set, but emerge through the interactions of multiple actors (who have various interests and perspectives) and context conditions (e.g., available funding and knowledge).

Three research gaps are identified that are addressed in this dissertation. First, a comprehensive conceptualization of learning in sustainability transitions is currently missing that comprises learning at multiple societal levels (ranging from individuals to policy-actors). Learning concepts are often not explicitly discussed in transition research (cf., Beers et al., 2014) even though learning is considered as fundamental for innovation processes (e.g., Bergek et al., 2008), niche formation and development (e.g., Kemp et al., 1998) as well as breakthrough and diffusion of innovations (e.g., Geels 2005). Second, methods for the analysis and design of transition governance processes are lacking that specify case-specific intervention points and roles of actors in the implementation of innovations (cf. Tukker Butter, 2007). Third, participatory modeling approaches are only applied to a limited extent in transition research (Holtz et al., 2015) despite a high potential for supporting communication and learning.

Based upon these research gaps, three research questions are specified that are addressed in this PhD research:

- **Research Question 1**: How can multi-level learning in transformation governance processes be conceptualized?
- **Research Question 2**: How can actors actively facilitate societal transformations towards sustainable development in specific regional contexts?
- **Research Question 3**: What role can modeling play in the governance of transition processes?

The aforementioned research questions are further specified and translated into three specific objectives of this research:

- **Objective 1:** Develop and apply a conceptual framework to understand societal transformations towards sustainable water, energy and food systems as multi-level learning processes.
- **Objective 2:** Develop and apply a methodological framework to analyze and actively facilitate transition governance processes.

- **Objective 3:** Analyze the opportunities of a modeling approach to be applied in transition governance processes.

Seven lead-authored research papers have been developed in the scope of this doctoral dissertation, including four articles *published* in peer-reviewed scientific journals (cf. Halbe et al., 2013, 2015a, 2015b, 2015c), one article *submitted* to a peer-reviewed scientific journal (Halbe et al., submitted), one article *to be submitted* to a peer-reviewed scientific journal (Halbe et al., to be submitted) and one published international *conference paper* (Halbe and Ruutu, 2015).

This doctoral dissertation synthesizes the content of these articles into a coherent conceptualization and methodology. The methodology is applied to three case studies in Canada, Cyprus and Germany. A synthesis of findings from the case studies as well as an overall discussion and conclusions with regard to research questions are provided.

Theory and Concepts

Transition research has to deal with the complexity of sustainability transitions. This complexity is apparent in the core characteristics of transitions. Thus, transitions involve multiple domains (e.g., production, consumption, regulation, and civil society), co-evolutionary processes, path-dependency and self-reinforcing mechanisms at multiple levels (Holtz, 2011). The governance of transitions requires consideration of further relevant characteristics of transitions, including the variety of actors from multiple domains and levels, as well as a strong future and normative orientation (Halbe et al., 2015c). Transition governance builds upon reflexive governance (Voss and Kemp, 2006), transition management and adaptive management (Voß and Bornemann, 2011).

The conceptualization of multi-level learning developed in this doctoral research (linked to Objective 1) differentiates between learning concepts that are related to (1) learning intensity, objects and outcomes, and (2) learning processes. Based upon this, the (3) subjects of learning and (4) contexts in which learning takes place are defined (see Halbe et al., submitted). Three learning intensities are differentiated, namely routine learning, reframing and paradigm change. Each learning intensity is associated with different objects (i.e., the primary objects of change), which can lead to various outcomes (i.e., secondary objects of change that result from a change in primary objects). Other learning concepts focus more on the process of learning, i.e., on specific mechanisms that explain how the objects of learning (e.g., mental models, values) can be altered. An agency-perspective with respect to a specific sustainability issue is applied to define learning contexts (i.e., the following question is asked: What is the social unit that primarily takes agency in a learning process that addresses a sustainability issue?). Four learning contexts are specified: (1) in an *individual learning context*, an individual takes action to tackle a sustainability problem; (2) in the *group learning context*, a group takes collective action to address a problem; (3) in an *organizational learning context*, individuals or groups act as representatives of an organization to solve a sustainability problem; (4) in the *policy learning context*, governmental and non-government actors (in the following called ‘policy actors’) interact in addressing a sustainability issue through public policy making and implementation.

A typology of model uses has been developed by Halbe et al. (2015c) to analyze the relevance of participatory modeling in transition research. The typology distinguishes the different purposes, contexts and epistemological foundations of modeling. Thereby, this typology allows for extracting unique challenges for each model use (cf. Objective 3). Three different model uses are identified the use of models for understanding transitions, for providing case-specific policy advice, and for facilitating stakeholder processes. 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. 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). 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, such as sustainability transitions. Due to the particular relevance of the model use of ‘facilitating stakeholder processes’ for transition governance, Halbe and Ruutu (2015) provide a review of participatory modeling methods and tools for each of the phases of transition governance processes (cf. Objective 3). In particular, systems thinking using causal loop diagrams is a promising approach in transition research. Halbe et al. (2015b) also uses systems thinking to teach participatory model building and the relevance of paradigms to undergraduate and graduate students.

Methodology for the governance of sustainability transitions

The methodology developed in this PhD research aims at the analysis and design of transition governance processes by specifying the various opportunities to contribute to sustainability transitions through purposeful action at different societal levels, as well as related roles of stakeholders in implementing such processes of change (cf. Objective 2). The methodology combines different streams of previous research (cf. Halbe et al., to be submitted): 1) a participatory modeling approach to identify problem perceptions, case-specific sustainability innovations as well as related implementation barriers, drivers and responsibilities (cf., Halbe et al., 2015a); 2) a systematic review to identify supportive and impeding learning factors from the general literature that can complement case-specific factors (Halbe et al., submitted); and 3) a method for the analysis and design of case-specific transition governance processes (cf. Halbe et al., 2013).

The participatory modeling process starts with a problem analysis based upon available data and information about the transition topic at hand. Due to the focus on sustainability innovations, the following stakeholders are particularly relevant: innovators (i.e., stakeholders who play a role in the implementation of innovations) and experts (i.e., stakeholders who can provide an overview on sustainability issues and innovations). In the second step, stakeholders (i.e., experts and innovators) who have been identified in the first research step are asked for an interview. The individual

interview process results in two different kinds of CLDs: experts build CLDs that show the sustainability issues and point to innovations that might address them; and innovators build CLDs that provide insight into the opportunities and issues of particular innovations, and promising approaches to foster the implementation of innovations. The resulting CLDs are interpreted by using the multi-level learning framework (see Halbe et al., submitted). The analysis of CLDs start with the identification of problem variables in each diagram, which represent learning objects. The next step involves the analysis of learning intensities (i.e., learning objects are linked to routine learning, reframing or paradigm change) and learning contexts (i.e., learning objects are related to a social unit). Factors that support learning are subsequently identified in the CLDs that were added to the CLDs by asking the interviewee for solution strategies. In addition, impeding learning factors are identified that are barriers towards a successful implementation of solution strategies. Various roles of actors in the implementation of supportive learning factors or avoidance of impeding factors are analyzed based upon information from stakeholders or a general literature review.

A systematic literature review has been conducted to complement learning factors perceived by stakeholders with general learning factors from the scientific literature All empirical information has been sorted into the categories of the conceptual multi-level learning framework and sorted according to learning contexts. Descriptive coding has been applied to consolidate learning factors at two different levels of abstraction (i.e., main categories and one level of sub-categories). Each factor has been qualified as being a supportive (abbreviation: Sup), impeding (Imp) or ambiguous (Sup/Imp) factor in learning processes. In addition, the factor's susceptibility to purposeful change is rated on an ordinal scale from endogenous (i.e., the factor can be directly influenced by learning processes within the respective context) to ambiguous (i.e., susceptibility unclear) and exogenous (i.e., factor cannot be influenced). The review resulted in a long list of learning factors for each learning context. Some factors comply across learning contexts (e.g., disturbance or crisis as a supportive learning factor). Thus, these factors can be critical for foster learning at multiple societal levels.

The purpose of the next step of the methodology is the design of learning processes that address case-specific learning objects. In the design of these learning processes, supportive and impeding learning factors are considered in order to facilitate effective and sustainability-directed learning processes. The Management and Transition Framework (MTF) is applied for ex-ante planning of learning processes including participating actors and aspired outcomes (cf. Halbe et al., 2013). Two distinct perspectives on transition governance are supported by the methodology: a) a structural view that reveals the structure of the transition governance system at a specific point in time, and b) a temporal view on transition governance that reveals the governance process over time. The structural analysis method allows for a systematic analysis, visualization and design of interactions between and among learning contexts. The temporal analysis of transition governance processes can be used as a collaborative tool that allows for context-specific design of transition pathways.

Three case studies in Canada, Cyprus and Germany have been selected to test and iteratively develop the methodology described above.

Results

The results for each case study reveal that there are learning objects (i.e., learning requirements) in all learning contexts, which underscores the importance of multi-level learning in sustainability transitions, ranging from the individual to the group, organizational and policy levels. Most learning objects in the Canadian and Cypriot case studies are related to the organizational learning context, while the German case study includes most learning objects in the context of individual learning. Given that learning objects are linked to sustainability issues and thus represent a learning requirement (cf. Halbe et al., 2015a), sustainability transitions in the food system in Ontario and the WEF nexus in Cyprus have to predominantly foster learning in organizations, including farming businesses, processing and distribution facilities and public organizations. In the case study on the refurbishment of space heating systems in Germany, learning is mainly required in the individual context, i.e., individual owners of residential property (e.g., with respect to deciding for or against an energetic refurbishment) and residents (e.g., with respect to energy consumption practices).

The numbers of learning factors (i.e., potential intervention points) generally correspond to the number of learning objects (i.e., a large number of learning objects implies a large number of learning factors). Actors have various opportunities to actively facilitate societal transformations towards sustainable development either directly through actions at their particular societal levels (i.e., context-internal learning) or indirectly through actions that influence learning at other societal levels. In fact, most of the learning factors require cooperation across learning contexts during the implementation process. The comparing of learning factors across case studies underline the importance of several factor categories, such as '*physical* a '*disturbance or crisis'*, '*information and knowledge'*. Of the 206 factors identified by stakeholders, 40 factors are case-specific and not contained in the general, review-based factor list. This underscores the value of participatory research, as general, top-down analyses might have overlooked these case-specific factors.

Across all case studies, organizations have the largest role in the realization of learning factors. In the Cyprus and German cases, policy-makers come second, while in the Canadian case group actors are slightly more in number than policy actors. Individuals have a smaller role in the implementation of learning factors in the Canada and Cyprus case; in the German case, individuals come are in third place. Nevertheless, individuals are involved in the implementation of more than 30% of learning factors in all case studies, which shows that individual actions still have an important role.

In general, the Canadian and Cyprus case studies show several similarities in the distribution of learning objects, factors and roles across learning context. The German case differs though with respect to the relatively high number of learning objects and factors in the individual learning context, and comparatively low number of learning objects and factors in the policy context. This can be explained through the already high level of effort in and commitment of policy-actors in Germany to energy transition. Thus, requirements for learning and interventions in the policy learning contexts are relatively low as perceived by stakeholders in the German case study. In contrast, the sustainability transitions in Cyprus and Canada are fostered more by bottom-up processes, and thus require more substantial changes at the policy level.

Discussion and conclusions

Research Question 1: How can multi-level learning in transformation governance processes be conceptualized?

The multi-level learning framework conceptualizes learning at different societal levels as specific learning contexts ranging from individual and group contexts to organizational and policy contexts. The conceptual framework further differentiates between learning processes, intensity, objects, outcomes, subjects and factors, allowing for a more detailed analysis of learning within and across learning contexts. Thus, learning contexts can be linked by processes that involve actors from different learning contexts (e.g., community groups and policy-makers), as well as exchanges of physical aspects, institutions and knowledge (in the form of 'learning factors'). A methodology has been developed based upon the conceptual framework that allows for the analysis and design of multi-level learning processes in specific case studies. In addition, the multi-level learning framework structured a systematic literature review that identified several factors that can support and impede learning across contexts.

Research Question 2: How can actors actively facilitate societal transformations towards sustainable development in specific regional contexts?

The methodology presented in this dissertation allows for the identification and analysis of case-specific intervention points for sustainability transitions at multiple societal levels. The methodology furthermore permits the analysis of interplay between individual, group, organizational and policy actions, which is a first step towards their coordination. The focus on sustainability innovations links the broad topic of sustainability transitions to a set of opportunities for practical interventions and overcoming their implementation barriers. The results demonstrate that all societal levels play an important role in sustainability transitions. Individuals, groups, organizations and policy actors can support sustainability transitions in a self-reliant way (i.e., endogenous factors). Most learning factors however require cooperation between actors from different societal levels. The methodology presented allows for the analysis and design of these interlinkages between learning contexts. While the methodology cannot provide any 'silver bullets' for inducing sustainability transitions, it is flexible enough to identify an appropriate abstraction level for analyzing and designing transition governance processes.

Research Question 3: What role can modeling play in the governance of transition processes?

This research has provided a classification of model uses in transition research (Halbe et al., 2014) that supports a purposeful discussion of the opportunities of modeling and promising future research directions. Halbe and Ruutu (2015) identify various participatory modeling methods that can be applied in the different phases of transition governance processes. The methodology developed in this doctoral research provides several contributions for the development of participatory modeling methods in transition research. Thus, the participatory method supports an integrated analysis of barriers and drivers of sustainability innovations, and allows application in practice and education. The temporal analysis and design of transition governance processes can also be applied in a participatory setting, which supports the proactive planning as well as monitoring of transition processes.

Limitations and future research opportunities

The conceptual multi-level learning framework should not be considered as a meta-theory of multi-level learning, but more as an approach to systematize and consolidate findings and guide transition governance processes in its attempts to organize effective interventions. Due to the more integrative nature of the framework, some aspects can be further specified and included in more detail in future research. Another limitation of this research is the qualitative nature of case study results which do not allow for a priorization of measures or an assessment of the effectiveness of interventions. Future research can include the application of the methodology in a larger research project that allows for an in-depth stakeholder analysis, an integrated assessment of sustainability innovations, and close involvement of stakeholders in the analysis and design of transition governance processes. The empirical basis of transition governance processes should be broadened in future research by using the developed conceptual and methodological frameworks for process design and evaluation. Finally, even though the analysis is considered as a good compromise between complexity and simplicity (as simple as possible, but as complex as needed), further visualization methods might be needed to support its widespread application.

Concluding remarks

The concepts and methods developed in this research project allow for reflection on transition governance processes from a systemic viewpoint. Experiences in the case studies underline the applicability of the concepts and methods developed for the analysis of case-specific transition governance processes. Despite substantial differences in the geographic location, culture and topics addressed, all case studies include promising sustainability innovations and the engagement of multiple actors in their implementation. The diversity and multitude of initiatives in the case study regions provides an optimistic outlook on future opportunities for large-scale sustainability transitions.

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Abbreviations

BAFA	Bundesamt für Wirtschaft und Ausfuhrkontrolle (Federal Office for Economic Affairs and Export Control)
BEI	Bremer Energie Institut
BGB	Bürgerliche Gesetzbuch (civil code of Germany)
BMUB	Bundesministerium für Umwelt, Naturschutz, Bau und Reaktorsicherheit (Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety)
BMVBS	Bundesministerium für Verkehr, Bau und Stadtentwicklung (Federal Ministry of Transport, Building and Urban Development)
BMWI	Bundesministeriums für Wirtschaft und Energie (Federal Ministry for Economic Affairs and Energy)
CLD	Causal loop diagram
CO_2	Carbon dioxide
EC	European Commission
EEA	European Environment Agency
EEWärmeG	Renewable Energies Heat Act
EEWRC	Energy, Environment and Water Research Center (Cyprus Institute, Nicosia)
EnEV	Energieeinsparverordnung (Energy Saving Regulation)
EU	European Union
FAO	Food and Agriculture Organization of the United Nations
GDP	Gross Domestic Product
IWU	Institut Wohnen und Umwelt
KFW	Kreditanstalt für Wiederaufbau (Promotional bank of the Federal Republic of Germany)
LANUV	Landesamt für Natur, Umwelt und Verbraucherschutz Nordrhein-Westfalen (State Agency for Nature, Environment and Consumer Protection)
MEA	Millenium Ecosystem Assessment
MTF	Management and Transition Framework
NGO	Non-governmental organization
NRW	North Rhine Westphalia
R&D	Research and Development
SDG	Sustainable Development Goal
UN	United Nations

UNDP	United Nations Development Programme
UNFCCC	United Nations Framework Convention on Climate Change
USA	*United States* of America
VTT2	Vásárhelyi Terv Továbbfejlesztése (Hungarian flood management policy)
WBGU	Wissenschaftliche Beirat der Bundesregierung Globale Umweltveränderungen (German Advisory council on Global Change)
WEF nexus	Water-Energy-Food nexus
WDD	Water Development Department
WVS	World Values Survey

1. Introduction

Increasing pressures on the Earth System suggest that profound transition in our society is required – either in form of a forced transition after abrupt global environmental change (cf. Rockström et al., 2009) and collapses in infrastructure (Broto et al., 2014), or a more pro-active societal transformation process (Smith et al., 2005). Over the last few decades, various scholars have pointed to the limits to growth (Meadows et al., 2004) and the need to reduce the material requirements of societies (cf. the Factor four concept, von Weizsäcker et al., 1995). Despite increasing evidence of the unsustainability of our contemporary way of life and the analysis of multiple solution strategies, only little progress has been made in reducing material consumption and environmental pollution from a global perspective. For instance, global anthropogenic greenhouse gas emissions are increasing (IPCC, 2007, 2014) and other challenges (e.g., fertilizer use or soil erosion) are becoming 'gigaton problems' (Xu et al., 2010).

The field of transition research has developed in the last decade in order to understand the lock-in of contemporary societies in an unsustainable regime (Holtz et al., 2008; Smith et al., 2010). A 'regime' is a coherent and dynamically stable system of technological, institutional, economic, social, cognitive and physical elements for the provision of societal functions (e.g., energy or water supply) (Holtz et al., 2008). The regime's dynamic stability implies that regime elements are only changing incrementally. Radical innovations face substantial barriers such as restrictive regulations, lacking finance and infrastructure, or incongruous user preferences (Holtz et al., 2008). Nevertheless, regime transformations are possible due to pressures from broad societal challenges and crises, such resource scarcity, natural disasters or market crises (cf. Karadzic et al., 2014). Besides these top-down pressures, innovations can also lead to structural changes in regimes from the bottom-up (e.g., the transition town movement, cf. Seyfang and Haxeltine, 2012).

The multi-level perspective is a conceptual framework that describes the interactions among three aspects: the regime, broader societal developments that cannot be addressed in the short run (called 'landscape') and socio-technical innovations that provide alternatives for the provision of societal functions (called 'niches') (Geels, 2002, 2004, 2011). Different transition pathways can emerge depending on the strength of landscape pressures, regime strength as well as the comparative advantage and maturity of niche innovations. Thus, landscape pressures can induce: (1) an adjustment of a regime by incumbent actors without changing its basic structure (transformation pathway); (2) an uptake of symbiotic innovations in the regime as 'add-ons' (reconfiguration pathway); (3) a replacement of the regime as a result of a breakthrough in innovations (technological substitution pathway); or (4) a disintegration of the regime followed by an initial co-existence of innovations before a new regime emerges (de-alignment and re-alignment pathway) (cf. Geels and Schot, 2007). There are several examples of past transitions that help to illustrate the dynamics of transition pathways (Geels and Schot, 2007), such as a 'transformation' from cesspools to sewer systems (Geels, 2006a), 'reconfiguration' from traditional factories to mass production (Geels 2006b), 'technological substitution' of steamships by sailing ships (Geels, 2002), and 'de-alignment and re-alignment' in the transition from horse-drawn carriages to automobiles (Geels, 2005a). In practice, ongoing transitions usually to not follow the aforementioned ideal-typical transition pathways, but might overlap or emerge in combination (Augenstein, 2015). For instance, the diffusion of transdisciplinary sustainability research into the German science system can be understood as a combination of 'transformation' and 'reconfiguration' pathways (Schneidewind and Augenstein, 2012). As another example, Vandermeulen et al. (2012) analyzes the transition towards a bio-based economy that starts with a 'transformation' and evolves into a 'technological substitution' or 'de- and re-alignment' pathway (Vandermeulen et al., 2012).

The German Advisory Council on Global Change (WBGU) distinguishes between 'transformation research', which is a new scientific discipline that focuses on the understanding of past and current transformation processes, and 'transformative research', which actively promotes transformations through innovations (WBGU, 2011, 2012). Transformative research requires methodological frameworks for proactive and participatory facilitation of sustainability transitions in general, and pertinent socio-technical innovations in particular. Reflexive governance approaches (Voss et al., 2006), including transition management (Loorbach, 2007) and adaptive management (e.g., Holling 1978), address such methodological demands. Reflexive governance transcends the notion of policy makers steering a system in a desirable direction using a command-and-control approach (Kemp and Loorbach, 2006). Adaptive management is a specific design of a reflexive governance process (cf. Voss and Bornemann, 2011), which particularly deals with managing change in social-ecological systems towards sustainability. Transition management is a reflexive governance approach that aims "at long-term transformation processes that offer sustainability benefits" (Kemp and Loorbach, 2006, p. 103). Transition management considers the importance of network governance, long-term collective goals, innovation, and learning in sustainability transitions (Loorbach, 2007). Foxon et al. (2008, 2009) considers adaptive and transition management as complementary approaches to understand and handle the complexity of transformation processes.

In addition to conceptual and methodological frameworks, analyzing and actively promoting transformation processes also requires analytical methods to handle the complexity resulting from multi-domain interactions, path dependency, drivers and self-reinforcement of change and multi-level processes (Holtz, 2011; Halbe et al., 2015c). Modeling approaches have several beneficial characteristics to address complexity and ambiguity of transitions, as specified by Holtz et al. (2015): Models are (1) *explicit and clear* with regard to underlying assumptions of system structures and processes, as well as (2) *systematic* with respect to the process of knowledge integration. Conceptual modeling, such as systems thinking, is particularly suitable for developing a common language during participatory system analysis (Halbe et al., 2015c; Holtz et al., 2015). Dynamic models also allow for (3) *inferences of complex system dynamics* that might not be intuitive due to multi-causality, feedback or time delays. Finally, dynamic models can (4) *facilitate systematic experiments* that might be impossible, impractical or unethical in a real system. Agent-based and system dynamics models are widely applied modeling approaches in transition studies, as they address core characteristics of transitions (cf. Halbe et al., 2015c). Thus, agent-based models allow for the analysis of emergent phenomena through multi-level interactions (e.g., Köhler et al., 2009) or path-dependencies due to lock-ins (e.g., Safarzinska and van den Bergh, 2010). System dynamics modeling is particularly suitable for analyzing multi-domain interactions as well as delay and feedback processes (e.g., Yücel, 2010) (cf. Section 2.3 for more details on transition modeling).

1.1 Definition of key terms and research gaps

The previous section has demonstrated the multiplicity of key terms that are used in transition research. This doctoral dissertation does not make a clear distinction between the terms of ‘transition’ and ‘transformation’. The term ‘transition’ is used in reference to a sustainability goal and the field of socio-technical transition research and ‘transformation’ refers to a process of fundamental change. The term ‘governance’ is understood to embrace the full complexity of multi-actor processes in the policy formulation and implementation (Pahl-Wostl, 2009). Governance of transformations accordingly points to the interaction process of multiple actors in societal transformation. The term ‘transition governance’ is used synonymously with this but places more emphasis on the normative goal of sustainability. The specific sustainability outcomes of the governance process cannot be controlled or pre-determined but emerge through the interactions of multiple actors (who hold different interests and perspectives) and context conditions (e.g., available funding and knowledge). Transition governance acknowledges the diversity of perspectives, intervention points and responsibilities at multiple societal levels supporting a sustainability transition.

There are currently a number of conceptual and methodological limitations that impede the effective facilitation and steering of sustainability transition. From a conceptual point of view, transition governance requires a concise understanding of the interlinkages between processes of change at multiple societal levels. Learning processes among actors ranging from individuals to high-level governmental organizations have to interact in order to induce regime transformation (Pahl-Wostl, 2009). Learning processes form the foundation of several key dynamics of transitions, including innovation processes (e.g., Carlsson and Stankiewicz, 1991; Bergek et al., 2008) as well as niche formation and development (e.g., Kemp et al., 1998; Geels 2005b). Despite the importance of learning, the underlying learning theory and mechanisms are often not explicitly discussed in transition research (cf., Beers et al., 2014) and even poorly defined (van Mierlo et al., 2010). The transition literature does not specify how exactly learning takes place and how learning processes can be supported (van de Kerkhof and Wieczorek, 2005). In particular, a differentiated understanding of learning is needed to facilitate sustainability transitions in a pro-active way (cf., Voss et al., 2006; Loorbach 2007). Van de Kerkhof and Wieczorek (2005) provide a narrative review that takes a first step towards understanding learning in transition governance processes. However, a comprehensive conceptualization of learning in sustainability transitions is currently lacking.

From a methodological point of view, methodologies are lacking that allow for the initiation and case-specific design of transition processes. The transition management approach includes integrated systems and stakeholder analysis in an "expert preparation phase", with the intention of providing a factual basis for the issue and selection of 10 to 15 stakeholders (Loorbach, 2007). However, a low numbers of stakeholders at the outset of the process might constrain the problem and solution perspectives. From a transition governance perspective, a sustainability transition might require broader engagement processes at various societal levels. In particular, the role of transition managers is considered a critical aspect of the transition management approach, as this small group of initiators can heavily influence the definition of the problem and selection of solution strategies (Shove and Walker, 2007; Genus and Coles, 2008). A lack of clear procedural rules can furthermore result in less democratic legitimacy, for instance by allowing powerful incumbents to influence policy design (Voss et al., 2009). In addition, the terminology of transition management can be too abstract for certain stakeholders (Avelino and Bressers, 2008), which can constrain their active participation. Thus, tangible methods for the analysis and design of transition governance processes are needed that specify case-specific intervention points and roles of actors for the pro-active facilitation of sustainability transitions at multiple societal levels.

A further research gap is related to the limited attention of transition modelers to the application of participatory modeling approaches in transition research (Holtz et al., 2015). Transition governance processes, involving multiple actors and normative goals, can be facilitated by participatory modeling to support communication and learning. Models can reveal diverging stakeholders' perceptions and values and thereby support a constructive discussion process (cf. Brugnach and Pahl-Wostl, 2007). Despite this high potential, there are only a few participatory modeling applications that explicitly refer to transition research (e.g., Trutnevyte et al., 2011, 2012). There is an extensive body of literature on the application of models to facilitate stakeholder processes in transition-related research areas of social-ecological modeling, integrated assessment and environmental modeling. A review of these experiences is required to assess the applicability of participatory modeling approaches in transition governance processes.

Based upon these research gaps, three research questions and objectives are specified in the following section that are addressed in this doctoral research.

1.2 Research questions and objectives

The overall goal of this doctoral research has been the development of concepts and methods for analyzing and designing transition governance processes in specific case studies. This requires the specification of solution strategies, implementation barriers and roles of actors at different societal levels. The aforementioned research challenges and gaps are translated into three specific research questions:

- **Research Question 1**: How can multi-level learning in transformation governance processes be conceptualized?

  This research question points to the need for a conceptualization of societal learning processes in sustainability transitions, comprising processes of individual, group, organizational and policy learning.

- **Research Question 2**: How can actors actively facilitate societal transformations towards sustainable development in specific regional contexts?

  Sustainability transitions have to consider the local/regional context and engage stakeholders in the process of change. In fact, a more regional provision of societal functions (e.g., supply of food, energy and water) can result in several sustainability benefits, such as the avoidance of externalities along global value chains, and a potentially higher consumer awareness and knowledge of the supply system. In contrast to an abstract national perspective on sustainability transitions, a more regional perspective supports the direct engagement of stakeholders in sustainability transitions by allowing tangible actions.

- **Research Question 3**: What role can modeling play in the governance of transition processes?

  Several studies have shown that models can play an important role in dealing with the complexity and ambiguity of transition processes. However, modeling of transition governance processes faces peculiar challenges, which have not yet been explored in a systematic way. For instance, modeling results need to be understandable for stakeholders comprising policy-makers and engaged citizens, among others, to assure tangible benefits from modeling activities

Transitions towards sustainable water, food and energy supply systems have been chosen as specific application areas for this doctoral research, as these systems are intended to meet basic needs that are fundamental for the provision of further societal functions (see Section 3.4 for more details). The aforementioned research questions are further specified and translated into three specific objectives of this research:

- **Objective 1:** Develop and apply a conceptual framework to understand societal transformations towards sustainable water, energy and food systems as multi-level learning processes.
- **Objective 2:** Develop and apply a methodological framework to analyze and actively facilitate transition governance processes.
- **Objective 3:** Analyze the opportunities of a modeling approach to be applied in transition governance processes.

The following section presents the original research papers that form the foundation of this dissertation as well as their link to the research objectives.

1.3 Articles related to this dissertation

Eight articles have been published in the scope of this doctoral dissertation, seven lead-authored articles, and one co-authored article. In all lead-authored articles, the core part of the study design, data collection and data analysis were conducted by the author of this dissertation. Furthermore, the author of this dissertation produced the first draft of each manuscript and revised the manuscript based upon comments from co-authors.

In this section, a list of articles is provided along with a short description of contributions from co-authors. The articles are linked with the research objectives, as explained after the list of articles. The lead-authored articles are different in status and type, including four articles *published* in peer-reviewed scientific journals, one article *submitted* to a peer-reviewed scientific journal, one article *to be submitted* to a peer-reviewed scientific journal and one published international *conference paper*.

<u>Lead-authored articles:</u>

- **Article 1**: Halbe, J. C. Pahl-Wostl, G. Scholz, H.Thomsen, J. Vinke-de Kruijf and U. Scheidewind, submitted. Learning in the governance of sustainability transitions – A systematic review. Research Policy.

  <u>Contribution from main author</u>: Study idea, study design, data collection (i.e., literature review: ~50% of articles), data analysis, manuscript preparation and revision.

  <u>Contributions from co-authors</u>: C. Pahl-Wostl, G. Scholz, H. Thomsen, J. Vincke-de Kruijf contributed to the literature review (~50% of articles); all co-authors contributed to the revisions of the study design, conceptual framework and manuscript.

- **Article 2**: Halbe, J., Pahl-Wostl, C., Lange, M. A., and Velonis, C., 2015a. Governance of transitions towards sustainable development – the water–energy–food nexus in Cyprus. *Water International* 40(5-6), 877-894. http://doi.org/10.1080/02508060. 2015. 1070328

  <u>Contribution from main author</u>: study idea, study design, data collection, data analysis, preparation of manuscript and manuscript revision.

  <u>Contributions from co-authors</u>: C. Pahl-Wostl was involved in the revision of the study design; M. A. Lange supported the empirical work by establishing contacts to key actors in Cyprus; C. Pahl-Wostl and M. A. Lange contributed to the revision of the manuscript; C. Velonis contributed to the application of the Viability Loops concept and provided some empirical data from literature in Greek language.

- **Article 3**: Halbe, J., Pahl-Wostl, C., Sendzimir, J., and Adamowski, J., 2013. Towards adaptive and integrated management paradigms to meet the challenges of water governance. *Water Science and Technology*, *67*(11), 2651–2660. http://doi.org/10.2166/wst.2013.146

Contribution from main author: Study idea, study design, data collection, data analysis, preparation of manuscript and manuscript revision.

Contributions from co-authors: C. Pahl-Wostl was involved in the revision of the study design; all co-authors contributed to the revision of the manuscript.

- **Article 4:** Halbe, J. C. Pahl-Wostl and U. Scheidewind, to be submitted. Analysis and design of case-specific transition governance processes. Ecology & Society.

  Contribution from main author: Study idea, study design, data collection, data analysis, preparation of manuscript and manuscript revision.

  Contributions from co-authors: C. Pahl-Wostl was involved in the revision of the study design; C. Pahl-Wostl and U. Scheidewind contributed to the revision of the manuscript.

- **Article 5:** Halbe, J., J. Adamowski and C. Pahl-Wostl, C., 2015b. The role of paradigms in engineering practice and education for sustainable development. Journal of Cleaner Production 106, 272-282. http://dx.doi.org/10.1016/j.jclepro.2015.01.093.

  Contribution from main author: Study idea, study design, data collection, data analysis, preparation of manuscript and manuscript revision.

  Contributions from co-authors: J. Adamowski and C. Pahl-Wostl contributed to the revision of the study design and the revision of the manuscript.

- **Article 6**: Halbe, J., D. E. Reusser, G.Holtz, M. Haasnoot, A. Stosius, W. Avenhaus and J. Kwakkel, 2015c. Lessons for model use in transition research: A survey and comparison with other research areas. Environmental Innovation and Societal Transitions 15, 194-210. http://doi.org/10.1016/j.eist.2014.10.001

  Contribution from main author: Study idea and study design (with support from co-authors as specified below); literature selection and analysis for Sections 2.2, 2.3, 3.2, and 3.3; preparation of comprehensive manuscript and its revision.

  Contributions from co-authors: D. E. Reusser contributed to the study idea (equal contribution to main author); D. E. Reusser and G. Holtz were involved in the design of the article (equal contributions to main author); D. E. Reusser organized the involvement of the transition modeler community (STRN) in the literature selection; D. E. Reusser and G. Holtz provided major contributions to drafting Sections 2.1 (~50 %) and 3.1 (~ 80%); all co-authors contributed to the revision of the manuscript.

- **Article 7**: Halbe, J. and R. Sampsa, R., 2015. Use of participatory modeling in transition governance processes. International Sustainability Transitions Conference 2015, Brighton, UK.

  Contribution from main author: Study idea, study design, preparation of manuscript and manuscript revision.

Contributions from co-author: Paragraph on modeling in foresight and operational research; revision of study design and manuscript

Co-authored article:

- Holtz, G., F. Alkemade, F. de Haan, J. Köhler, E. Trutnevyte, T. Luthe, J. Halbe, G. Papachristos, E. Chappin, J. Kwakkel, S. Ruutu, 2015. Prospects of modelling societal transitions: Position paper of an emerging community. Environmental Innovation and Societal Transitions 17, 41-58. doi: 10.1016/j.eist. 2015.05.006

  Contribution from J. Halbe: Drafting of section on participatory modeling in transition research (Section 6.3.1), and contributing to the revision of the manuscript.

Figure 1 displays the linkages of articles to the three dissertation objectives. The development and application of a conceptual learning framework (**Objective 1**) is accomplished in Article 1 (Halbe et al., submitted). The development and application of a methodological framework for the analysis and design of transition governance processes (**Objective 2**) is accomplished in Articles 2-5. Article 2 provides a method for the analysis of case-specific requirements for the implementation of sustainability innovations (Halbe et al., 2015a). Article 3 presents a method for the analysis and design of transition governance processes (Halbe et al., 2013). Article 4 synthesized the methods from Articles 1-3 into an overall methodology for the case-specific design of transition governance processes (Halbe et al., to be submitted). Article 5 proposes a teaching approach in higher education to sensitize students to the role of paradigms in sustainability issues by using the method developed in Article 3 (Halbe et al., 2015b). The role of modeling in transition governance processes (**Objective 3**) is analyzed in Articles 6 and 7, as well as in a co-authored article. Article 6 presents a conceptual framework of different model uses in transition research, including the model use for facilitation stakeholder processes, and provides a review of experiences in other related research areas (Halbe et al., 2015c). Article 7 offers a review of participatory modeling methods and tools assigned to different phases in transition governance processes (Halbe and Ruutu. 2015). Finally, the co-authored article is conceived as a position paper from the “transition modelers community” aimed at presenting the various benefits of a modeling approach in analyzing and facilitating sustainability transitions, including the promising role of participatory modeling approaches (Holtz et al., 2015).

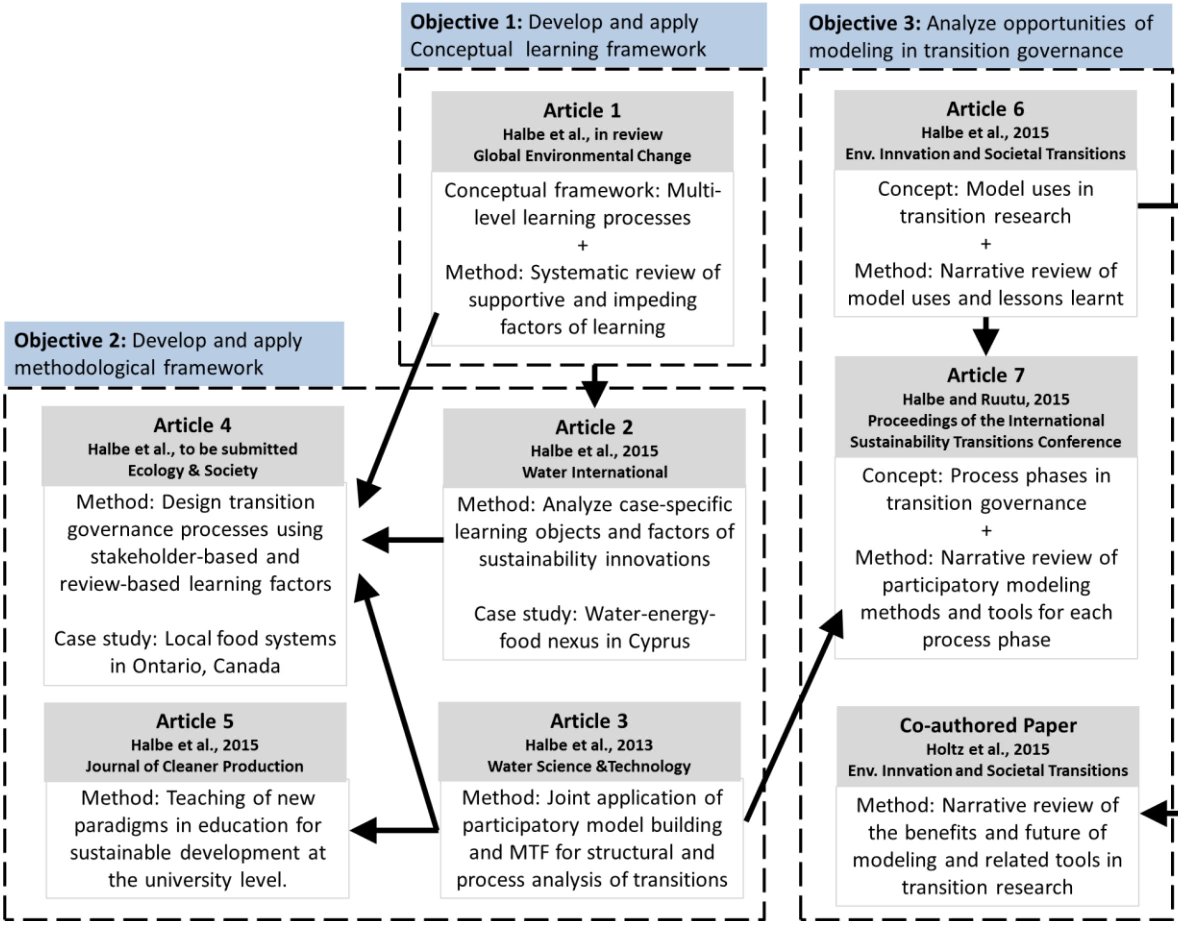

Figure 1: Overview of and linkages between articles comprising this doctoral dissertation sorted according to objectives addressed.

1.4 Structure of doctoral dissertation

Figure 2 shows how the objectives and articles are translated into the structure of this doctoral dissertation. First, Section 2.1 provides an overview of transition governance approaches (based upon Article 6) as well as a conceptualization of different process phases (Article 7). A conceptual framework of multi-level learning processes in sustainability transitions (Article 1) is presented in Section 2.2. Section 2.3 provides a conceptualization of model uses in transition research (Article 6), and a review and assessment of participatory modeling methods with regard to their application in transition governance processes (Article 7). In addition, a problem-based learning approach is presented to teaching participatory model building at the university level (Article 5).

Section 3 presents the methodological contributions of this research. Section 3.1 presents a systematic review of supportive learning factors from the general literature that specify intervention points for facilitating sustainability transitions (Article 1). Section 3.2 introduces a participatory modeling approach that allows for the identification of case-specific learning factors (Articles 2 and 4). Section 3.3 presents a method for the analysis and design of transition governance processes (Articles 3 and 4) that builds upon a synthesis of learning factors from the systematic literature review and the participatory modeling method.

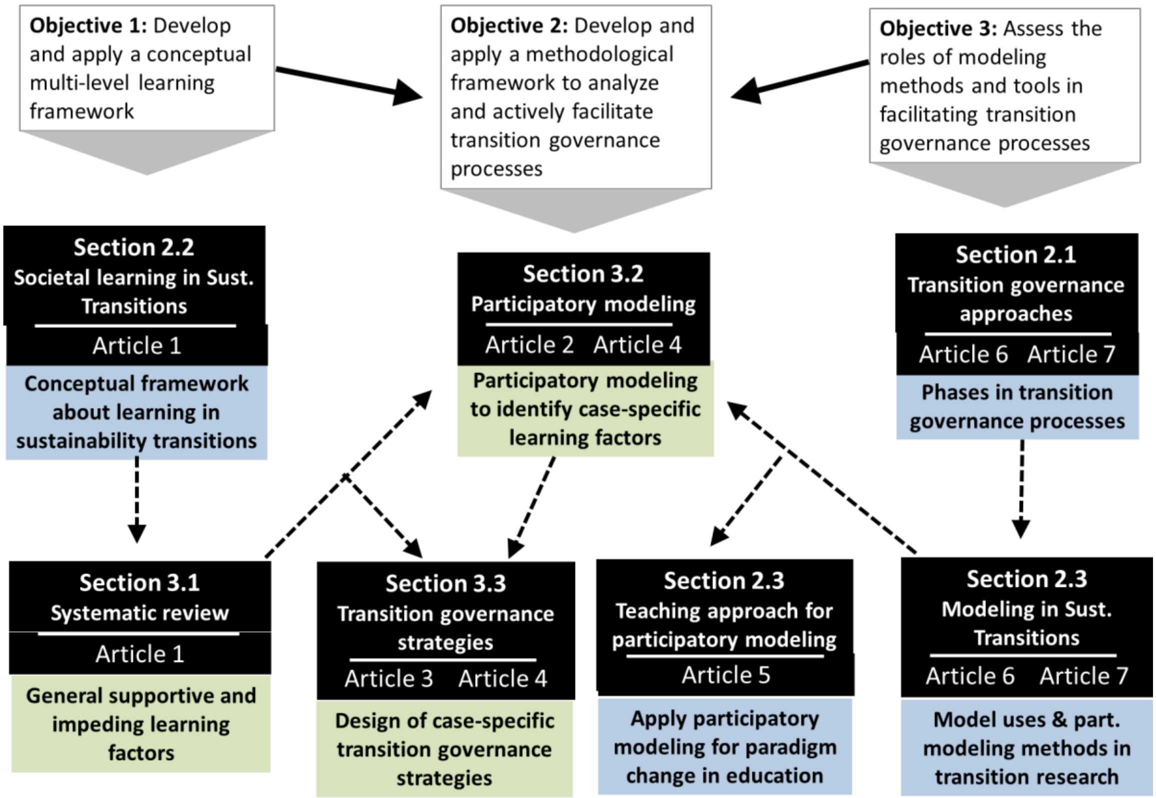

Figure 2: Structure of doctoral research based upon research objectives and related articles. Conceptual contributions are the blue-shaded boxes, and methodological contributions are the green-shaded boxes

Section 3.4 includes the selection and design of three case studies in Canada, Cyprus and Germany. Section 4 presents the application of the methodology in the three case studies and provides a synthesis of results. Case study results have been partly included in the articles presented (see Figure 1). Results from the Canadian case study are included in Article 4, while results from the Cyprus case are described in Article 2. Section 5 provides a general discussion and a succinct summary of key conclusions for each research question. In addition, Section 5 includes a critical reflection on conceptual and methodological contributions and a discussion of promising future research avenues.

2 Theory and Concepts

Transition research has to deal with the complexity of sustainability transitions. This complexity is apparent in the core characteristics of transitions (Holtz, 2011): First, transitions involve **multiple domains** (e.g., production, consumption, regulation, and civil society) that are interconnected in co-evolutionary processes (e.g., Yücel, 2010). Second, regimes typically have developed over time and constitute a dynamically stable system. A regime's historical development is thus represented in the regime's structure and which creates **path-dependency**. This tends to favor incremental as opposed to radical change (e.g., Rip and Kemp, 1998). Third, there are also **drivers of change and self-reinforcing mechanisms** that can induce instability and make transitions possible. The interconnectedness of regime elements and the non-linearity of processes within the regime provide the potential for the self-reinforcement of change once it has been induced (e.g., through pressures from the landscape or niches, e.g., de Haan, 2008). Fourth, transitions involve **multiple levels** ranging from the micro-scale (e.g., behavior of individuals) to the macro-scale (e.g., national and international institutions) that interact in co-evolutionary processes (Safarzynska et al., 2012).

The governance of transitions requires the consideration of the following further relevant characteristics of transitions (Halbe et al., 2015c): First, transitions usually **involve a variety of actors** from multiple domains. These actors may stabilize current regimes (e.g., actors from the incumbent regime) or challenge them (e.g., niche actors) (e.g., Augenstein, 2015). Second, 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). Finally, transition research also addresses **normative elements** through the consideration of desired system states (e.g., a sustainable energy system). Goals and visions of different actors, such as politicians and interest groups, need to be considered in transition governance (e.g., Trutnevyte et al., 2011).

As this dissertation develops concepts and methods for an active governance of transitions, existing governance frameworks are introduced and compared in the following section (Section 2.1). In Section 2.2, a conceptual framework of multi-level learning for transition governance is presented. Finally, Section 2.3 provides a conceptualization of model uses in transition research and an overview of suitable participatory modeling approaches in different steps of transition governance processes. In addition, Section 2.3 presents experiences in the teaching of participatory modelling at the university level.

2.1 Transition governance approaches

In this doctoral dissertation, the term 'transition governance' is used as an umbrella term for the steering of sustainability transitions, which requires the engagement and coordination of multiple actors in the absence of a primary subject of steering. 'Reflexive governance' is a broad governance approach addressing the challenges of complexity, ambiguity and distributed control in sustainable development (Voss and Kemp, 2006). 'Transition management' has a more specific focus on steering socio-technical sustainability transitions, while 'adaptive management' is intended to increase the resilience of social-ecological systems (Voß and Bornemann, 2011). In the following sections, these different governance approaches are defined and compared in order to specify the transition governance approach applied in this dissertation.

2.1.1 Reflexive Governance

Reflexive governance developed against the background of increasing disappointment with the limited practical success of sustainability strategies (Voss and Kemp, 2006). Voss and Kemp (2006) describe five reflexive governance strategies: First, *integrated knowledge production* refers to inter- and transdisciplinary research that integrates knowledge from different disciplines and stakeholders. Second, *experiments and adaptivity of strategies and institutions* means that solution strategies and related institutions have to be considered as experiments which need to be monitored continuously. Third, *anticipation of long-term systemic effects* can be accomplished through participatory scenario development in order to reveal undesired side-effects. Fourth, *iterative and participatory goal formulation* must 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. Fifth, *interactive strategy development* draws upon the resources and influence of various stakeholders. A collective action strategy has to be developed that coordinates the actions of actors who might have diverse interests.

2.1.2 Transition Management

Transition management is a specific reflexive governance approach that provides pro-active facilitation of socio-technical sustainability transitions (Voß and Bornemann, 2011). Transition management comprises different activity clusters that form a transition management cycle (Loorbach 2007, 2010): strategic, tactical, operational and evaluation activities. The *strategic activity cluster* includes participatory problem structuring to find a common language between actors and a shared conceptualization of the system at hand. This allows for the development of sustainability visions which are inspiring pictures of the future. Strategic activities usually start with a group of innovative individuals who are thinking and acting outside of conventional boxes. The *tactical activity cluster* introduces organizations, businesses, NGOs and others who are able to further promote and specify sustainability visions. This involves the development of concrete transition images (e.g., for public transport or solar energy) which together fit into the overall sustainability vision. Transition paths are specified which are a series of 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 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 continuously assess and adapt actions.

2.1.3 Adaptive Management

Adaptive management demands an integrated and multidisciplinary approach to reducing surprising side-effects and unintended outcomes of management actions, but it also assumes that surprises are inevitable due to complexity (Holling 1978). Thus, adaptive management builds upon a reflexive and experimental approach that allows for continuous learning from past actions (Lee 1999; Berkes et al. 2002; Pahl-Wostl 2007). Various adaptive management frameworks are available that share several commonalities but use different terminology (Plummer, 2009). Pahl-Wostl (2008) provides a general AM framework that distinguishes five steps in an iterative adaptive management cycle, all of which require strong stakeholder participation and transparent decision-making: (1) *Problem definition and goal setting* that takes multiple perspectives into account; (2) *Policy formulation* through scenario analysis to assess policy performance under different possible futures; (3) *Policy implementation* that considers the correctability of decisions; (4) *Monitoring and evaluation* that includes different kinds of knowledge; (5) *Policy assessment* that is accomplished in a transparent way. Other adaptive management frameworks include the setting of alternative issue-specific hypotheses in the problem definition phase which are later tested through management actions (Allen and Gunderson, 2011). Adaptive co-management also highlights the importance of horizontal and vertical integration in resource governance systems (Armitage et al., 2008) in order to cooperate and coordinate stakeholder actions (Olsson et al., 2004a). This requires the conscious and continuous analysis and assessment of stakeholder participation throughout the process (Foxon et al., 2009).

2.1.4 General process phases in transition governance processes

Transition governance requires (1) a reflexive governance approach to deal with the challenges of complexity and distributed control, (2) a focus on fundamental socio-technical change (related to transition management), while (3) basic social-ecological functions (e.g., ecosystem stability or water supply) are maintained (related to adaptive management). Thus, governing sustainability transitions involves the purposeful steering of fundamental socio-technical change while maintaining basic social-ecological functions (such as the supply of food, water, energy and housing). 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, the comparison shows some form of conceptual consolidation with respect to the process phases required for a governance of transformation towards sustainable development. The following sequence of six process phases have been synthesized from the three transition governance frameworks mentioned above:

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

- **Process phase 2: Stakeholder analysis and selection**: Stakeholder analysis, problem definition and goal formulation are closely related, and thus have to be conducted in parallel. Transition governance 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 continuing facilitation of stakeholder involvement is required.
- **Process phase 3: Participatory visioning and goal formulation**: Common goals must be discussed among stakeholders that integrate various perspectives and interests. The objective of this process phase is to bring together different interests, and to develop a vision that motivates stakeholders and functions as a reference point for action. A potential process goal could also comprise the testing of different hypotheses to learn about the system.
- **Process phase 4: Interactive strategy development that anticipates long-term systemic effects:** In this process step, the outcomes and possible side-effects of different strategies are assessed with respect to the achievement of the future vision, as well as potential trade-offs between goals. 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: Coordinate the implementation of experimental actions of multiple actors**: Multiple actions can be implemented in an experimental fashion to test hypotheses or to achieve a 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 duplication or negative side-effects.
- **Process phase 6: Systematic monitoring and assessment of actions**: The effectiveness of actions needs to be systematically monitored in order to achieve process goals. The identification of indicators can be helpful for systematically describing the various consequences of actions. Responsibilities and the process of monitoring should be clear and distributed among various stakeholders. The actual outcomes of actions need to be compared to the anticipated effects from phase 4. The assessment process should be transparent and involve all participants in order to account for different appraisals of a situation. The assessment phase should lead to a revision of problem definition, stakeholder selection, goal formulation, strategy development and implementation of experiments.

The similarity of the process phases in all reflexive governance approaches supports a transfer of findings and experiences with regard to learning processes (Section 2.2) and participatory modeling (Section 2.3). The following section presents a conceptual framework of multi-level learning processes in sustainability transitions based upon the socio-technical and social ecological systems literature.

2.2 Conceptual framework of multi-level learning in sustainability transitions

The conceptualization of multi-level learning developed in this doctoral research (see Halbe et al., submitted) differentiates between learning concepts that are related to (1) learning intensity, objects and outcomes, and (2) learning processes (cf. Bennett and Howlett, 1992; van der Kerkhof and Wieczorek, 2005). Based upon this, the (3) subjects of learning and (4) contexts in which learning takes place are defined. Due to the complexity of transition processes, a qualitative review and synthesis approach is required that allows for the appraisal of different concepts of learning as well as data from the literature. Thus, Halbe et al. (submitted) conducted a conceptual review that "aims to synthesize areas of conceptual knowledge" (Petticrew and Roberts 2006, p. 38) and guides the development of a conceptual framework. The conceptual framework is subsequently applied to structure a systematic review on supportive and impeding factors for learning in transition processes (see Section 3.2). The a priori development of a conceptual framework that provides categories for a subsequent review is also known as "framework-based synthesis" (Dixon-Woods 2011; Caroll et al., 2011, 2013). Details on the review process is provided in Halbe et al. (submitted), including the selection of literature, iterative development of the framework and extraction of data from the literature.

2.2.1 Learning intensities, objects and outcomes

Learning can proceed at different levels of intensity ranging from low order to high order learning (Brown et al., 2003). Each learning intensity is associated with different objects (i.e., the primary objects of change), which can lead to various outcomes (i.e., secondary objects of change that result from a change in primary objects). For instance, learning can change the want structure of individuals (primary learning object), which can result in a new consumption behavior (secondary learning object) (Buenstorf and Cordes, 2008). Van de Kerkhof and Wieczorek (2005) discuss single- and double-loop learning in transition management processes to define learning objects. Single-loop learning denotes the incremental improvement of strategies without questioning the underlying assumptions, while double-loop learning relates to a reframing of a problem conceptualization, which includes a reflection on underlying strategies and assumptions (Argyris and Schön, 1978). Double-loop learning can also be related to a change in mental models, which include "our beliefs about the networks of causes and effects that describe how a system operates, along with the boundary of the model […] and the time horizon we consider" (Sterman, 2000, p. 16). Subsequent work has included a triple-loop learning level that refers to a paradigm change through a reconsideration of values and goals (cf., Flood and Romm, 1996; Pahl-Wostl, 2009). Thus, these concepts of learning intensities point to different primary objects of learning, ranging from the incremental refinements of instruments and practices (single-loop learning) to a reframing (double-loop learning), and deep paradigm changes through the rethinking of values and goals (cf., van de Kerkhof and Wieczorek, 2005; Pahl-Wostl, 2009). The conceptual framework which is developed in this section builds upon these conceptualizations, and distinguishes between three learning intensities, namely routine learning, reframing and paradigm change. Table 1 illustrates these learning intensities and the related primary learning objects, as well as examples of learning outcomes.

Table 1: Learning intensities, primary learning objects and outcomes (Halbe et al., submitted).

Learning Intensity	**Learning objects**	**Examples of learning outcomes**
I: Routine learning	Iterative improvement of *strategies* (Argyris and Schön, 1978) and *actions* (Sabatier 1988) within current mental models (Sterman, 2000).	Changing *parameters* without changing the system structure (Meadows, 1999), such as: - Increase the heights of dikes to address higher flood levels (Pahl-Wostl et al., 2013). - Merely solving technical problems in innovation experiments (e.g., Beers et al., 2014).
II: Reframing	Reconsideration and revision of underlying strategies and *assumptions* (Argyris and Schön, 1978; Pahl-Wostl, 2009), *fundamental positions* (Sabatier 1988) and *mental models* (Sterman, 2000).	Consider *alternative options* and *viewpoints*: - Allow for river-landscape flows and restoration of the floodplain in flood management (Pahl-Wostl et al., 2013). - Accommodate frames held by heterogeneous actors in the design process of a sustainable building (Brown and Vergragt, 2008).
III: Paradigm change	Reconsideration and revision of *values and beliefs* (Flood and Romm, 1996) including *fundamental normative and ontological axioms* (Sabatier 1988).	Change in *rules, goals*, and *mindsets* (Meadows, 1999): - Structural change in water governance and management systems with the ambition of improving overall sustainability (Herrfahrdt-Pähle and Pahl-Wostl, 2012). - Promote a culture of experimentation in protected spaces to support active learning in water management (Farrelly and Brown, 2011).

2.2.2 Learning processes in transition research

Other learning concepts focus more on the process of learning, i.e., on specific mechanisms that explain how the objects of learning (e.g., mental models, values) can be altered. Two general types of learning processes can be differentiated: First, learning through interactions with the actual (problem) situation by means of direct *experience and experimentation*; second, learning about the behavior, values, goals and beliefs of others through *social interactions*. Some learning concepts comprise both types of learning processes. For instance, Wenger's (1998, 2000) concept of communities of practices involves learning through the interplay of socially-constructed competence (i.e., learning through social interaction) and experience of a joint enterprise (i.e., learning through experience/experimentation). In this section some examples of process-related learning concepts in transition research are presented, separated into learning based upon experience/experimentation and social interactions. A comprehensive overview of learning concepts is provided in Halbe et al. (submitted).

Learning through direct experience and active experimentation is described in the experiential learning concept (Kolb, 1984). Learning is conceived as a four-step process comprising concrete experience, reflective observation, abstract conceptualization and active experimentation. Transition scholars mainly refer to the experiential learning concept to explain processes of individual learning (e.g., Geels and Raven 2007). *Learning-by-doing* and *doing-by-learning* are further learning concepts in this group of experience-based learning concepts that are repeatedly applied by transition scholars (e.g., Seyfang and Longhurst, 2013; Bos et al., 2013). These concepts describe the processes of developing theoretical knowledge and testing it through practical experience (learning-by-doing), and developing empirical knowledge and testing it against a theory (doing-by-learning) (van der Brugge et al., 2005). *Trial-and-error learning* has been used in the transition literature to describe the process of conducting an experiment and optimizing the outcome through iterative revisions (Sosna et al., 2010). *Learning-by-exploring* and *learning-by-searching* are more related to learning processes in research or business organizations (e.g., Hekkert et al., 2007). Learning-by-exploring includes basic research activities that are conducted by universities and similar research organizations (Lundvall, 2010). Learning-by-searching describes more profit-oriented learning in the business sector through R&D departments in firms (Lundvall, 2010).

Learning based upon social interactions is often linked to *social learning* concepts in the transition literature (e.g., van den Bergh et al., 2007; Safarzynska et al., 2012; Broto et al., 2014). Various definitions of social learning exist. Reed et al. (2010, p.6) reviewed social learning concepts and, based upon this, defined social learning as a “change in understanding that goes beyond the individual to become situated within wider social units or communities of practice through social interactions between actors within social networks”. Scholz et al. (2014) add to this definition the convergent character of constructive social learning processes (e.g., development of shared vision) as social interaction processes can also result in increased conflict and stalemate positions (see also van Mierlo et al., 2013; Vinke-de Kruijf et al., 2014; van der Wal et al., 2014). *Learning-by-imitation* is another concept originally proposed by Bandura (1977) under the term ‘social learning’. It refers to the learning of individuals from the observation and imitation of others. Learning-by-imitation can also be relevant for organizational learning, for instance through the imitation of the successful strategies of other organizations (cf., Geels 2004) and the transfer of policies between political bodies (cf., Grin and Loeber, 2007).

2.2.3 Learning subjects and contexts

Van de Kerkhof and Wieczorek (2005) distinguish between individual learning processes (e.g., learning of a policy maker, scientist, and another stakeholder) and mutual learning processes where these stakeholders learn together. On the one hand, participants of group processes learn individually from others’ behaviors and statements. On the other hand, groups can develop formal and informal rules that affect their group's internal as well as external interactions, so that such collective learning processes also become situated beyond the individual (cf., Reed et al., 2010). Thus group processes are a particular context of learning that involves specific learning processes (e.g., social learning) and outcomes (e.g., rules for group discourses). In this chapter, an agency-perspective with respect to a specific sustainability issue is applied to define learning contexts (i.e., the following question is asked: What is the social unit that primarily takes agency in a learning process that addresses a sustainability issue?). In the following paragraphs, four learning contexts (i.e., individual, group, organizational and policy learning contexts) are specified.

In an *individual learning context*, an individual takes action to tackle a sustainability problem. The individual can belong to a social group (e.g., member of a community) but acts on her/his own behalf. Two types of interactions, as defined in Section 2.2.2, can be distinguished in the individual learning context: First, an experiential learning process through interactions with the environment (e.g., experimentation with certain practices) or the exploration of personal motives and genuine aspirations (i.e., a more introspective experiential process), and, second, a learning process based upon social interactions with other individuals (e.g., to receive resources or inspirations).

In the *group learning context*, a group takes collective action to address a problem. Guzzo and Shea (1992) define a group by it having three properties: (1) the group is considered an entity by its members and by non-members who are familiar with it, (2) group members share some degree of interdependence, and (3) group members have different roles and duties. In contrast to organizations, groups have low levels of hierarchical differentiation (i.e., a flat hierarchy) and formal cohesion of group members (i.e., there is no formal structure that binds group members; participation is more voluntary and can be stopped without significant consequences). In a group context, two types of interactions take place to deal with a task or a problem in a collaborative way. First, group members have to interact to find common ground for actions (i.e., social interactions) and discuss procedural rules, which can be explained through processes of social learning. Second, the group has to interact with its environment, which can include group-external stakeholders (social interactions) or physical aspects (i.e., experimental interactions) (cf. Beers et al., 2014).

In an *organizational learning context*, individuals or groups act as representatives of the organization or a sub-division to solve a problem in an organizational structure. Organizations have some form of hierarchical structure, are partitioned in different divisions (e.g., manufacturing, sales department), and members are bound together through formal arrangements (e.g., employment contracts) (see DeWine 2000). Organizations have the function of accomplishing a certain task or addressing a societal issue that requires experiential interaction with the environment. For instance, a farming business interacts with the environment (e.g., farmland, livestock) to provide food for its customers (often by way of intermediaries). Learning in organizations involves individual learning of their members (e.g., employees and directors) (see Kim 1993) and group learning processes (e.g., within task forces) (cf., Wenger 1998). Furthermore, public or private organizations interact with external individual stakeholders (i.e., social interactions), such as customers or clients, or collective stakeholders, such as action groups. Another interactive process involves interactions between organizations (cf., Easterby-Smith et al., 2008). The formalization of these interactions can be influenced by legislative demands, contracts or more informal agreements in networks.

In the *policy learning context*, state actors can fulfill a public interest through a hierarchical mode of governance (e.g., laws, bureaucracies), cooperation with relevant non-state actors in policy networks, or allowing institutionalized self-regulation, which can be voluntary (e.g., industry-led standardization processes) or commissioned (e.g., labor agreements) (Mayntz, 2004). According to this notion, governmental and non-government actors (subsequently referred to as 'policy actors') interact in addressing a sustainability issue through public policy making and implementation. The hierarchical governance mode includes regulatory, distributive and redistributive policies, as well as constituent policies (e.g., establishment of a new public organization) (Lowi, 1972). Formal and informal linkages between governmental and other actors in policy networks are becoming increasingly important in public policymaking and implementation (Rhodes 1997; Rhodes, 2007). Network processes involve some form of direct interaction and cooperation between state and private actors (Mayntz, 2006). The delegated self-regulation of a state function to private actors is a more indirect form of cooperation. Mayntz (2006) highlights that the state still has to monitor the effectiveness of these arrangements and reserve its right to intervene (e.g., in case public interests are not catered to). The policy learning context includes the context of individual learning (e.g., policy makers that make decisions based upon past experiences, cf. Schneider and Ingram, 1988), group learning (e.g., in meetings of policy networks, cf. Colvin et al., 2014), as well as organizational learning (e.g., through learning within governmental organizations, such as ministries) (cf., Grin and Loeber, 2007).

2.3 Modeling in transition research

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 (cf. Voss and Kemp, 2005; Sendzimir et al., 2006; Ruth et al., 2011). Loorbach (2007) proposes the application of participatory modeling for problem structuring and the envisioning of transition paths as part of strategic activities in transition management. In the transition research community, the use of models for facilitating transition governance processes has not yet been systematically explored. Only a few researchers explicitly discuss the purposes and uses of various models. Yücel (2010) distinguishes three uses of models in transition research: (1) modeling for case-specific insight development, which aims to replicate reality in order to assess the 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. 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 the consequences of alternative policies in order to improve the 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.

An all-encompassing categorization of model uses and purposes in transition modeling is hence currently missing. A typology of model uses has been developed by Halbe et al. (2015c) that integrates the classifications mentioned above and also addresses the use of models in transition governance processes. This typology distinguishes between the different purposes, contexts and epistemological foundations of modeling and allows the extraction of the 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). Without considering the different types of scientific inquiry, a comparison of modeling applications can lead to a polarized debate that does not consider the complementarity of fundamental, applied and post-normal research (cf. Grunwald (2015) and Schneidewind (2015) pointing to a similar discussion on the role of transformative 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.

2.3.1 Model uses in transition research

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

Model use for *providing case-specific policy advice* is problem-driven and refers to applied science (Funtowicz and Ravetz, 1993). This particular use 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 the different assumptions of threshold effects (Brugnach and Pahl-Wostl, 2007). This allows the exploration of the influence of underlying model assumptions on system behavior.

Finally, model use for facilitating stakeholder processes is based on post-normal science (Funtowicz and Ravetz, 1993). Post-normal science addresses societal issues with high epistemological and ethical uncertainties. In such cases, the “hard” facts of core and applied science must be complemented by “soft” measures such as public participation and ethical considerations. Models in this context can be tools for supporting stakeholder engagement and learning and for contributing to communication between researchers and stakeholders (Brugnach and Pahl-Wostl, 2007). Joint model development can reveal the 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 provides an overview of model purposes, contexts and epistemological foundations assigned to the three designated model uses.

Table 2: Model use in transition research (Halbe et al., 2015c).

	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

In addition to the classification of model uses, Halbe et al. (2015c) also review the literature with respect to the status quo of model uses in transition research as well as experiences in other related research areas (i.e., social-ecological systems research, integrated assessment and environmental modeling). Experiences with participatory modeling in other research fields have shown that 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. Halbe et al. (2015c) suggest that transition governance approaches can support the effective application of participatory modeling methods by providing an overall structure for the organization and implementation of participatory processes. Thus, transition governance approaches can guide the systematic application of participatory methods aimed at facilitating multi-level learning processes. Halbe and Ruutu (2015) follow this research direction by providing a review of participatory modeling methods and tools for each of the process phases of transition governance defined in Section 2.1.4. The following section presents some selected results from this review.

2.3.2 Modeling in transition governance processes

The review in Halbe and Ruutu (2015) is based upon literature from transition research, as well as other relevant research fields. Halbe and Ruutu (2015) go into detail and propose specific participatory modelling methods for each phase in transition governance processes.

Integrated knowledge production for problem definition (Phase 1): Facilitated problem structuring methods are mainly qualitative modeling methods that deal with the challenge of multiple plausible problem perspectives held by stakeholders. Conceptual modeling is a particularly appropriate approach for developing a common holistic understanding of a problem situation, and thus supports communication and learning between modelers, decision makers and other stakeholders (cf., Liu et al., 2008). For instance, systems thinking is a method for the qualitative analysis of systems using Causal Loop Diagrams (CLDs) to visualize multi-causal relationships and feedback processes (cf., Vennix 1996; Sterman 2000; Senge 2006). Conceptual modeling is already applied by some transition scholars. Videra et al. (2014) applies conceptual modeling in a participatory process of researchers and degrowth activists. Auvinen et al. (2015) also use CLDs to analyze important feedback processes between conventional and innovative transportation systems. Halbe et al. (2015a) applies CLDs and the concept of Viability Loops (Hjorth and Bagheri 2005) to link innovations as part of a solution strategy to a particular problem perspective (see Section 3.1.2).

Stakeholder analysis and selection (Phase 2): Various methods and approaches for stakeholder analysis exist that can be differentiated between methods for (1) identifying stakeholders, (2) categorizing stakeholders, and (3) investigating relationships between stakeholders (Reed et al., 2009). A brainstorming process can be a good starting point for developing an initial list of stakeholders, which can be complemented by a literature review, interviews, or focus group discussions (Prell et al., 2011; Inam et al., 2014). Stakeholders can be categorized by assigning roles, such as decision-makers, users, experts or implementers (EC, 2003). A prioritization of stakeholders can be conducted by assessing their interest, power, legitimacy, and the urgency linked to a particular problem situation (Mitchell et al., 1997). Social network analysis is a widely used approach for the empirical investigation of relations between actors (Scott, 2013). For instance, a Net-Map approach can be applied in interviews, which is an intuitive and low-tech mapping tool for a qualitative and quantitative analysis of social networks (Schiffer and Hauck, 2010).

Participatory visioning and goal formulation (Phase 3): Methods for developing joint visions can be sorted into four groups. First, visions of desirable future system states can be created through the use of non-technical methods that tap into the creative potential of participants, such as written vision statements (e.g., National Civic League, 2000; Auvinen et al., 2015), collages (e.g., Kok et al., 2006), or even role plays (e.g., Oels, 2002). Second, future visions can be developed in a more guided process supported by conceptual frameworks or reference scenarios (cf. Elle 1992). Such frameworks and reference scenarios assure that visions cover specific elements (e.g., different sectors or locations) and include key concepts. Third, qualitative modeling approaches can be applied to achieve a more systematic vision (e.g., Iwaniec et al., 2014). For instance, conceptual modeling can be used for analyzing barriers and drivers of innovations (Halbe et al., 2015a) or institutional structures, such as alternative paradigms (Halbe et al., 2013). Fourth, quantitative modeling approaches can be applied to develop visions that are systematic and testable in quantitative terms (e.g., Trutnevyte et al., 2011, 2012).

Interactive strategy development that anticipates long-term systemic effects (Phase 4): Scenarios are a suitable approach for analyzing and designing implementation processes that comprise several intermediate steps towards a long-term vision. Exploratory scenarios (also called forecasting scenarios) start from the current condition and describe different plausible futures depending upon uncertain processes and events (e.g., MEA, 2005). Anticipatory scenarios (also called backcasting) are more normative by starting with a desired or feared vision in order to define effective policies (Mahmoud et al., 2006). Similar to visioning processes, backcasting scenarios can be designed by using non-technical approaches, conceptual frameworks or reference scenarios, as well as qualitative and quantitative modeling methods. These different types of methods can be combined to make use of their particular advantages (cf. Alcamo, 2008; van Vliet et al., 2010). Auvinen et al. (2015) combine qualitative modeling (i.e., CLDs) with the use of a conceptual transition framework (i.e., multi-level perspective) to design system transition roadmaps from a current socio-technical system to a future vision. Halbe et al. (2015a) present a qualitative modeling approach that helps to analyze the various roles of actors in transformation processes towards sustainability. CLDs are used to define actor-specific learning requirements to support a broader implementation of innovations.

Coordinate the implementation of experimental actions of multiple actors (Phase 5): Design methods for transition governance processes are currently in an early phase of their development. Detailed planning tools are needed that help depict key elements of transition governance processes, including events, responsibilities and expected outcomes. A promising tool is the Management and Transition Framework (MTF), which is a conceptual and methodological framework that allows for the description, analysis and assessment of transition processes (Pahl-Wostl et al., 2010). The MTF is introduced in more detail in Section 3.3. The application of the framework for a prospective design of transition paths has already been explored by Halbe et al. (2013). Another analytical-evaluative framework is presented by Forrest and Wieck (2014) that allows for the structured analysis and evaluation of community transition processes. The framework helps to reconstruct transition processes starting from the intervention outputs and tracing the sequence of events that led there (Forrest and Wieck, 2014). Even though the framework has been only applied in an ex-post analysis, the same framework could be applied in an ex-ante planning exercise.

Systematic monitoring and assessment of actions (Phase 6): Systematic monitoring and assessment requires a clear understanding of the process, aspired outcomes (i.e., goals) and responsibilities. The selection of suitable indicators for process monitoring can be guided by the process goals defined in phase 2. However, these process goals might be too unspecific for practical process monitoring and assessment. For instance, process goals could be related to long-term processes, such as the recovery of the local economy. Thus, approaches are needed that support combining process-specific indicators with more systematic approaches for indicator selection. Reed et al. (2006) provide an overview of expert-based and participatory approaches for indicator development, 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. Modeling methods and tools can also play a significant role in the monitoring and assessment of actions. The comparison of model results to empirical data can challenge the mental models held by model builders and induce reflection about potentially false or incomplete perceptions (Sterman, 2000).

2.3.3 Teaching participatory modeling at the university level

In addition to transformative research (cf. Chapter 1), the establishment of transformative science also requires the development of transformative education (Schneidewind and Singer-Brodowski, 2014). The transformative learning concept considers adult learning as a process involving critical reflection about frames of reference, “which are structures of assumptions and expectations on which our thoughts, feelings, and habits are based” (Mezirow, 2009, p. 22). Halbe et al. (2015b) present a problem-based learning approach (cf. Savery, 2006) to encourage students to reflect on paradigms related to sustainability issues and to teach participatory model building at the university level. Pahl-Wostl et al. (2011) provide a practical definition of paradigms for the management of natural resources. A management paradigm is understood as “a set of basic assumptions about the nature of the system to be managed, the goals of managing the system and the ways in which these goals can be achieved” (Pahl-Wostl et al., 2011, p. 840). Based upon this definition, Halbe et al. (2013) present an approach for the elicitation and analysis of paradigms using participatory modelling. Here, a paradigm is defined by a specific ‘system perspective’, selected ‘solution strategies’, as well as ‘risk and uncertainty management strategies’. Risks and uncertainty management strategies comprise (1) the reduction of uncertainties and control of risks, (2) the acceptance of uncertainties through an adaptive management approach, (3) the discussion of perceptions of uncertainties with communities, and (4) building of confidence in traditional approaches. By linking these risks and uncertainty management strategies to the system and solution perspectives in included in CLDs, various paradigms can be identified such as a “predict and control” paradigm that focuses on the controlling of the environment.

A combination of lectures, exercises and projects is proposed by Halbe et al. (2015b) that were tested at the University of Osnabrück in Germany, and McGill University in Canada to teach participatory model building and the relevance of paradigms to undergraduate and graduate students[1]. Individual and group modeling exercises are used

[1] The teaching approach presented in Halbe et al. (2015b) focuses but is not limited to engineering paradigms and education. The engineering focus of the article is due to the fact that it was originally presented at the Engineering Education for Sustainable Development Conference 2013 (EESD2013) in Cambridge, UK. The conference paper was selected for publication in the Journal of Cleaner Production by the scientific committee. The teaching approach was developed and tested at the Department of Bioresource Engineering at McGill University, Canada, and the Institute of Environmental Systems Research at the University of Osnabrück, Germany.

to provide students with experience dealing with the method of participatory modeling in the "safe environment" of the classroom. In the individual modeling exercise, students learn to build a CLD of their individual perceptions with regard to a specific environmental issue (e.g. water scarcity) (a detailed description of the modeling method is provided in Section 3.1.2). In a group modeling exercise with the students, the same method is applied in a group setting, i.e., a group of students (about 4 to 8 students) construct a CLD jointly. This exercise can be combined with a role playing game. For example, in a group model building exercise on the issue of water scarcity, students assume the roles of farmers, hoteliers, citizens, governmental representatives, and engineers to learn the applicability of the method in stakeholder discussions.

In group projects, students finally learn to apply participatory modeling with real stakeholders. Locally-relevant and current topics are selected that can ideally be related to an on-going participatory process. During the duration of the project, students are assisted by a tutor who helps with questions related to the methodology and organization of stakeholder involvement. Each stakeholder interview is conducted by a sub-group of two students, and takes place at the university or at the workplace of one of the participant. An interview takes approximately 1.5 hours, and proceeds using the same steps that the students learned during their exercises (see Section 3.1.2). Each subgroup of students has the task of completing at least two interviews. After the interviews students compare the individual models, analyze diverging points of view as well as complementary aspects. In addition, students develop a holistic model that contains all the perceptions of the stakeholders and highlights the points where opinions differed. Finally, the project results are presented to the stakeholders in a final meeting. In addition to the presentation of results, students moderate a discussion among the various stakeholder groups. Feedback from the students indicates that they find this teaching approach highly useful in better understanding the concept and method of participatory modeling and its ability to analyze and visualize stakeholder perceptions. The detailed evaluation results are provided in Halbe et al. (2015b).

Based upon the conceptual multi-level learning framework and reviews of theories and methods of transition research, the following chapter presents the methodology for a pro-active governance of sustainability transitions that has been developed in this doctoral research.

3 Methodology for the governance of sustainability transitions

The methodology presented in this section was developed to analyze and design transition governance processes by specifying (1) the various opportunities to contribute to sustainable development through purposeful action at different societal levels, as well as (2) related roles of stakeholders in implementing such processes of change. The methodology focuses on practical sustainability innovations, understood as innovative approaches for the provision of societal functions (e.g., for water, energy and food supply) which reside at a niche level today, but might be an important element of a sustainable supply system in the future (cf., Halbe et al., 2015a). The term innovations is defined after Rogers (1995, p.11) as an "idea, practice, or object that is perceived as new by an individual or other unit of adoption". Thus, sustainability innovations must not necessarily be novel but can also include well-known practices that are currently applied on a small scale and could potentially contribute to the solution of sustainability issues. Based upon the conceptual multi-level learning framework (see Section 2.2), the methodology considers processes of societal change as learning processes that take place in various contexts (i.e., ranging from the individual to the group, organizational and policy contexts), which are linked to different societal levels (cf. Section 2.2). Factors are identified that support or impede learning in different contexts and thereby guide the design of transition governance processes. The methodology combines a structured expert approach to examine general learning factors based upon a systematic literature review with participatory modelling to examine case-specific learning factors.

In the following section, a methodology is presented that combines different streams of previous research: 1) a participatory modeling approach to identify problem perceptions, case-specific sustainability innovations as well as related implementation barriers, drivers and responsibilities (cf., Halbe et al., 2015a); 2) a systematic review to identify supportive and impeding learning factors from the general literature that can complement case-specific factors (Halbe et al., submitted); and 3) a method for analyzing and designing case-specific transition governance processes (cf. Halbe et al., 2013).

The methodology addresses all phases in transition governance processes that have been identified in Section 2.1.4. Thus, the participatory modeling process supports the interrogation of the problem and related stakeholders from a scientific and participatory point of view (Phases 1+2). Sustainability innovations are analyzed, which reflect different visions of a sustainable water, energy or food supply system (Phase 3). Both the general and case-specific learning factors support systematic strategy development (Phase 4). The analysis and design of transition governance processes supports the coordination of actions at different societal levels (Phase 5). Finally, an explicit process design also supports process monitoring and assessment by specifying process steps and expected outcomes (Phase 6).

3.1 Participatory modeling to analyze problems, innovations and case-specific learning factors

The participatory development of conceptual models supports a structured and in-depth analysis of stakeholder perceptions of a complex sustainability issue (cf. Inam et al., 2015). In this section, a participatory modelling approach is presented based upon previous research (cf., Halbe et al., 2013; Halbe et al., 2015a). The participatory modelling approach includes three steps: 1) General problem and stakeholder analysis; 2) participatory modeling with experts and innovators; and 3) case-specific identification of learning factors.

3.1.1 General problem and stakeholder analysis

The first step in the participatory modeling process includes the gathering of data and information about the transition topic at hand. This step should be considered as a preparatory step in order to obtain an initial overview of potential issues, solution strategies and stakeholders. Societal transitions are complex phenomena, due to multi-domain and multi-level interactions as well as path-dependent and self-reinforcing processes (Holtz 2011). Thus, analytical approaches are required to structure a preliminary problem and stakeholder analysis (cf. Section 2.3.2). The multi-level perspective (Geels 2002, 2011) can guide data collection and gathering of relevant information (cf. Auvinen et al., 2015). Various transition scholars have applied the multi-level perspective to analyze elements of past transition processes including case-specific niches (e.g., sustainability innovations), regime elements, and landscape signals (e.g., Geels, 2005b; Broto et al., 2014). The preliminary analysis involves a description of landscape pressures, structures and processes in the regime, as well as niches in the form of sustainability innovations. Conceptual modeling using causal loop diagrams (CLDs) can be applied as a supplementary approach to structure available information and analyze feedback structures (see Auvinen et al., 2015).

After the preliminary problem analysis, a selection of relevant stakeholders is needed to prepare the participatory modeling process. Inam et al. (2015) presents a structured approach for stakeholder selection progressing from a divergent brainstorming process of potential stakeholders to their categorization by examining their roles (e.g., decision-makers, experts, users, implementers), and prioritization through analyzing attributes, such as power, interest and legitimacy. Two types of stakeholders can be distinguished: experts (who can provide an overview of perceived problems and solution perspectives) and innovators (who can offer more in-depth information on innovations and their barriers and drivers) (cf. Halbe et al., 2015a). Innovators are considered to be actively engaged in the development of innovations with sustainability benefits. Experts are considered to hold a more of observer's perspective on sustainability issues and potential innovations. Experts and innovators can stem from the regime as well as niches. Regime actors prefer innovations that support an ‘endogenous renewal’ of the regime (Geels and Schot, 2007), i.e., innovations are favored that can be implemented in a planned way and do not change the basic structure of the regime. More radical innovations that would require a fundamental restructuring of the incumbent regime are, however, developed in niches.

3.1.2 Participatory modeling with experts and innovators

In the second step, stakeholders (i.e., experts and innovators) who have been identified in the first research step are invited for an interview. The advantages of CLDs are the flexible application to physical, environmental as well as social processes, and the opportunity to include participants in the model-building process (Vennix, 1996). CLDs help to systematically depict a stakeholder's perspective through variables that are written on cards or post-it notes, placed on a large sheet of paper, and connected with causal arrows (for an example see Figure 3). The CLDs are later analyzed and digitized by the process facilitators (e.g., by using the software program Vensim[2]).

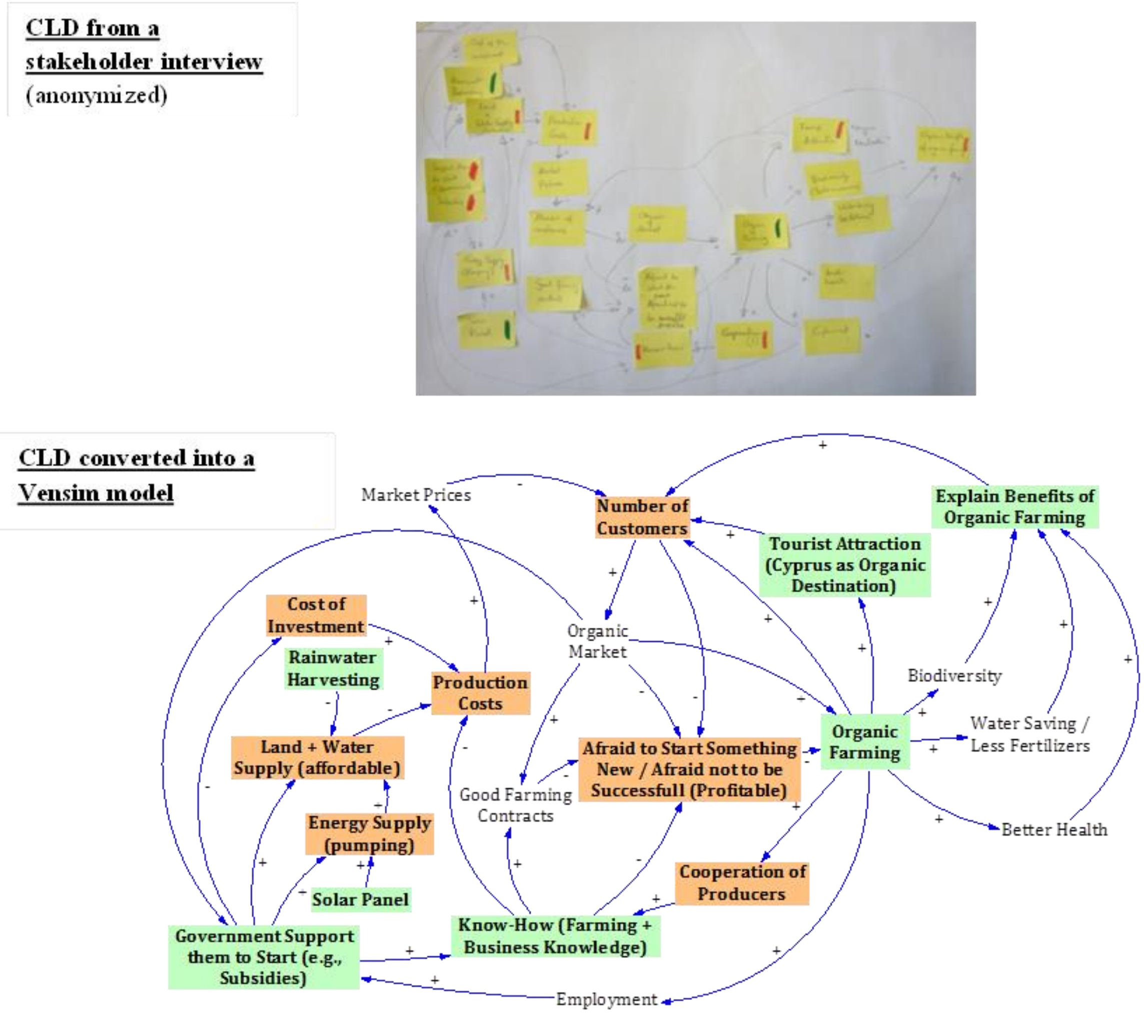

Figure 3: Example of a CLD from an innovator in the organic farming sector with the original model above and the digitized and analyzed model below. The green variables represent the innovations and measures that foster their implementation. Variables marked in orange are problem variables that need to be addressed to support the organic farming sector (cf. Halbe et al., 2015a).

[2] http://vensim.com/free-download/ (retrieved: 08 January 2016)

A positive link indicates the parallel behavior of variables: in the event of an increase in the causal variable, the variable that is affected also increases, while a decrease in the causal variable implies a decrease in the affected variable. A negative link indicates an inverse relationship between variables. A further central concept in system dynamics is the elaboration of feedback loops. Two different sorts of feedback loops exist that can be detected in CLDs: the self-correcting 'balancing loop' and the self-amplifying 'reinforcing loop' (Sterman, 2000). During the interview (which is 1 to 1.5 hours in length), experts are requested to build a CLD that represents their system perspective on sustainability issues. Innovators are asked to develop a model of the barriers and drivers of a specific innovation. The interviewer provides only methodological support without influencing the content of the model (for more details on building CLDs in individual interviews, see Inam et al., 2015). The interview process is similar for innovators and experts and is described in detail in the remainder of this section.

Experts start with the definition of sustainability issues. The second step involves the identification of the causes of the defined problems as well as the polarity of causal links. In the third step, the consequences of the problem are studied. In the fourth step, the interviewee is encouraged to find feedback loops (Vennix, 1996). In the fifth step, potential strategies and innovations for solutions are included to address the problems. In the sixth step, the interviewee identifies stakeholders who could play a role in implementing these strategies and innovations. Finally, in the seventh step, the barriers to potential solutions and innovations are added. In summary, the approach presented encourages the structured construction of a holistic system that includes a representation of the participants’ mental models of the status quo as well as their preferred strategies and challenges related to the problem being explored.

Innovators start with the definition of factors that influence their particular sustainability innovation (e.g., efficient irrigation technologies, energy-efficient buildings or organic farming practices). These can be problems, or aspects that motivated them to implement the innovation. In the second step, the consequences of the innovation are added (e.g., desirable effects on the environment), and in the third step potential feedback processes are included. In the fourth step, the interviewee is asked to consider solution strategies to address problems, as well as further barriers to the implementation of these solutions (fifth step). In the sixth step, stakeholders are identified by the interviewee who could play a role in implementing the solution strategies. The individual interview process results in two different kinds of CLDs: those developed by experts that reveal sustainability issues and point to innovations that might be used to address them; and CLDs developed by innovators that provide insight into the opportunities provided by, and issues associated with, particular innovations, and promising approaches to foster the implementation of these innovations (see Figure 3, which shows a CLD built by an innovator).

Supplementary questionnaires and interviews (without participatory modeling) can complement findings from the participatory modeling process. These questionnaires and interviews should follow the structure of the participatory modeling process in order to assure the compatibility of findings. This can also be achieved by translating interview data into a CLD. The ability of CLDs to integrate information and data from various sources, including interviews, questionnaires or documents, has been demonstrated by several studies (cf. Forrester, 1980; Luna-Reyes and Andersen, 2003).

3.1.3 Identification of case-specific learning objects and learning factors

In the third step, empirical results are interpreted by using the conceptual framework of multi-level learning processes, as specified in Section 2.2. Available empirical data is analyzed to identify learning objects, learning contexts, supportive/impeding factors, and roles in the provision of learning factors. Empirical data mainly stems from the participatory modeling process, but can also be complemented by data from questionnaires or semi-structured interviews, as described in Section 3.1.2.

The analysis of CLDs starts with the identification of problem variables in each diagram, which represent potential learning objects. Second, the learning intensity of the learning objects identified is determined (i.e., learning objects are linked to routine learning, reframing or paradigm change; see Section 2.2.1 for a detailed description of learning intensities). In the third step, it is determined whether or not problem variables reflect a learning object (i.e., a primary object of change) or a learning outcome (i.e., a secondary object of change). Learning outcomes (e.g., unsustainable consumer behavior) are subsequently translated into the underlying learning object (e.g., consumer preferences and values) using the classification in Table 1 in Section 2.2.1. In the fourth step, the learning context is determined by examining the social unit which is related to learning objects (i.e., an individual, group, organization or policy actor). For instance, unsustainable consumer preferences and values are related to an individual learning context as the learning object pertains to the individual. An environmentally-adverse strategy of a firm, for example, would be related to an organizational learning context given that solutions require a reframing of corporate strategies (e.g., a new strategy could consider pollution prevention instead of end-of-pipe approaches). Fifth, factors that support learning are identified in the CLDs that act as drivers of innovations by helping to overcome learning objects. These case-specific learning factors have been added to the CLDs by asking the interviewee for solution strategies to address the identified problem variables. Supportive factors can take the form of knowledge (e.g., skills), institutions (e.g., a piece of legislation), or operational aspects (e.g., infrastructure). In addition, impeding learning factors that are barriers to the successful implementation of solution strategies are identified. Sixth, the roles of actors in the implementation of supportive learning factors or avoidance of impeding factors are analyzed based upon information from stakeholders or a general literature review.

The CMaps[3] knowledge management tool (Novak and Cañas, 2008) can help to sort factors and their linkages to learning objects. Thus, learning objects and supportive learning factors are written into box elements and linked through arrows (in contrast to CLDs, arrows in CMaps reflect hierarchical linkages instead of causal linkages). The visualization of hierarchical linkages helps to deal with different abstraction levels of learning factor categories. For instance, “process facilitation” can be a main factor

[3] http://cmap.ihmc.us/download/ (retrieved: 16 December 2015)

category in group processes, while “collaborative visioning exercises” or “development of a shared problem perspective” are more specific factor sub-categories (cf. Halbe et al., submitted).

3.2 Systematic review to derive general learning factors from the literature

Participatory research processes can reveal case-specific problem and solution perspectives that are based upon local knowledge. However, stakeholder processes might disregard important aspects of sustainability. Thus, expert-led approaches are still necessary to provide scientific rigor and a factual basis for stakeholder processes (cf. Reed et al., 2006). Within the scope of this research, the conceptual multi-level learning framework (see Section 2.2) guided a systematic literature review of factors that support/impede learning in sustainability transitions. A systematic review is defined as “a review of a clearly formulated question that uses systematic and explicit methods to identify, select, and critically appraise relevant research, and to collect and analyze data from the studies that are included in the review” (Moher et al., 2009, p. 1). The review question was formulated as follows: What are factors that support and impede learning in the governance of sustainability transitions?

The literature database Scopus was used to identify original research articles, reviews and editorials that apply learning concepts in the sustainability transitions literature. Research on societal transitions in the socio-technical and social-ecological system research fields have been considered as relevant for our review (cf. Smith and Stirling, 2010; van der Brugge and van Raak, 2007; Foxon et al., 2009). As part of the systematic review, the quality of the literature was checked in terms of the conceptual and empirical rigor as well as thematic proximity. Thus, a weak thematic proximity resulted in the exclusion of the paper from the review process. Papers with weak empirical rigor were not included in the identification of factors that supportive and impede learning. If a conceptually weak paper did not provide sufficient information for the identification of learning contexts, the paper was also excluded from the review of learning factors. After screening the full text, 63 publications entered the review process.

All empirical information has been sorted into the categories of the conceptual learning framework (see Section 2.2). Descriptive coding has been applied to consolidate learning factors at two different levels of abstraction (i.e., main categories and one level of sub-categories). Summarizing and essence-capturing codes (Saldana, 2012) are assigned to synthesize factors with the same or similar meaning. Each factor has been qualified as being a supportive (abbreviation: Sup), impeding (Imp) or ambiguous (Sup/Imp) factor in learning processes based upon the description in the literature. The identification of a supportive or impeding factor reflects the description generally provided in the supporting literature. If different papers included semantically-congruent factors but used an inverse formulation (e.g., “monitoring” as a supportive factor and “lack of monitoring” as an impeding factor), references that mentioned factors in an inverse way were allocated to the same factor category and marked with the abbreviation “inv”.

In addition, the factor's susceptibility to purposeful change is rated on an ordinal scale from endogenous (i.e., the factor can be directly influenced by learning processes within the respective context) to ambiguous (i.e., susceptibility unclear) and exogenous (i.e., factor cannot be influenced). The rating is influenced by the respective learning context since the same factor category (e.g., sustainability-oriented legislations) can be exogenous in one context (i.e., in the organizational learning context) and endogenous in another (i.e., in a policy learning context that can actively influence legislation). In particular, endogenous factors are key leverage points that actively facilitate learning in learning contexts. Exogenous factors however point to aspects that cannot be addressed in the respective context due to exogenous events (e.g., a natural disaster) or interdependencies between learning contexts. For instance, a community garden project (related to a group learning context) can be supported by policy-makers who provide public land (related to a policy learning context). Thus, the results of the systematic review point to the importance of addressing endogenous factors as well as inter-context linkages through exogenous factors in the design of transition governance processes (e.g., by developing communicative interfaces, cf. Adomßent, 2013).

Halbe et al. (submitted) also identified similar factor categories across learning contexts (see column "similar factors" in Appendix 1). Finally, factors were sorted into four groups to structure their presentation: factors that are related to (1) the motivation of actors to engage in a learning process, (2) experimental processes, (4) social interaction processes, and finally (4) resources (cf. factor groups in Appendices 1.1 – 1.4).

Table 3 summarizes the results of the review by providing an overview of main factor categories by learning contexts and the numbers of underlying references at a scale from low (1-2) to medium (3-5), large (6-10) and very large (>10). The literature reviewed suggests a disturbance or crisis as a supportive learning factor *in all learning contexts*. The choice of the topic for experiments and participatory processes is another factor supporting learning in all contexts. The same applies to the factors 'planning/implementation of multiple experiments' and 'design of experimental processes', as well as physical resources, information and knowledge. In the *individual, organizational and policy learning contexts*, societal values that favor sustainability, the setting of a leading sustainability vision and the existence of forerunners are mentioned as supportive factors. A strong commitment of actors (based upon their awareness of sustainability issues and a sense of responsibility), process facilitation, leadership and trust are supportive learning factors in the group, organizational and learning contexts.

Table 3: Comparison of main categories of learning factors across learning contexts. The number of references are rated using the following scale: low number (o) := 1-2 references; medium number (+) := 3-5 references; large number (++) := 6-10 references; very large number (+++) := >10 references).

	Sup/ Imp	**IDs***	**Individual Context** (Total #: 6)	**Group Context** (Total #: 16)	**Organizational Context** (Total #: 18)	**Policy Context** (Total #: 38)
Disturbance or crisis	Sup	I-1; G-1; O-1; P-1	o	o	+	+
Change of government	Sup/ Imp	G-2; P-2		o		+
Societal values that favor sustainability	Sup	I-2; O-2; P-3	o		++	+
Sustainability oriented institutions	Sup	O-3; P-4			++	++
Choose topic that arouses attention and motivation	Sup	I-3; G-3; O-6; P-5	+	++	++	++
Provision of a leading sustainability vision	Sup	I-4; O-8; P-7	o		+	+
Commitment (awareness and responsibility)	Sup	G-4; O-9; P-6		o	+	+
Existence of forerunners	Sup	I-6; O-9; P-8	+		o	+
Externalities and lock-in effects	Imp	O-4; O-5			o	
Experimental and social interaction process						
Planning/implementation of multiple experiments	Sup	I-7; G-5; O-10; P-9	o	+	++	+++
Structures that support participation	Sup	O-11; P-10			++	+++
Policy instruments	Sup	P-11				+++
Design of participatory processes	Sup	I-8; G-6; O-12; P-12	+	++	+++	+++
Process facilitation	Sup	G-7; O-13; P-13		+++	++	+++
Leadership	Sup	G-8; O-14; P-14		+	+	+++
Resources						
Physical resources	Sup	I-9; G-9; O-15; P-15	+	++	++	+++
Information and knowledge	Sup	I-10; G-10; O-16; P-16	o	+++	++	+++
Trust	Sup	G-11; O-17; P-17		o	o	++

* ID stands for factor identifier, as provided in Appendices 1.1 – 1.4.

In the next step of the proposed methodology, learning factors from the systematic review and the participatory modeling process are compared. The design of transition governance processes considers these general, literature-based learning factors and case-specific, stakeholder-based learning factors in order to induce learning at multiple societal levels. The methodology for the analysis and design of transition governance is introduced in the following section.

3.3 Analysis and design of transition governance processes

The proposed method for analyzing and designing transition governance processes specifies the various interlinked activities, responsibilities and roles of stakeholders involved, as well as opportunities to purposefully facilitate learning in different contexts. Based upon the literature-based and participatory analysis of supportive learning factors, the method allows for the synthesis of findings and design of more detailed collaborative processes. More specifically, the purpose of the next step of the methodology is the design of learning processes that address case-specific learning objects (see Section 3.1.3). In the design of these learning processes, supportive and impeding learning factors are considered in order to facilitate effective and sustainability-directed learning. Supportive and impeding learning factors that were originally identified in the participatory modeling process are compared to literature-based factors. The comparison can reveal gaps in the factors based upon stakeholder perceptions or point to case-specific factors that are not included in the general factors list from the literature.

Conceptual and methodological frameworks are needed that help to depict key elements of transition governance processes including specific processes, roles and expected outcomes (Halbe and Ruutu. 2015). A useful tool that is mentioned in Section 2.3.2 is the Management and Transition Framework (MTF), which is a conceptual and methodological framework that allows for the description and analysis of resource governance processes (Pahl-Wostl et al., 2010). The MTF builds upon the three conceptual pillars of adaptive management (e.g., Holling 1978), social learning and transformation processes (Pahl-Wostl et al., 2007), as well as the Institutional Analysis and Development Framework (which is intended to analyze the role of institutions in collective choice processes, c.f. Ostrom, 2005).

The MTF helps to formalize structural elements of a resource system (which are denoted as “classes”) as well as policy and learning processes. Central classes in the MTF are the following (Pahl-Wostl et al., 2010): An **‘Action Situation’** refers to formal or informal interaction processes that lead to relevant outcomes for the governance process. Results can be ‘**Institutions’** (e.g., new water legislation), ‘**Knowledge’** (e.g., increased understanding of stakeholder perspectives of a problem) or ‘**Operational Outcomes’** (i.e., direct physical interventions in the system such as the development of infrastructure or distribution of water to different uses). In this way, the MTF provides a common language for analyzing and discussing complex governance systems. Relational databases are used to support formalization and standardization of data collection and analysis protocols (cf., Knieper et al., 2010). A graphical interface supports data input and analysis. To date, the MTF has been mainly applied for understanding processes of change in water resource issues through ex-post analysis (e.g., Schlüter et al., 2010; Sendzimir et al., 2010; Knueppe and Pahl-Wostl, 2011). However, the same framework can also be applied in an ex-ante planning exercise that defines the action situations, participating actors, and desired outcomes. The application of the framework for the design of transition paths has already been explored by Halbe et al. (2013).

Figure 4 is a graphical representation of the different elements of the MTF and their linkage to key concepts in this doctoral dissertation. Action situations are interpreted as learning processes of multiple actors intended to address a learning object. Thus, learning objects are the defining characteristic of action situations. Learning factors can be input or output factors of action situations. Learning factors can take the form of institutions, knowledge or operational aspects (as expressed by different geometrical shapes). Roles in the learning process are included in the visualization by connecting actors to action situations. The responsibilities of the actors' roles have been defined in the participatory modeling process (see Section 3.1.3) with regard to the implementation of learning factors. Thus, actors that are connected with an action situation include all actors that play a role in the implementation of output factors (i.e., learning factors that are produced through learning processes within an actin situation). These output factors can function as input factors to other action situations.

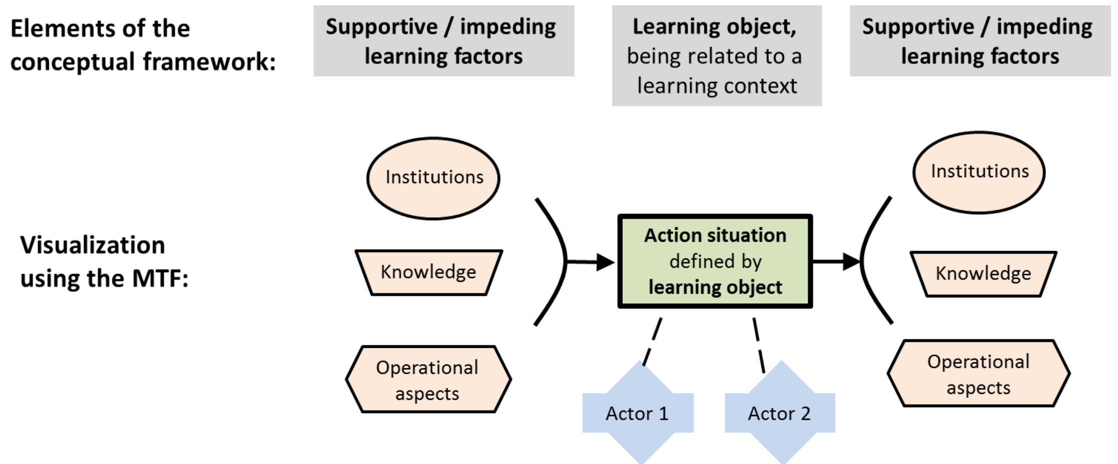

Figure 4: Link between elements of the conceptual learning framework and the visualization approach, based upon the MTF.

Two distinct perspectives on transition governance are supported by the methodology: a) a structural view that presents the <u>structure of the transition governance system</u> at a specific point in time, and b) a temporal view of transition governance that reveals the <u>governance process through time</u>. In the first case, a structural governance system analysis provides a snapshot of the relationships between action situations at a specific point in time. In the second case, a transition process is depicted as a temporal sequence of action situations which are linked by institutions, knowledge or operational outcomes. While temporal analysis is more suitable for planning transition governance processes over time, a structural analysis allows for the comprehensive analysis of the status quo at specific points in time.

3.3.1 Methodology for structural analysis and design of governance processes

The structural analysis method presented in Halbe et al. (2013) was adapted to allow for a learning perspective on governance processes (in contrast to a paradigm-perspective, as described in Halbe et al., 2013). The methodology is applied at two different levels of abstraction: (1) an overall inter-context analysis that shows interactions between learning contexts, and (2) a detailed intra-context analysis of interaction processes within learning contexts. The methodology thereby supports the analysis of exogenous factors that can be addressed by linking different learning contexts as well as endogenous learning factors (i.e., that can be addressed through learning processes within a learning context) (see Section 3.2 on exogenous/endogenous factors).

Figure 5 demonstrates these two types of analysis. In the overall inter-context analysis, a small number of overall action situations are defined that subsume context-internal learning objects. For instance, an overall action situation might be the development of consumer awareness of sustainable consumption, which may subsume a number of learning objects such as those related to consumer values and knowledge. Thus, learning objects are subsumed as much as possible in overall action situations, each addressing learning objects of a similar type in a particular learning context. In Figure 5a, an overall action situation is defined for each of the individual, group and policy learning contexts. However, two high-level action situations are included for the organizational learning context as these action situations address different types of learning objects (e.g., firm-internal processes, such as waste management, versus firm-external processes, such as public relations) and, thus, have different linkages to other learning contexts. As depicted in Figure 5a, the linkages between learning contexts (represented by overall action situations) are expressed through operational outcomes, institutions or knowledge.

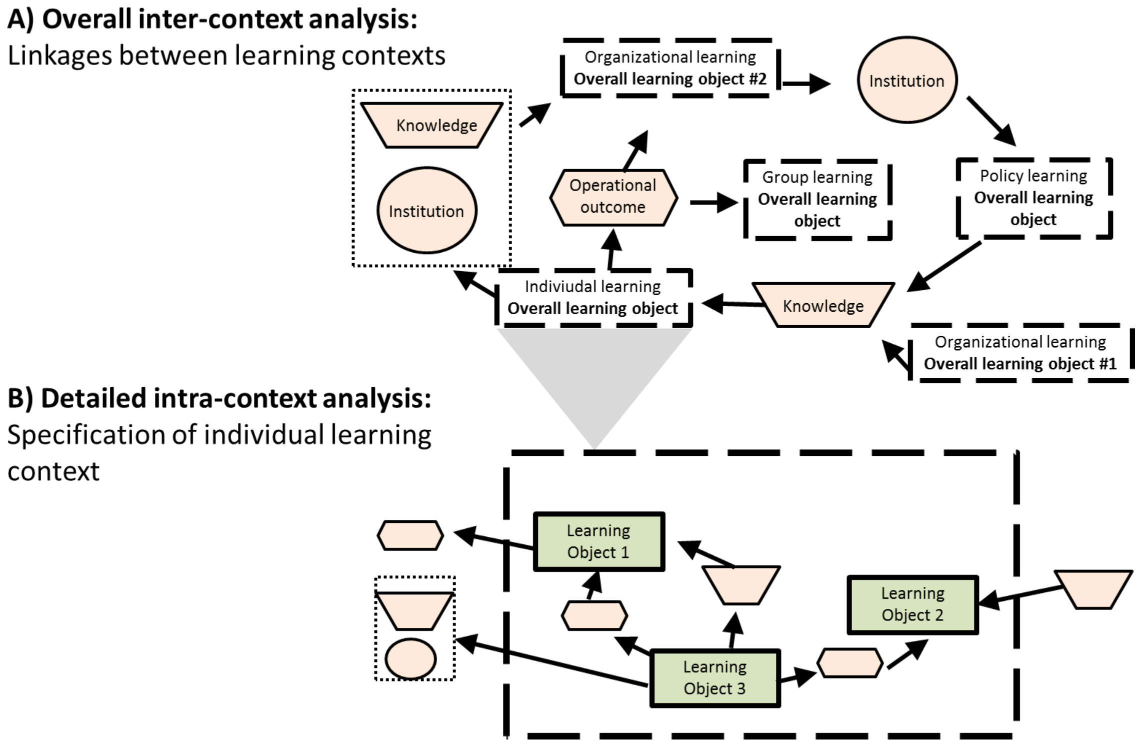

Figure 5: Layout of a structural analysis of a transition governance process.

In the detailed intra-context analysis, a context-internal analysis is conducted for each overall action situation comprising detailed action situations (i.e., interaction processes) that address specific learning objects within a learning context (see Figure 5b). Following the above example, the detailed system analysis of the individual learning context would include detailed and interlinked action situations that address consumer values, knowledge and behavior. In addition, operational outcomes, knowledge and institutions from context-external action situations are added to reveal the inputs and outputs of this particular learning context.

3.3.2 Methodology for temporal analysis and design of governance processes

The methodology for a temporal analysis of transition governance processes is based on the approach presented in Halbe et al. (2013). Figure 6 shows an example design of a transition governance process from a more hierarchical flood management to a more integrated and adaptive flood management that was developed for a case study on the Hungarian reach of the Tisza river (Halbe et al., 2013). In Halbe et al. (2013) a special focus was devoted to the analysis of flood management paradigms that are highlighted by using different colors in Figure 6 (see Section 2.3.3 for details on the paradigm concept). The transition governance process starts from a present action situation comprising the reinterpretation of a flood management policy called VTT2[4] (cf., Sendzimir et al., 2010), which reflects the mindset of the dominating “Control Floods” paradigm. Two action situations are envisioned to lead to the desired outcome. First, a round table is advised with the participation of the Ministry of Environment and Water, responsible engineers and water managers, local activists, national NGOs and the Village Municipalities Association (cf., Sendzimir et al., 2007). This round table sets the rules for a working group for the development of a long-term flood strategy (institution) that includes all participating actors, and facilitates the institutionalization of a community of practice at the ministerial level. The community of practice is supposed to link the various departments and facilitate a continuous deliberative process for the development of innovative solutions to the flood management problems in the Tisza Basin. These activities together with experiences of other EU countries with innovative flood management approaches could form the basis for the development of a new flood management policy (named VTT3) that may lead to the institutionalization of a stakeholder platform at the local and regional scales as well as more experimentation with alternative approaches (e.g., through pilot studies). The established institutions and the experimental approach would result in the “Integrated and Adaptive Flood Management” action situation that brings together the ministerial “community of practice” and the stakeholder platform.

Even though the sample pathway of a transition governance process in Figure 6 is only a simplification of a more complex real-world process, this example shows the capacity of the method to visualize the interlinkages between multiple interaction processes, their participants as well as different forms of inputs and outcomes. All types of supportive learning factors - institutional, knowledge and operational - can be included in the visualization.

4 In Hungarian: „Vásárhelyi Terv Továbbfejlesztése“

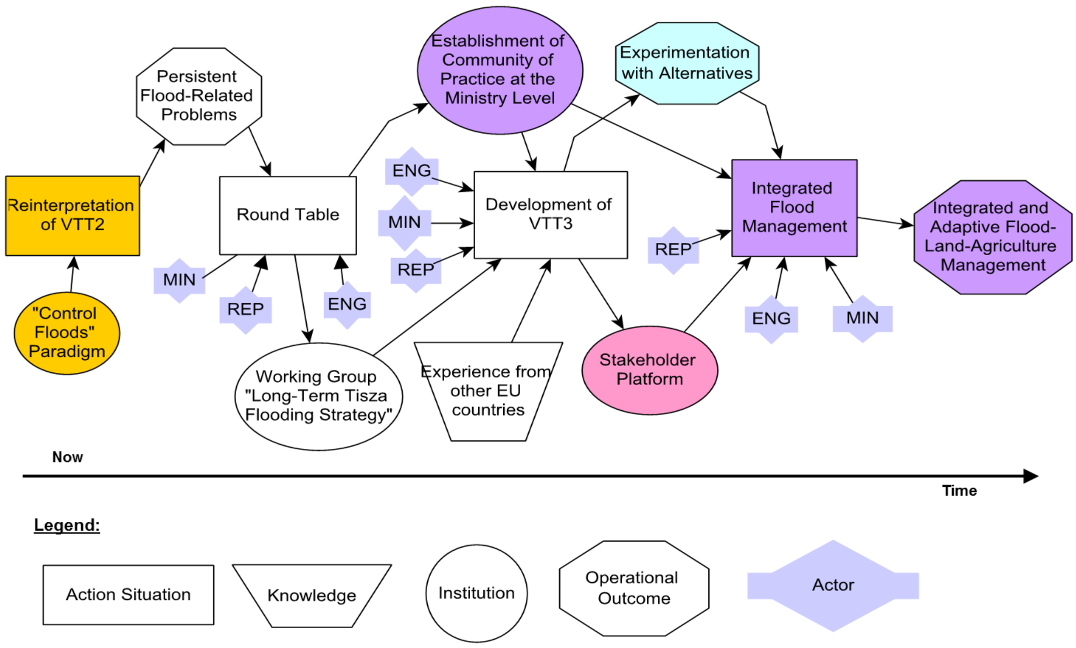

Figure 6: Design of transition governance process for integrated flood management. The colors indicate the paradigms that underlie different system elements (purple variables reflect an innovative 'integrated and adaptive paradigm'; orange reflects a more hierarchical 'control floods paradigm'; light blue represents an 'adaptive management paradigm'; pink refers to a 'community involvement paradigm') (Halbe et al., 2013).

The proposed methodology presented in Sections 3.1 to 3.3 was implemented in three case studies. In the following section, the case study design of this doctoral research is presented.

3.4 Case studies

Three case studies have been selected to test and iteratively develop the methodology described above. The case study design resembles a multi-case replication design approach (cf. Yin, 2009), as the methodology was applied and tested in different contexts, which helps identify the potential limitations of the methodology. The case study research was however a more exploratory process focusing on the iterative development and refinement of the method. Thus, a clear methodology did not exist at the outset of the research, which would have been needed to qualify for an explicit experimental approach that replicates results (in this case the successful application of a methodology) (Yin, 2009). Thus, the findings of a comparative analysis of case study results can only be provided in an interpretative way, and, thus, are provided in the discussion and conclusions chapter (Chapter 5).

In this section, we describe the various factors that were considered in the case study choice. Four factors were considered critical to the success of the methodology, and thus should be present in all case studies: (1) a focus on a basic need, (2) a regional scale, (3) existing stakeholder networks, and (4) a democratic society. However, moderate cultural diversity was also considered to be advantageous in the case studies in order to test the influence of cultural predispositions on the methodology's performance.

First, the application of the methodology is tested for **water, energy and food supply**, as these basic needs are particularly important for sustainable development. This is reflected in the central role of food, water and energy supply in the recently announced Sustainable Development Goals (SDGs) (UN, 2015a). They are explicitly included in the SDGs ‘Zero Hunger’, ‘Clean Water and Sanitation’ and ‘Affordable and Clean Energy’ goals, as well as implicitly in all other SDGs. The international research platform ‘Future Earth’ also highlights the central role of food, water, and energy in the transformation to a sustainable world. In their list of eight focal challenges for achieving a sustainable and equitable world, water, energy and food supply is included as the number one challenge: “Deliver water, energy, and food for all, and manage the synergies and trade-offs among them, by understanding how these interactions are shaped by environmental, economic, social and political changes” (Future Earth, 2015, p. 3). This statement also reflects the need to consider the interrelationships among water, food and energy supply. Thus, a **water-energy-food (WEF) nexus** perspective was also considered in the choice and design of case studies.

As already mentioned in the introduction, sustainability transformations are considered to involve broad societal learning processes that require learning among individuals, groups, organizations and policy actors, which should be reflected in the case selection and design. The **regional scale** is considered a particularly suitable intermediate scale for transition governance because at this level it is possible to balance the sustainability benefits of local bottom-up initiatives, such as developing personal relationships among stakeholders and connectedness to place, to initiatives and networks at higher scales, thus allowing for the upscaling of sustainability innovations.

Third, an **excellent stakeholder network** is helpful for transdisciplinary research, as conducted in this doctoral project. Case study partners are needed that have a broad network including niche actors, such as those involved in local initiatives or organizations dedicated to innovation, as well as regime actors, such as policy-makers or incumbent firms. Even though the consideration of available and established contacts usually contradicts the systematic selection of cases, this approach is justified by the exploratory and participatory character of this research.

Fourth, the **similarity of the general socio-economic context** was considered in the selection of cases. As a result of the general bias of methods and concepts used in transition research towards western-industrialized countries, a similar focus was selected for this doctoral research. In particular, a **democratic society** is considered a fundamental requisite for transition governance processes that are intended to facilitate collaboration between civil society and economic/political actors. The potential limitations and opportunities of a transition governance approach in more autocratic societies or societies with weak governmental structures are intriguing research questions which, nonetheless, go beyond the scope of this dissertation.

Fifth, a modest degree of **cultural diversity** was sought in order to explore the limitations and challenges of the methodology. However, as this research focuses more on methodological development and its exploratory testing and iterative development, the assessment of its effectiveness in different cultural contexts is not conducted in a systematic way. Nevertheless, the different cultural tendencies in the case studies will be explicitly considered in the reflection on experiences. For this purpose the cultural map of Inglehart and Welzel (2015) is used to assess cultural tendencies in the case studies. Based upon data from the World Values Survey[5], cultures are mapped according to two dimensions: (1) Secular-rational values versus Traditional values (i.e., importance of religion and parent-child ties), and (2) Survival values versus Self-expression values (i.e., levels of trust, tolerance and environmental values).

Based upon these factors, three case studies with varying thematic foci (food, energy, and WEF nexus) and geographical locations (regions in Canada, Cyprus and Germany) were chosen. While the socio-economic development in the case study regions are similar (Human Development Index: 0.90 (Canada), 0.85 (Cyprus), 0.91 (Germany)), the cultural dimensions vary across cases following the classification of Inglehart and Welzel (2015). Thus, Canada is among the countries with highest self-expression values (~ 2.1), while Germany is more moderate (~ 0.7) and Cyprus is even leaning towards survival values (~ -0.4). Germany has strong secular rational values (~ 1.0) compared with Canada and Cyprus, which are lean more towards traditional values (both ~ -0.5).

3.4.1 Sustainable Food Systems in Southwestern Ontario

A case study of sustainable food systems in Southwestern Ontario, Canada, comprising the Bruce, Grey, Huron, Wellington and Middlesex counties (comprising an area of about 18,000 km^2) was developed. The case study was conducted in close collaboration with the University of Guelph which had excellent contacts with stakeholders in the region. Between 2012 and 2014, a participatory modeling process comprised of individual interviews with organic and urban farmers, distributors, customers, representatives of the federal government and other stakeholders in the case study area was developed. In total 20 interviews were conducted by the author, while seven additional interviews were carried out by Master's students from the University of Guelph (Rohan Hakimi and Elisa Cooper). CLDs have been built in 21 interviews, while six interviews proceeded in a more informal way without the construction of a CLD. One of the students was trained by the author through joint interviews (i.e., the Master's student participated in six stakeholder interviews). In addition, a survey was prepared to ask participants of an organic food conference in Guelph about sustainable farming approaches and their perceived barriers and drivers (55 surveys were completed). Two types of surveys were prepared (see Appendix 5): a more detailed survey for farmers and a general survey for other participants.

The study defines different visions of a sustainable food system and strategies for its implementation. The focus is on regional and organic food systems due to multiple benefits from such systems including potentially lower resource inputs for farming (e.g., pesticides) and outputs (reduced CO_2 emissions) as well as increased consumer awareness. A transition governance approach is particularly suitable for local food

5 http://www.worldvaluessurvey.org/images/Cultural_map_WVS6_2015.jpg

systems as multiple actors have to cooperate along the value chain. In addition, consumer values and behavior have to be addressed together with food regulations that are tailored to intensive agriculture.

3.4.2 The Water-Energy-Food Nexus in Cyprus

A case study of the WEF-Nexus was conducted in the Republic of Cyprus (covering an area of about 6,000 km^2). The Energy, Environment and Water Research Center (EEWRC) at the Cyprus Institute in Nicosia has been the scientific partner in the Cyprus case study. The research agenda of the institute comprises key research topics that are of interest to this research project such as integrated impact assessment and holistic water management. A successful participatory modeling process that involved the EEWRC was already organized in the past (cf. Halbe 2009). Between 2014 and 2015, 35 individual interviews have been conducted with regime actors (e.g., governmental agencies, farmer associations) as well as niche actors (e.g., organic farmers, community gardening initiatives). CLDs were developed in 28 interviews; 7 interviews proceeded in an informal way (i.e. without building a CLD). All interviews were conducted by the author.

The highly prevalent issues of water scarcity and fossil-fuel dependency of the country's economy have created pressure for innovative and effective solutions in Cyprus. Such immediate problems motivated several stakeholders to become involved in this case study. Sustainability transitions in the context of the WEF nexus require development of inter-sectoral strategies and the involvement of multiple actors, which favors a transition governance approach.

3.4.3 Sustainable Heating Supply in the Ruhr region of Germany

A case study of sustainable energy supply was undertaken in the Ruhr region (in German: Ruhrgebiet) in western Germany, in cooperation with the Wuppertal Institute for Climate, Environment and Energy. The study is linked to the EnerTransRuhr Project that develops a transformative research design for the analysis and active fostering of an energy transition in the Ruhr region. From 2013 to 2015, a participatory modelling process was developed that elicits the mental models of relevant stakeholders including homeowners, energy consultants, craftsmen, interest groups, banks, professional associations, public organizations and NGOs. A total of 24 stakeholder interviews were undertaken in the analysis: three interviews were conducted by the author (as doctoral candidate), nine interviews were done by a Master student of the University of Osnabrück (Sebastian Weide). CLDs were constructed in all interviews. In addition, recordings of 12 interviews with residential property owners, conducted by members of the EnerTransRuhr project team, were used in the analysis by translating the interviewees' perspectives into CLDs.

This case study investigates potential barriers to and drivers of the transition processes for the introduction of sustainable energy systems for heating (including insulation of buildings, efficient heating systems, heat pumps as a technical innovation and consumption behavior). Despite the considerable efforts of policymakers to foster the broader implementation of energy refurbishment measures through favorable credits, energy consulting and building standards, the refurbishment rate is still low and energy saving potentials remain underutilized (Diefenbach und Enseling, 2007; Weiß and Dunkelberg, 2010). A transition governance approach was considered to be suitable for analyzing the barriers to top-down policies from an integrated perspective, and, based upon this, identifying innovative transition governance strategies.

4 Results

The methodology for analyzing and designing case-specific transition governance processes was tested in the three case studies (as outlined in Section 3.4). The presentation of case study results begins with an overview of the specific sustainability topic from a broader perspective including the link of the regional case study to national and international developments. Subsequently, the results of each case study are presented in four steps that correspond to the proposed methodology in Chapter 3:

1) General analysis of problems, sustainability innovations and stakeholders in the case study;
2) Analysis of case-specific supportive and impeding learning factors through a participatory model building process;
3) Development of a complete list of learning factors by comparing case-specific and general review-based learning factors;
4) Analysis and design of a case-specific transition governance process based upon identified learning factors, including a structural analysis and a temporal analysis.

In steps 1 to 3, analytical approaches are applied based upon empirical data. The structural analysis of the governance system and particularly the temporal analysis have a stronger design component, and thus require more interpretation. Stakeholders should be involved in the application of these methods. In the scope of this research, the full engagement of stakeholders in step 4 was not possible. A workshop in the Ontario case was only organized to discuss the method with a group of interested stakeholders. Nevertheless, a sample application of the structural and temporal analysis of transition governance processes is provided to exemplify the application of the methodology. For the sake of brevity, an intra-context analysis that defines opportunities for action within learning contexts (i.e., addressing endogenous learning objects) is only provided in the Canadian case study.

4.1 Canadian case study of sustainable food systems

The design of a sustainable food system is an important topic with global relevance. Indicators for the first Millennium Development Goal "Eradicate extreme poverty and hunger" have shown promising trends in the last two decades, such as a decrease in undernourished people in developing regions by about 50% since 1990 (UN, 2015b). Despite these achievements, the sustainability of agriculture is challenged by increasing global food demand as a result of rising population as well as changing diets. Peters et al. (2007) found that the dietary choice can cause a nearly fivefold difference in land requirements depending mainly upon meat consumption and dietary fat content. Global meat production quadrupled in the last 50 years (1961-2013) (FAOSTAT, 2015a). While meat production (measured in tons) in the EU and USA roughly increased by a factor of

2.5 in this time frame, China's meat production has skyrocketed by a factor of 33 (FAOSTAT, 2015a). Projections also suggest a doubling of crop demand by 2050 (base year: 2005) (Tilman et al., 2011) and meat production is expected to further increase by about 75% by 2050 (Alexandratos and Bruinsma, 2012). Higher production can be achieved by a process of intensification (Tilman et al., 2011) and/or extension of agricultural land (e.g., Laurance et al., 2014). However, these strategies pose serious environmental threats through eutrophication of aquatic and terrestrial ecosystems (Tilman, 1999), and loss of tropical and semi-arid ecosystems respectively (Laurance et al., 2014).

Several alternative strategies have been proposed to achieve a sustainable agricultural system that provides sufficient food while minimizing ecosystem impacts. Some scholars suggest a "moderate intensification" (Tilman et al., 2011, p. 20260) through technology improvement and technology transfer from affluent to poorer nations that allow for higher yields, as well as more precise application of nutrients and pesticides (Tilman, 2009; Tilman et al., 2011). Organic agriculture is also a widely proposed solution. Based upon a 21-year study, organic farming implies a 20% reduction of crop yields while fertilizer and energy inputs are reduced by 34-53%, and soil fertility and biodiversity improves (Mäder et al., 2002). Local food systems represent another opportunity to reduce food miles and support the local economy (Blay-Palmer, 2010). Due the rise in populations living in urban areas globally, urban agriculture is a promising approach for contributing to local food supply (cf. Nasr et al., 2010). Post-harvest and post-consumer food waste are further issues that impact the sustainability of global food systems and which are hard to quantify due to limited data (Parfitt et al., 2010).

This section has provided a sketch of the complexity of sustainable food systems at a global scale. A silver bullet that minimizes environmental effects and provides food for a rising global population appears to be lacking. The Canadian case study addressed this topic on a regional scale.

4.1.1 General analysis of problems, sustainability innovations and stakeholders in the Canadian case study

Agriculture in Ontario is an important sector which is reflected in the fact that the province leads other provinces in terms of the number of farms (Statistics Canada, 2011). The agricultural regime in Ontario is mainly based on large-scale, conventional farming. Small farms (less than 10 acres / ~4 hectares) account for only 5% of the total number of farms in Ontario. Certified and non-certified organic farming remains at a niche level, representing roughly 1% and 5% of farms, respectively (Statistics Canada, 2006). Data on farming for own consumption (e.g., community gardening) is currently unavailable as official statistics focus on commercial forms of agriculture. However, farming for self-supply could become a significant activity for developing farming skills as well as raising awareness of local food production, e.g., in the form of community gardens (cf., Wakefield et al., 2007). There are several challenges currently (e.g., a changing climate), as well as likely challenges in the future (e.g., depletion of fossil fuel and phosphate resources) that could pose significant challenges to the food system at the landscape level (cf. multi-level perspective; Geels, 2011).

Alternative visions were collected through a literature review, as well as a survey (see questionnaire in Appendix 5) and a visioning exercise at an organic food conference in Guelph in which conference participants (comprising interested individuals, actors from the organic and local food value chains, NGOs, and governmental representatives) were asked to outline their personal vision of a sustainable food system. In addition, 27 individual stakeholder interviews were conducted in the course of a participatory modeling process. The interviews and conference surveys (55 surveys were completed) revealed the existence of multiple alternative visions of a sustainable food system: some participants envisioned a large-scale organic food production system while others stressed the importance of a localized food system including small-scale organic agriculture and urban farming (Halbe et al., 2014). The focus of the case study was set on local food systems that combine food production for self consumption (e.g., urban gardening) as well as organic and diversified[6] farming systems in the case study region. The local food movement in the case study region can be considered a dynamic and developed niche, which is reflected in the high number of initiatives and different organizational forms involved ranging from non-profits to businesses, and government agencies to cooperatives (see Mount et al., 2013).

The initial stakeholder analysis was informed by a literature review and the results of the survey at the organic food conference in Guelph. Questionnaire results pointed to several innovators in the field of sustainable agriculture including community gardening initiatives, actors that foster the development of more regional food systems (e.g., owners of local food stores, and small-scale, diversified farmers), and governmental initiatives that support newcomers to farming (e.g., FarmStart). Our literature review complemented the list of stakeholders by adding interest groups at the provincial and national level (e.g., National Farmers Union; Canadian Organic Growers; Canadian Organic Food Association) and governmental agencies (e.g., Ministry of Agriculture, Food and Rural Affairs; Agriculture and Agri-Food Canada).

4.1.2 Analysis of stakeholder-based learning factors in the Canadian case study

CLDs and questionnaires from regime and niche actors were analyzed according to the methodology specified in section 3.1. In this section, the resulting case-specific learning objects and associated learning factors are presented. A comparison of results from case study research and the systematic review is provided in the subsequent section (4.1.3). All case-specific learning objects, supportive factors and actor roles that have been derived from the analysis of CLDs and surveys in the Ontario case study are listed in Appendix 2.

[6] Kremen et al. (2012) describe diversified farming systems as an alternative approach to industrial agriculture. By definition, a diversified farming system “includes functional biodiversity at multiple spatial and/or temporal scales, through practices developed via traditional and/or agroecological scientific knowledge” (Kremen et al., 2012, p.q)

A crisis of conventional agriculture was considered to be a supportive learning factor with regard to most learning objects in the individual, group, organizational and policy learning contexts, as a crisis urges people to rethink the current regime and actively look for alternatives. On the contrary, the rising global demand for food was mentioned as an impeding factor to learning as this implies the demand for large quantities of food which strengthens the existing food regime. However, all other learning factors can be related to specific learning objects, as presented below.

The *individual learning context* generally deals with improving consumer awareness and demand for local and organic food. Contemporary consumer preferences and values (learning object no. 1) focusing on the price of products (i.e., food has to be cheap) and its outer appearance (products have to look perfect) have constrained the development of a sustainable food system. Several interviewees indicated that consumers need to acknowledge the benefits of a regional and organic food system in order to develop the willingness for paying higher prices. Various factors have been proposed to address this issue, such as raising public awareness through the media, clear labelling of food (e.g., local food labels), as well as actions that enhance human connectedness to nature and place. In particular, leading by example (e.g., having a healthy diet, and buying regional/organic products) has been proposed to induce rethinking of preferences and values by people in their personal environment. Interviewees complained about a general lack of knowledge with respect to food and agriculture (learning object no. 2), a factor that can be addressed through consumer education on alternative farming approaches and healthy nutrition, as well as translation of related research findings into generally understandable wording. In addition, community gardens and urbans farms are considered to play a key role in educating the public. Another related issue is the reluctance of people to take action (e.g., by informing themselves, developing new habits) (learning object no. 3). Stakeholders proposed the development of a clear vision of a desirable future as well as stronger leadership among public organizations (e.g., by offering local food in cafeterias) to address this learning object.

The *group learning context* includes the issue of lack of cooperation within the farm community due to a more individualistic lifestyle among farmers (learning object no. 4). Cooperation can gain momentum through actions that offer visible results and tangible benefits for farming. A farm community research center and an alliance to educate the public have been mentioned as potential starting points for joint actions within the farm community. In addition, programs that connect young farmers to each other are seen as critical intervention points. According to stakeholders, local/organic agriculture needs to develop a positive reputation in order to foster a feeling of identity within the farm community. Another collective effort is required in the development of a seed-saving network and infrastructure, which is largely lacking today (learning object no. 5). Thus, some stakeholders propose the development of a regional seed-saving network. A lack of farming knowledge and equipment (learning object no. 6) can also be tackled through more intensive cooperation among farmers (by sharing equipment and knowledge) and potentially facilitated by online platforms. Local fertility management (learning object no. 7) can also be addressed by cooperation of neighboring farms. Lack of skilled labor (learning object no. 8) can be addressed through a marketing and information platform (e.g., online) to help people to identify ways that they can contribute to a local food system, which can best be implemented through a group effort. The aforementioned activities are sorted by the group learning context because a local food system is based upon more personal exchange between farmers and other stakeholders.

Most of the objects of learning take place in the context of a farm, and were thus allocated to the *organizational learning context*. Each is described here. First, starting a new farm business in the organic/local food sector is challenging due high costs and initially low revenues (learning object no. 9). The stakeholders proposed special programs or subsidies for diversified farming systems so that organic farmers can bear the costs of buying a farm or transitioning to organic. In addition, training programs are considered important for newcomers to develop an understanding of standards and improve farming and business skills. Another issue is the need to increase the customer base despite higher prices compared to conventional products (learning object no. 10). This can be achieved by producing and marketing high-quality premium products for customers who accept higher prices. Active consumer education (e.g., by information campaigns) is another complementary solution to inform customers about the production process and particular quality of products. This also involves active networking with retail stores and restaurants to increase their willingness to accept and market their produce. In this respect, a personal connection of farmers to consumers and other actors along the distribution chain is particularly helpful. Some stakeholders considered the need to upscale production (i.e., depart from the ideal of a diversified farm to some form of specialization in the local food system) in order to become economically sustainable. Planting of perennial crops was suggested for lowering work and equipment requirements on the farm (learning object no. 11). On-farm fertility management (learning object no. 12) can be addressed by integrating livestock or increasing crop rotation. The lack of food distribution infrastructure (learning object no. 13) is a major problem for local food systems. Stakeholders proposed the application and improvement of practical marketing models that provide access to local food, such as community-supported agriculture, supermarkets offering fresh farm products, farmers markets, and wholesalers that distribute local food. Some interviewees also mentioned the need among farmers to acquire new knowledge about marketing and distribution as they would often neglect business aspects of farming (in contrast to primary farming tasks). There is also a lack of regional storage and processing facilities (e.g., abattoirs) (learning object no. 14), which can be addressed by the strengthening of local food production as well as specific regulations that are adapted to supporting smaller facilities. Interviewees pointed to limited financing opportunities (learning object no. 15) which can be addressed with more opportunities for grants and micro-loans tailored to small-scale farming. A community-supported agriculture approach can also help finance small-scale farmers.

In the *policy learning context,* current land use planning policies are mentioned as an issue as they reduce the availability of affordable land (learning object no. 16) due to proliferation of residential areas and land speculation. To address this issue regulations are required that allow planning bodies to protect agricultural land from conversion into residential areas. Some stakeholders demanded the rezoning of urban/suburban lands for small-scale production (e.g., designating a "small farm enterprise zone"). A landscape design approach was proposed to achieve productive ecosystems that only require limited external inputs. Another important issue mentioned was the contemporary power of the conventional agriculture regime which is reflected in legislation, standards, infrastructure and funding opportunities (learning object no. 17). Lobbying organizations can contribute to the broadening of this focus by pointing to the importance and (synergetic) benefits of local/organic food systems. This can result in the development of specific regulations supporting small scale farmers (e.g., with respect to safety management or quotas), as well as subsidies for local/organic agriculture and products. Democratic practices were considered as an important leverage for inducing this change in governmental policies (e.g., vote for people who support local/organic food, or write to representatives, such as ministers). As a consequence of the contemporary regime, research funding is more focused on conventional agriculture (learning object no. 18) and the stakeholders therefore demanded more research on local food systems. A further key issue mentioned was the lack of integration of knowledge and management levels to identify best practices for specific locations (learning object no. 19). University research on local/organic food systems (e.g., on soil fertility, distribution systems and water use) play a key role in resolving this issue. In addition, the integrated assessment of sustainable agriculture and food systems that also considers the possible advantages of the interplay between local and international food systems was considered pivotal. This is impeded by a lack of dialogue between regime (conventional agriculture) and niche actors (e.g., organic, local agriculture) (learning object no. 20), which could be addressed through integrated research as well as identification of best practices among countries (i.e., best practices that demonstrate the benefits of integrated food systems).

The analysis reveals several linkages between learning contexts. For instance, “Availability of affordable land” was included as an object of learning in the organizational learning context that can be supported by a change of land use planning policies, which is a learning object in the policy learning context. These linkages between learning contexts should be highlighted in the design of transition governance processes as described in section 4.1.4. Section 4.1.3 first provides a comparison of these case-specific learning factors with more general learning factors from a literature review

4.1.3 Comparison of stakeholder-based and literature-based learning factors in the Canadian case study

The comparison of stakeholder-based learning factors (see Appendix 2) and review-based factors (see Appendix 1) reveals several consistencies and gaps. In the following section, consistent factors are presented first along with factor identifiers that are linked to review-based factors (see Appendix 1). Review-based factors that can fill potential gaps in the stakeholder-based factor list are subsequently presented. Finally, case-specific factors are provided (if present), which are only included in the stakeholder-based factor list.

Case study and review results both confirm that a crisis in society (I-1, G-1, O-1, P-1) is a key factor in weakening the current regime and supporting alternatives. Given the tendency towards the increase in destabilizing landscape pressures (e.g., climate change, depletion of fossil fuels and phosphate), pressure on the political system might increase in the future as well as the willingness of regime actors (e.g., policy-makers) to consider alternative approaches. Physical resources (I-9; G-9; O-15; P-15), information and knowledge (I-10; G-10; O-16; P-16) are also found to be relevant in all learning contexts.

With respect to the *individual learning context*, the case study and review results suggest that environmental values (I-2) are considered as important in the development of a local food system, as people have to restore their connectedness to nature and place. A clear vision of the future (I-4) is another supportive factor that is consistent between general and case-specific factors. Further factors that are consistent refer to the importance of inspiration (I-6), for instance through role models that lead by example or TV shows about local food. Interactive concepts are another supportive factor (I-8.1), which can be achieved through use of the internet. Public organizations can further support individual learning (I-9.3), for instance by actively promoting local food in their cafeterias. Finally, increased knowledge exchange is another consistent factor in case study and review results (I-10.2). However, the list of factors from the literature review point to gaps - further important aspects - that can influence individual learning objects. First, educational efforts (e.g., on the part of schools or citizen groups) require the continuous observation, evaluation, and reflection of this process and its outcomes (I-7.2). Second, campaigns should highlight the relative advantages as well as compatibility with current consumer practices in order to reach a broader population (I-3). A case-specific learning factor in the individual context is the clear labelling of food products that allows consumers to make conscious decisions. This factor can be included as a sub-category of ‘knowledge and information’ (I-10), as product labels allow consumers to make informed decisions.

In the *group learning context*, consistent stakeholder and literature-based factors are as follows. Similar to the case study results, the literature review also underlines the relevance of tangible community actions (G-3.1) (e.g., exchange of seeds) that address urgent problems (G-3.4) (e.g., lack of locally-adapted plants). Some activities also require active networking with external actors (G-6.4) such as a seed-saving network or marketing activities to attract skilled workers. Developing a positive reputation requires the development of a clear vision of the future (G-7.8). Further case study results point to the relevance of measures for exchanging physical resources (e.g., farm equipment) (G-9) and knowledge (e.g., education programs for young farmers) (G-10.1). Knowledge integration is another consistent factor (e.g., connect scientific findings with experiential knowledge through a famer-led research center) (G-10.2). Several learning factors from the literature review were not mentioned in the case study results (see Appendices 1 and 2). A few examples of further learning factors that should be considered in the design of effective group learning processes are provided here. The complexity of joint actions and experiments should remain manageable in order to allow time and resources to reflect on the social aspects of the process as well (G-5.2). A continuous process of monitoring and evaluation should also be conducted (G-7.1) to separate viable from less viable solutions (G-5.1). A purposeful stakeholder selection process (G-6.1) and design of an involvement strategy (G-6.2) are also important supporting factors. Learning from the experiences of other actors could be achieved by looking for innovative solutions and potential coalitions (G-6.5). Thus, group processes of like-minded actors from the local food system can together bring in stakeholders from the regional/provincial levels and external actors who can contribute to the implementation of innovative solutions. Some form of leadership within the group process is required (G-8) as well as the development of trust between participants (G-11) which requires a long-term engagement rather than short-term projects.

In the *organizational learning context*, stakeholder-based factors related to societal appreciation of sustainable products (O-2), a supportive institutional context (e.g., regulations tailored to local food systems) (O-3) and networking skills to facilitate cooperation among actors along the value chain) (O-11.4) all correspond with the results of the literature review. In addition, low-regret experiments (O-10.4) that only involve a low financial risk are mentioned as a supportive factor. Further factors that are consistent are related to programs that provide resources (O-15; O-15.1) for a local/organic food system (e.g., subsidies for or funding of education programs) and support knowledge exchange (O-16.1) between farms as well as among other actors in the food system. However, the literature review revealed a number of further factors that were not mentioned in the interviews and questionnaires. A self-critical attitude and awareness among organization members with regard to their own practices, problems and responsibilities can also be key factors for learning (O-7.2). A number of additional factors are related to the purposeful design of participatory processes, such as aligning the process and solution strategies with other opportunities at the landscape level (cf. multi-level perspective, Geels, 2011) (O-12.3) rather than sticking to ideal solutions. An overarching vision of a local food system (O-13.5) can be helpful to guide activities within and across organizations. Leadership is required with respect to inter-organizational processes as well as within organizations (e.g., farming businesses, distributors, retailers) (O-14). Case-specific learning factors are focusing on agricultural practices, such as crop rotation and integrating livestock on farms. Further specific factors are related to business and marketing strategies (e.g., production of premium products; distribution via ‘community supported agriculture’ model or local shops and restaurants).

In the *policy learning context*, stakeholder-based and literature-based learning factors include a change of government as a supportive factor for policy learning (P-2). In addition, results are consistent with respect to visionary leadership among policy-makers (P-7) that gives consideration to the benefits local/organic food. An important role for networks that connect local with (inter-) national lobbying efforts is also important for sharing experiences (P-9.6). Supportive contextual factors (P-11.1) are also important for facilitating the development of the local food system (e.g., through tailored legislation, subsidies or land use planning). This requires the acknowledgement of the value of a diverse food system (e.g., based upon a mix of local and international food systems) (10.7). In addition, the role of lobbying organizations promoting local/organic food is also seen as important (P-12.6). Knowledge exchange and integration (P-16.1; P-16.2) is considered pivotal, for instance, to allow for integrated land use planning and integrated assessment of measures. Governments can further provide resources for research and initiatives in the local food system (P-15.1). Case study results also confirm some impeding factors, such as the dominance of a command-and-control approach (e.g., with respect to food safety) (P-10.4) and lock-in effects due to entrenched power structures (P-10.5). The literature review adds further potentially important factors to this list. The existence of active communication with forerunners in the case study region can support policy learning (P-8). Policy entrepreneurs could also play a key role in fostering local/organic food (P-10.1), for instance by supporting transdisciplinary research processes (P-11.4) that integrate knowledge and achievement of tangible outcomes. Public involvement programs require a neutral party for process design and facilitation (P-12.1) which actively addresses power asymmetries (P-13.4). Participatory policy processes also require continuation over the long term and institutionalization (P-13.12), for instance by actively fostering capacity building within the network (P-10.6). Learning can be supported by a purposeful selection of stakeholders (P-12.2). For instance, participatory processes can bring together innovative regime actors and frontrunners from niches as well as "boundary spanners" that connect different networks (P-12.7).

4.1.4 Analysis and design of a transition governance process in the Canadian case study

A proactive steering of transitions requires interactions between actors within and across learning contexts. The proposed analysis and design approach specifies these requirements for interactions through the design of action situations that define actors and input factors required to address specific learning objects. In this section, the results of the structural analysis are provided first followed by the results of the temporal analysis.

The structural inter-context analysis results in an overview of learning contexts and their linkages as depicted in Figure 7a. The action situation in the **individual learning context** is named 'c*onsumer awareness and engagement'* and comprises learning objects no. 1 – 3. Consumer awareness and engagement can be actively facilitated by individuals such as citizens (e.g., lead by example) and parents (e.g., teach the importance of healthy food to their children). However, the other learning contexts also play an important role. Thus, policy actors can foster the clear labelling of local/organic food, offer local/organic food in public cafeterias, and require a translation of research findings from projects that are funded by public funds into formats that are easily interpreted by the public. In addition, actors in the local food system can contribute by engaging consumers (e.g., through community-supported agriculture) and bringing agriculture to people (e.g., through urban farms). In this respect, community gardens run by citizen groups can also be an important element.

The **group learning context** addresses the overall learning object of '*cooperation within the local food system'*, which comprises learning objects no. 4 - 8. Learning in the group context is supported by consumer awareness and engagement (individual learning context), local food infrastructure (organizational learning context), as well as general physical infrastructure (including cyber infrastructure), regulations, payment schemes and research/training programs (policy learning).

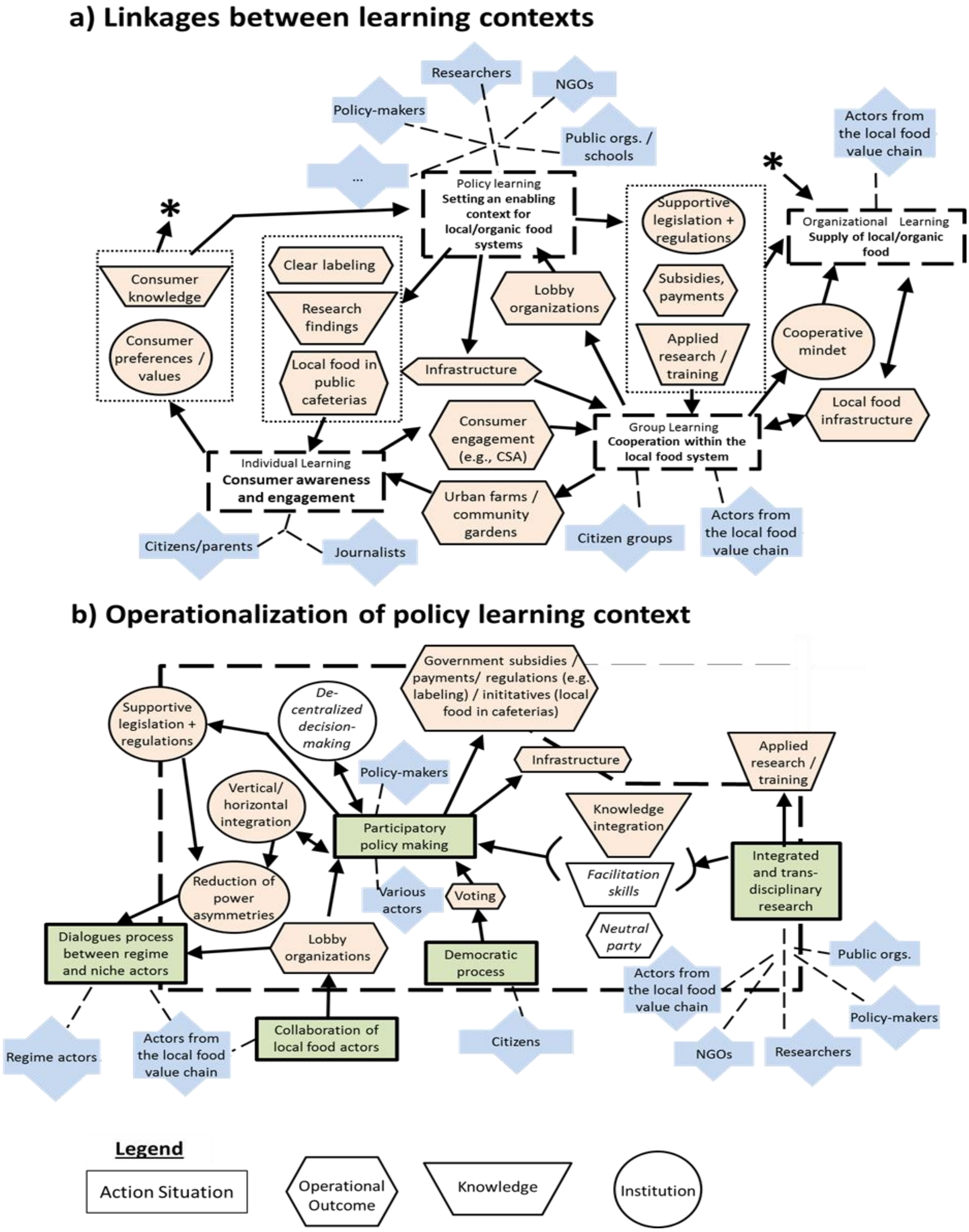

Figure 7: Visualization of transition governance process design from an overall systems point of view (i.e., overall inter-context analysis, see Figure 7a), and a context-internal perspective (i.e., detailed intra-context analysis, see Figure 7b). Orange elements are derived from case study research, while white elements stem from the general literature review. Action situations are the green boxes, and actors are the blue symbols.

The **organizational learning context** addresses '*supply of local/organic food'* and includes learning objects no. 9 - 15. The organizational learning context is influenced by supportive legislation, subsidies and applied research projects from the policy learning context. Learning in this context is further supported by a cooperative mind-set among actors in the local food system as well as infrastructure (which depends upon the cooperation of food system actors as well as the availability of sufficient supply).

Finally, the **policy learning context** addresses the overall learning object of "*setting an enabling context for local/organic food systems*", which comprises more specific learning objects (i.e., learning objects no. 16 - 20). Policy learning is fostered by outcomes of the individual learning context, including consumer knowledge and preferences that could lead to pressure on the political system to take action (e.g., by an increasing number of voters that are interested in food-related issues). Lobbying organizations in the group learning context can also support policy learning.

Figure 7b displays a **structural intra-context analysis for the policy learning context**. Specific action situations are identified for each learning object. Thus, a participatory policy-making process is required to tailor subsidies, payment schemes, land use planning and infrastructure investments to local/organic food systems. Supportive legislation and regulations as well as vertical/horizontal integration can reduce power asymmetries and thereby foster a dialogue between regime and niche actors. The democratic process is another action situation within the policy context that allows citizens to influence the policy process (e.g., voting for policy-makers that favor local food systems). Some action situations are located at the boundary of the policy learning context pointing to the fact that these action situations also include external actors. For instance, the interaction of integrated and transdisciplinary research has an integral function by bringing actors from different learning contexts together. These 'inter-context action situations' can support participatory policy making, e.g. through integrated and transdisciplinary research (e.g., to provide facilitation skills) or more informal dialogues between regime and niche actors.

The **temporal analysis** of the transition governance process has a stronger design component compared with the structural analysis. An sample pathway is described here that includes a sequence of key action situations leading towards a food regime in which a local food system plays a more prominent role. The temporal analysis should be used as a participation tool in future research so that transition pathways are based upon joint stakeholder discussions.

Figure 8 provides a sample transition pathway including action situations that address cross-context linkages in particular. At the outset, local food initiatives, such as community-supported agriculture, urban gardens and local farmers markets, allow for a continuous engagement of and communication with citizens. This can lead to higher demand for local/organic food and a greater number of people who actively engage in the local food movement. Actors from conventional food system (e.g., supermarkets), public organizations (e.g., cafeterias) and the local food system can work together in small and tangible projects and, thus, can gradually publicize successful cases (e.g., an increased customer base due to the offering of local food) and develop trust through personal relationships. Another important process can be the in-depth dialogue of local food actors and related NGOs in order to develop an all-encompassing vision of a future food system as well as representative organizations that can speak for the sector. Transdisciplinary research projects can include some of the aforementioned activities and bring together researchers, policy-makers and actors from the local food and conventional food systems. Transdisciplinary research can support deliberation through reflexive methods (e.g., visioning exercises, monitoring programs) and provide integrated knowledge about food systems.

A organization representing the local food system, a clear future vision, integrated knowledge, successful cases, trust across actor groups, and increased demand for and activism in local/organic food can together lay the foundation for a constructive dialogue between regime and niche actors on a level playing field. This dialogue process between policy-makers and representative organizations can result in legislation, subsides, payment schemes and infrastructure development that are more tailored to the requirements of a local food system.

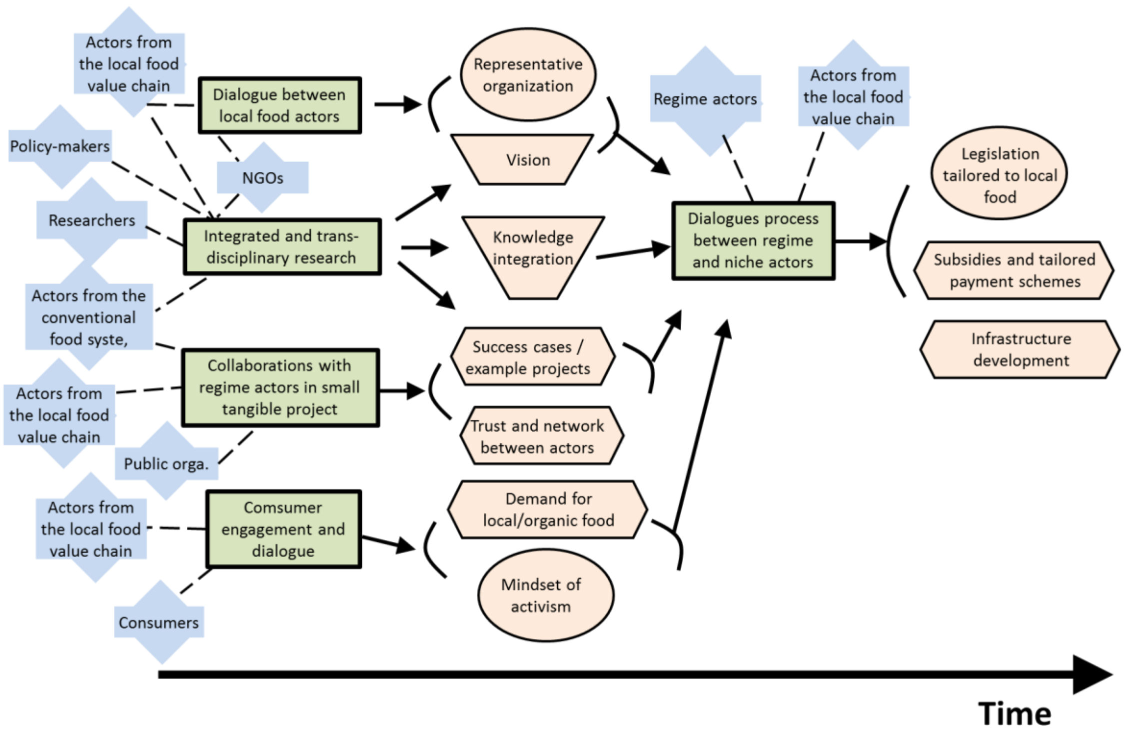

Figure 8: Hypothetical example transition pathway towards a more localized food system. See Figure 7 on page 52 for a legend explaining the meaning of geometric forms.

4.2 Cyprus case study on sustainability in the water-energy-food nexus

Water, energy and food are often managed in isolation without considering trade-offs and synergies (cf. Hussey and Pittock, 2012). The WEF nexus is an integrated concept that highlights the inter-dependencies and linkages that need to be addressed for sustainable development (Bazilian et al., 2011; Hoff, 2011). The nexus is often framed as a security nexus due to the general importance of water, energy and food security for prosperity and peace (Lawford et al., 2013). While the integrated water resources management approach focusses on the water sector, the WEF nexus gives equal importance to these sectors (Bach et al., 2012)) and thus provides a better starting point for dialogue and cooperation across sectorial ‘silos’.

The link between water and food supply is particularly evident given that freshwater withdrawal for agriculture accounts for about 60% of total global water abstractions (FAOSTAT, 2015b). Energy and water supply is connected by energy-intensive seawater desalination, which is expected to become increasingly relevant in the future (Lattermann et al., 2010). Further examples are hydropower plants and energy requirements for groundwater pumping (Hussey and Pittock, 2012). First-generation biofuels even provide an example of a ‘full nexus topic’, due to the negative impacts on water resources and food security (Mohr and Raman, 2013).

Sustainable solutions to increasing global pressures, such as climate change, population growth and aspirations for better living standards, will increasingly require nexus thinking (Bogardi et al., 2012). Knowledge about suitable policy instruments and technical solutions to address nexus challenges is currently limited and demands further research. Policies at different levels need to be coordinated, which also requires new governance approaches (Halbe and Knüppe, 2015). Integrated assessment approaches can be helpful in analyzing the implications of social and technical innovations on water, energy and food security (Halbe et al., 2015a). In the Cyprus case, multiple sustainability challenges in the WEF nexus are merging, such as water scarcity problems and fossil fuel dependence. This section presents the Cyprus case, which can be termed a ‘nexus hotspot’ (cf. Keskinen et al., 2015).

4.2.1 General analysis of problems, sustainability innovations and stakeholders in the Cyprus case study

Cyprus is member of the EU and has a GDP per capita near the EU average. Despite the high level of economic development, the water, energy and food sectors face substantial sustainability challenges. The Water Exploitation Index in Cyprus, measuring the annual total water abstraction as a percentage of available long-term freshwater resources, shows the highest value in the EU at ~ 64%, which is far higher than the following countries of Belgium (~32%) and Spain (~30%) (EEA 2010). This is mainly caused by the limited availability of freshwater resources per capita, which is the second lowest in the EU (Malta’s is the lowest) (Eurostat, 2015a). Between 2008 and 2012, the agricultural sector’s share in overall freshwater use was, on average, 84%, followed by the domestic sector (11%) and industry (5%) (FAOSTAT, 2015c). Deteriorating freshwater resources induced a shift in water supply policy to the development of non-conventional water sources. The capacity of the desalination plants (more than 200,000 m3/day) is sufficient to satisfy the full potable water demand in Cyprus (WDD 2011a, 2014). However, the energy requirements of desalination plants are substantial (cf. Koutsakos et al., 2005; Sallangos, 2005). The energy system in Cyprus is heavily dependent on oil imports, which is reflected in a share of petroleum products in gross domestic energy consumption of about 94% in 2013 (Eurostat, 2015b). The EU accession of the Republic of Cyprus in the year 2004 was a major driver for institutional innovation in Cyprus; for example, through the implementation of the Water Framework Directive (WDD, 2011a). The EU Renewable Energy Directive (EU, 2009) and the recent Paris-agreement on a limitation of global average temperature increases well below 2°C (UNFCCC, 2015) are among the further drivers that will affect the Cypriot energy system. The European debt crisis starting in 2009 was a major landscape event for Cyprus that resulted in the questioning of current business models (cf. Stephanou, 2011) as well as a reduction in trust in political institutions (Roth, 2009).

Initial expert interviews revealed that several sustainability innovations already exist, but are constrained by such socio-economic aspects as consumer habits or lack of financial support (cf. Halbe et al., 2015a). *Organic agriculture* was selected as a sustainability innovation due to several benefits, such as improved biodiversity (Topping, 2011), pollination (Gabriel and Tscharntke, 2007) and soil fertility (Mäder et al., 2002). The share of the organic food sector in Cyprus is increasing at a high pace (it increased 32 times between 2004 and 2012), but still accounts for only 3% of the total utilized agricultural area (Eurostat, 2014a). *Cultivation of traditional plants adapted to the local climate* (e.g., xeriscaping), such as herbs that can be used for pharmaceutical and cosmetic products, or teas, was mentioned as a related sustainability innovation (cf., Small and Catling, 2008). Data on traditional crops in Cyprus are currently not available. *Urban gardening* (e.g., community gardens) is a more bottom-up initiative in urban areas to secure food supply and improve social cohesion (Nasr et al., 2010). Data on urban gardening initiatives in Cyprus is lacking. However, part-time and smallholder farming is traditionally a widespread activity in Cyprus (cf. Davidova, 2014), which suggest beneficial spillover effects to gardening initiatives. *Aquaponics* is an innovative soil-less farming approach that can be adopted for personal consumption and as a business. Fish and vegetables are produced in a closed-loop system in which water is pumped between different basins. Accumulated ammonia in the fish tank is converted by bacteria into nitrates, which are consumed by plants (Borg et al., 2014). *Aquifer recharge* was mentioned by several stakeholders as an important approach for increasing groundwater levels and avoiding seawater intrusion (cf. Koussis et al., 2010). Artificial recharge through recycled wastewater and water from the reservoirs is conducted at a small scale today, but its increase is recommended in the future (WDD, 2010). *Rainwater harvesting* (Palla et al., 2012) and *grey water recycling* (Memon et al., 2012) can significantly reduce water consumption in the agriculture, domestic, tourism and industry sectors (UNDP 2011). Infrastructure (as well as data) for rainwater drainage and harvesting is currently limited in Cyprus (WDD, 2011b). Grey water recycling has been supported by government subsidies (UNDP, 2011), but actual numbers of the installed capacity were not available. *Decentralized renewable energy* systems using photovoltaics (cf., Dincer, 2000) was mentioned by several stakeholders as an option for improving energy security and reducing CO_2 emissions. The share of renewable energy in gross final energy consumption increased from 3.1% (2004) to 6.4% (2012), which is, however, far below the European Union average of 14.1% (Eurostat, 2014b). However, the potential for solar energy is considerable due to the high intensity of solar radiation (cf. Koroneos et al. 2005). *Conscious water, energy and food use* can also be considered sustainability innovations and which are currently supported through various measures, such as education in schools or awareness campaigns in the mass media (e.g., WDD 2011a; UNDP 2011). Energy productivity[7], which increased by 22% between 1995 and 2012, can be used as a rough proxy to assess the improvement in energy use efficiency (Eurostat, 2014c). Data on food use is completely absent, while the consciousness and efficiency of water use can be measured by fresh water abstraction per capita, which decreased by 7% between 2000 and 2012 (Eurostat, 2014d).

The stakeholder analysis revealed the important role played by government agencies (e.g., Water Development Department, Department of Agriculture, Department of Environment, Cyprus Energy Agency), water boards, farmer unions and research institutes (e.g., Agriculture Research Institute, Cyprus Institute, University of Cyprus). In addition, various types of innovators were contacted and interviewed, including innovative individuals (e.g., people who constructed an aquaponics system in a household context), community groups (e.g., who started a community garden), organizations such as businesses and special-interest groups (e.g., that lobby for organic agriculture), and policy-makers (e.g., who advocate innovative policies or initiatives). Each innovator represented at least one of the innovations mentioned in this section.

4.2.2 Analysis of stakeholder-based learning factors in the Cyprus case study

The economic crisis and climate change were mentioned by stakeholders as general factors that address learning objects, as they urge people to seek alternatives. All other learning factors are more specifically sorted to learning objects, as described below.

Learning objects linked to the *individual learning context* address consumer preferences and values with respect to water, energy and food. The learning object "environmental awareness and conscious resource use practices" (learning object no. 1) can be addressed by citizens and organizations that lead by example. Consumer education is another supportive factor that can be provided by parents and schools, as well as NGOs or media. Water demand management is mentioned as a supportive factor that requires action from policy-makers and public water management organizations (e.g., water boards). "Self-sufficiency at a personal level" is another learning object (learning object no. 2) in the individual learning context that requires changes in personal values and mindsets. Start-up support for self-sufficiency measures (e.g., solar panels) is a supportive factor that can be provided by the government or NGOs. Other supportive factors point to the key role of experiments, opportunities for information exchange (e.g., on the internet) and basic farming and craftsman skills of individuals. Resources can also be provided by individuals themselves or their communities, which however requires the ownership of resources (e.g., land) and the willingness to invest them in self-sufficiency measures. The "low number of customers for local, organic food" (learning object no. 3) is related to learning object no. 1 and requires changes in the value system of food consumers. This can be fostered by farmers explaining the benefits of local/organic food and traditional farming, as well as new distribution channels. Another supportive factor

[7] Definition by Eurostat (2014c): "The indicator results from the division of the gross domestic product (GDP) by the gross inland consumption of energy for a given calendar year"

can be the drafting of a new tourism strategy that envisions Cyprus as an “Organic Destination”, and which might attract new customers for organic and local products. Finally, the learning object “self-motivation to get informed and active” (learning object no. 4) requires changes in the mindset of individuals towards more active engagement. This can be supported by open access to data and information, and a re-framing of practices, such as urban gardening, as pleasurable leisure time activities.

In the group learning context, learning objects generally are oriented towards the development of a cooperative mindset. “Cooperation in the community to become more self-sufficient” (learning object no. 5) can be achieved through tangible community activities (e.g., community gardens) and exchange platform for resources (e.g., tools). This is linked to the “development of stable networks (e.g., for learning or exchange)” (learning object no. 6) that can be fostered through the provision of funds for community projects (e.g., from NGOs or public organizations) and the design of stable structures, including clear rules and responsibilities. Finally, “cooperation of farmers in the local, organic food sector” is another learning object (learning object no. 7), that again can be supported by joint workshops to exchange knowledge and skills, or exchange of physical resources, such as seeds.

In the organizational learning context, learning objects address alternative strategies and paradigms for water, food and energy management. “High water consumption for outside facilities and golf courses” has been mentioned as an object of learning (learning object no. 8). Xeriscaping in public gardens can be a supportive learning factor by serving as a good example to other organizations. Other supportive factors are policies that constrict activities with high water requirements, such as golf course development. Due to high water consumption, “mass tourism” is mentioned as another learning object (learning object no. 9), which can be addressed by a new tourism strategy. “High energy requirements of desalination plants” are also seen as problematic (learning object no. 10). Supportive factors are seen in an optimization of that technology as well as research on innovative desalination methods. Several learning objects are also related to organic food businesses. Thus, “high hurdles for start of a new organic farming business” are considered as learning objects (learning object no. 11). Supportive learning factors are startup support (e.g., loans, knowledge, subsidies, land), which can come from public organizations or NGOs, or be based upon the cooperation between food producers. Market studies to learn about customer demands and the development of a viable business plan have been mentioned as further supportive factors. The learning object of “fertility management” (learning object no. 12) can be addressed through on-farm measures, such as farming in close loops including composting. Another issue is the assurance of an “affordable land, energy, and water supply for organic, local farms” (learning object no. 13), which can be achieved through technologies that support self-sufficiency (e.g., rainwater harvesting, solar panels). Another supportive factor is the use of plants and animals that are adapted to the climate, as they usually require lower resource requirements. The application of advanced technologies, such as hydroponics or precision agriculture, has been also proposed by stakeholders. Policies can furthermore promote water-efficient crops. An impediment is however the limited land availability due to the topography of Cyprus (i.e., being an island with high mountains) and the division of the island.

In the policy learning context, stakeholders consider an “improvement of the current water resources management” as an issue (learning object no. 14). Supportive factors are EU water regulations and policies that demand increased stakeholder participation, transparency and accountability. Water demand management was, furthermore, mentioned as a critical measure as well as the consideration of environmental flows and ecosystem services. Further supportive measures are groundwater recharge, rainwater harvesting, and the re-use of treated wastewater, which needs to be closely monitored though. Studies on agricultural water use and options for groundwater recharge are also considered supportive factors. The issue of leaking water infrastructure (learning object no. 15) can be addressed through the provision of sufficient funding for investments in maintenance and repair. Another learning object is related to “investments and development of the grid for decentralized, renewable energy” (learning object no. 16). Stakeholders mentioned the development of a long-term vision and a regulatory framework for a decentralized, renewable energy system as supportive factors. Requirements to secure CO2 certificates are considered a further supportive factor. A related learning object is the lack of “knowledge and design of integrated local/regional energy system (electricity, heat, mobility)” (learning object no. 17), which can be can be fostered through further research and pilot projects.

In the next research step, stakeholder-based factors (Appendix 3) were compared with general learning factors (Appendix 1), as presented in the next section.

4.2.3. Comparison of stakeholder-based and literature-based learning factors in the Cyprus case

Across all learning contexts, case study and review results underline the relevance of a drastic societal crisis (e.g., an economic crisis or climate change) (I-1, G-1, O-1, P-1; see Appendix 1 for factor identifiers) as well as the availability of physical resources (I-9; G-9; O-15; P-15), information and knowledge (I-10; G-10; O-16; P-16). More context-specific results (i.e., factors that are not included in all contexts) are presented below.

A consistent supportive factor in the *individual learning context* is a curious mindset (I-5) that might result in the motivation to experiment with sustainable practices. Further supportive factors are inspirations from others (I-6) (e.g., through a new tourism strategy or role models) and application of the experimental methods (I-7) that are found in the case study and review results. Physical resources from governmental programs (I-9.3) and knowledge exchange (I-10.2) also play an important role. Several gaps can be identified by comparing case study results to the general factor list from the literature review, including a deep understanding of environmental processes (I-2) and a sense that experiments and innovations are related to everyday life (I-3). The realization of no-regret experiments (I-7.3), as well as the consideration of the social context of experiments (I-8) can also be supportive learning factors (I-7.3). The creative usage of available materials (I-9.1) and acknowledgement of the relevance of local and traditional knowledge can be further factors for supporting individual learning. A case-specific learning factor is water demand management that can be interpreted as an institution urging individuals to appreciate the value of water and change their consumption behavior.

In the *group learning context*, a consistent supportive factor is related to the commitment of actors to community action (G-4). Clear structures for collaborative processes, such as clear rules (G-7.1), furthermore comply across case study and review results. Finally, physical resources, such as funds for community project (G-9.1) and opportunities for knowledge exchange are found as success factors. Gaps in the case study results point to further relevant factors, such as relating community projects to everyday problems (G-3.4). The design of low-risk experiments can be a helpful approach (G-5.3) for finding viable solutions. The design of group processes can also explicitly consider networking with group–external actors (G-6.4) to receive support, close observation of other related processes (G-6.5), and the development of representative organizations (G-6.5) to achieve visibility and the consolidation of experiences. Furthermore, the collaborative development of a future vision (G-7.8) of sustainable food, water and energy systems, as well as provision of leadership (G-8) can be further supportive factors.

In the *organizational learning context*, sustainability-oriented institutions (O-3) (e.g., policies that enforce water-saving) are found to be consistent factors in the case study as well as review results. Furthermore, consistent factor relate to the application of innovations to obtain a competitive advantage (O-6.1) (e.g., precision agriculture), the existence of forerunners (O-9) and implementation of multiple experiments (O-10). Finally, physical resources, for instance from governmental programs (O-15.1), and knowledge exchange (O-16.1) are found to be consistent factors. The results show various gaps in the case study results. The literature review point to some impeding factors that are also relevant in Cyprus, such as a lock-in of an industry due to prior investments (O-5), which can be related to the mass tourism sector in Cyprus. Supportive learning factors can be the setting of sustainability visions by organizations (O-8), the development of skills for networking and collaboration (O-10.6) and active observation of the landscape for opportunities (O-12.3) (e.g., a trend in tourism towards outdoor and health-related activities). Case-specific factors in the organizational learning context are related to farming practices, such as farming in close loops.

In the *policy learning context*, consistent factors are related to a societal crisis (P-1), legislation that prescribes a participatory approach (P-4) (e.g., EU regulations and directives) and guiding visions (P-7) (e.g., of a decentralized energy system). Further supportive factors that are consistent across case study and review results are experimentation with multiple measures (P-9) (e.g., a rainwater harvesting system) and the implementation of policies that support sustainable behavior (P-11.1) (e.g., water demand management, or requirements to secure CO2 certificates). Policy learning also requires the continuous monitoring and evaluation of measures (P-13.11), knowledge integration (P-16.2) (e.g., using concepts of ecosystem services) and trust between actors (P-17) by assuring transparency and accountability. Examples of supportive factors that are included in the literature-based factor list, but not in the case study results, include societal values that favor sustainability (P-3) and the selection of a tangible topic for participatory processes (P-5.1). Further relevant supportive factors can be the existence of forerunners (P-8) (e.g., other countries or actors in Cyprus), the development of facilitation skills in the policy sector (P-10.6) and the general appreciation of a diversity of solutions (P-10.7). Policy learning processes could furthermore benefit from a balance between informal processes (e.g., through informal discussions with local initiatives) and formal processes (e.g., workshops) (P-12.4). Policy actors can support learning by providing leadership (P-14) through funding of promising initiatives (P-14.2) or facilitating information exchange (P-14.1).

4.2.4. Analysis and design of a transition governance process in the Cyprus case study

The structural inter-context analysis points to several linkages between learning contexts, as depicted in Figure 9. In the **individual learning** context, learning objects address changes in consumer values and knowledge, as well as their active engagement in sustainability topics. Thus, the overall action situation in the individual learning context is referred to as "*sustainability knowledge, values and engagement*". The policy learning context can affect individual learning through leading by example (e.g., public organizations that offer organic food or install water-saving fittings), education programs, sustainability-related legislation (e.g., water demand management) as well as the provision of funding and knowledge (e.g., for grey-water recycling or solar energy applications in households). Community groups can also support individual learning through leading by example (e.g., community gardens), and educating about sustainable practices and sharing of resources (e.g., land). Organizations can offer their knowledge and products, which can support the experimentation by individuals with innovations (e.g., installation of a rainwater harvesting system). **Group learning processes** are mainly aimed at the development of *networks for cooperation and exchange* of knowledge and equipment. The policy learning context can provide funds and infrastructure for knowledge exchange. Individuals can become engaged in community activities, and organizations can provide their skills and resources. **Organizational learning** involves strategies for *sustainable production processes* (i.e., low water, energy and land requirements) *and products* (e.g., organic food). The policy learning context can deliver various supportive learning factors, such as sustainability-related institutions, a future vision, resources, knowledge and leadership. Farm community groups can be pivotal in providing knowledge and resources. Individuals can support organizational learning by considering sustainability in their purchase decisions. **Policy learning** mainly addresses the *design and implementation of alternative water, food and energy supply systems* that have sustainability benefits. Policy learning can be supported by the visions and values of groups and individuals (e.g., through direct interactions or elections), as well as the expertise of businesses.

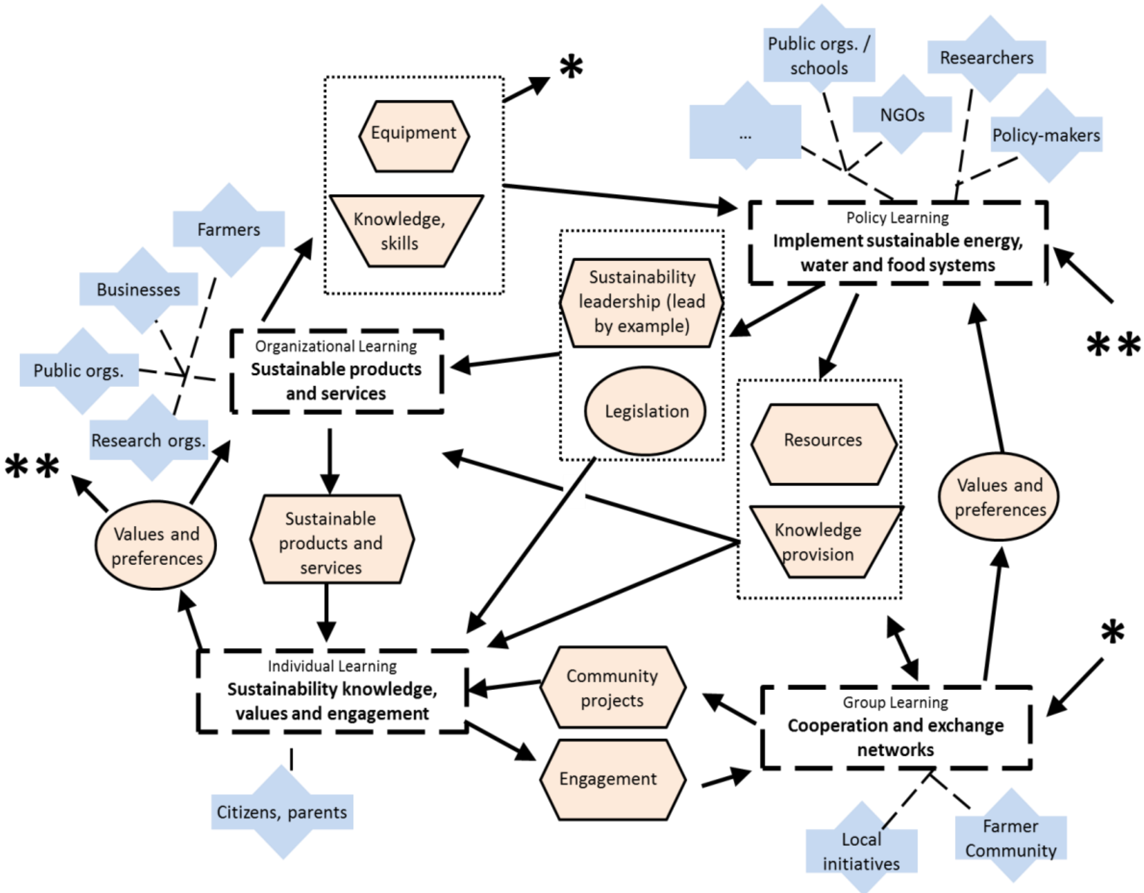

Figure 9: Inter-context analysis for the water-energy-food system in Cyprus. See Figure 7 on page 52 for a legend explaining the meaning of geometric forms.

As described in Section 4.1.4, the **temporal analysis** method is considered a participatory tool that requires strong stakeholder engagement. Based on the empirical results of the Cyprus case, an example of a transition pathway is presented in Figure 10 to illustrate the application of the methodology. The transition pathway starts with integrated and transdisciplinary research to address knowledge requirements that were mentioned by stakeholders. This research could analyze the designs of integrated water, energy and food supply systems, which can be used in local visioning processes (e.g., on a city, town or village scale). Pilot projects can be implemented in selected locations that provide reality checks for local visions and system designs. These experiences can feed into policy networks for water, energy and food supply in order to envision an upscaling of system designs at the national scale. This process can also include the vision of a new tourism strategy, as mentioned by stakeholders. In parallel, local initiatives, businesses and public organizations can collaborate to develop platforms of exchange for knowledge and resources (e.g., equipment). These platforms can contribute to the development of stable networks and provide critical resources for initiatives at the individual, community or organizational levels. Exchange platforms can attract new actors to participate and eventually develop a societal trend toward self-sufficiency and do-it-yourself. This can result in a broader uptake of sustainability values, and support local pilot projects and national policy initiatives that foster sustainability innovations (e.g., supportive legislation).

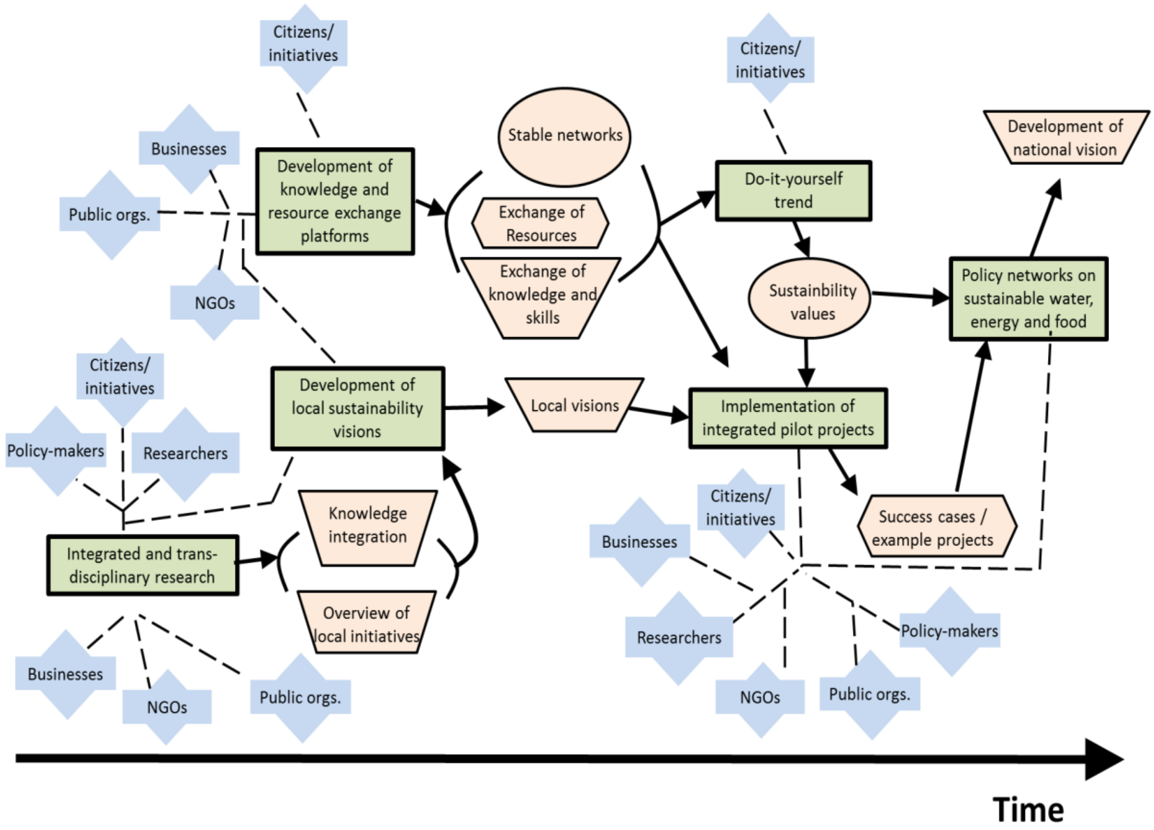

Figure 10: Example of transition pathway towards sustainable water, energy and food systems in Cyprus. See Figure 7 on page 52 for a legend explaining the meaning of geometric forms.

4.3 German case study on sustainable heating systems

In Germany, 19.4 % of the total final energy consumption[8] is attributed to space heating in residential buildings (BMWI, 2014a). The energy transition strategy of the federal government of Germany has the goal of reducing the heat demand of residential buildings by 20% between 2008 and 2020 (Bundesregierung 2010). Inter alia, a doubling of the annual energetic refurbishment rate[9] with respect to the insulation of the building envelope from 1 to 2% is the goal (Bundesregierung 2010; BMVBS, 2013). Property owners shall be encouraged to invest in the insulation of the building envelope, installation of efficient heating systems and use of energy from renewable sources (Bundesregierung 2010). Several instruments are mentioned in the German energy transition strategy to support the construction of energy efficient buildings and the use of renewable energy sources, such as the Energy Saving Regulation (EnEV) and the Renewable Energy Heat Act (EEWärmeG) (Bundesregierung 2010).

Energy consumption by buildings varies considerably due to the stepwise development of thermal insulation standards beginning in 1979 (BMWi, 2014b).

[8] The European Environment Agency provides the following definition: “Final energy consumption covers energy supplied to the final consumer for all energy uses” (EEA, 2015).

[9] The annual energetic refurbishment rate refers to the area of structural elements of the building envelope (e.g., external walls, roof, basement ceilings, windows) that underwent energetic refurbishment per year divided by the total area of the building envelope (BMVBS, 2013).

Buildings constructed after the EnEV already have a relatively low level of energy consumption at 71 kWh/m²a (under EnEV 2002/2007) and 50 kWh/m²a (under EnEV 2009) compared with 208 kWh/m²a for buildings that were constructed without thermal insulation standards between 1949 and 1978 (BMWi, 2014b). However, data on the building stock from IWU and BEI (2010) show that residential buildings that were built after 2002 only constitute about 6% of the housing stock, while buildings with a low energetic standard built between 1949 and 1978 constitute 40% of the housing stock (homes built before 1949: ~26.5%; between 1979 and 2001: ~27.5%). The high share of pre-1978 buildings underscores the fact that energetic refurbishment of residential buildings is of major importance for the implementation of the energy transition process in Germany. However, energetic refurbishment of the current housing stock requires specific instruments, including loan and incentive programs, provision of information and (on-site) advisory services, amendments to tenancy law and the leadership of public authorities by refurbishing state-owned real estate (Bundesregierung 2010, 2015).

From 2008 to 2013, some progress has been made in Germany which is reflected in the decrease of final energy consumption for space heating in private homes by 11 % from 161 to 144 kWh/m2 (these values are corrected for fluctuations in outdoor temperatures) (BMWI, 2014a). Prognoses, however, foresee that it is likely that the reduction target of 20% in the German energy transition strategy will not be met (cf. BMWI, 2014a). An expert commission on the progress of the German energy transition strategy point to shortcomings of instruments and ambiguity of their interplay. In addition, the targets are not ambitious enough to achieve long-term goals by 2050, and the energetic refurbishment measures implemented are not entirely conforming to minimum standards (Löschel et al., 2014). Several instruments are proposed by the expert commission, such as tax reductions and influencing user behavior (i.e., to avoid rebound effects). In addition, existing incentive programs should be aligned to reduce complexity and foster comprehensive and high-standard refurbishments rather than singular and superficial measures (Löschel et al., 2014).

The case study in the Ruhr region in the federal state of North Rhine Westphalia (NRW) has involved an analysis of barriers to and drivers of energetic refurbishment in residential buildings as perceived by stakeholders. This chapter presents the results of the participatory research process that focused on the City of Dortmund, which is the largest city in the Ruhr region.

4.3.1 General analysis of problems, sustainability innovations and stakeholders in the German case study

The government of NRW passed a climate protection law in 2013 that sets reduction goals for greenhouse gases (Landesregierung NRW, 2013). By 2020, greenhouse gas emissions shall be reduced by 20% compared with the total emissions in the year 1990. By 2050, a reduction by as much as 80% is envisioned. The central instrument is a 'climate protection plan' that specifies intermediate steps, contributions of economic sectors, as well as targets for resource protection, resource and energy efficiency, energy savings and use of renewable energy (Landesregierung NRW, 2013). According to the

NRW climate protection plan, greenhouse gas emissions in the ‘buildings, trade, commerce and services’ sector should decrease by 30% by 2020 and at least by 81% by 2050 (reference year is 1990) (LANUV, 2015). Several strategies are proposed for the ‘residential and non-residential buildings’ sector: increase the number of energetic refurbishments (in German: Sanierungsrate); heighten the ambitions of energetic refurbishments (in German: Sanierungstiefe); increase the share of renewable energy use in the building sector; and the implementation of integrated solutions (e.g., zero-energy homes) that combine energy self-generation and load management. Proposed measures range from improving public funding opportunities to better energy consulting services, technical innovation, monitoring programs and education initiatives (LANUV, 2015). In addition to the efforts at the level of the state government, several cities have developed their own masterplans and initiatives to translate high-level goals into city-specific strategies. For instance, the City of Dortmund developed a master plan for energy transition (Masterplan Dortmund 2014) and the City of Bottrop developed the master plan for climate-focused urban redevelopment (in German: Masterplan klimagerechter Stadtumbau) (Masterplan Bottrop, 2014). In addition to these policy initiatives, economic developments also provide incentives that stimulate actors to invest in energy efficiency measures. For instance, monthly heating costs of tenants have increased by 63% between 2005 and 2013 from 0.76 €/m² to 1.24 €/m² (Mieterbund, 2006, 2014).

Given the definition of innovation as an “idea, practice, or object that is perceived as new” Rogers (1995, p.11), we consider technical and social measures for energy efficiency in buildings as innovations in this case study. Even though a measure like building envelope isolation is a well-known object, energy transition plans (e.g., the NRW climate protection plan) consider it as a key approach that needs to be implemented on a larger scale. Stakeholders mentioned further technical sustainability innovations in the residential heating system, such as energy-efficient heating technology (e.g., condensing boiler), hydronic balancing (i.e., optimization of current heating system), sensors for heating control, heat exchange devices, renewable energy (e.g., photovoltaic, solar heat, geothermal energy), and combined heat and power (e.g., local heat networks). Social innovations have also been mentioned such as raising consciousness of heating behavior, energy consulting (including thermal imaging) as well as the improvement of education and apprenticeship of architects, craftsmen and other professional actors (in order to allow for effective implementation of measures).

Data on the implementation rate of the aforementioned sustainability innovations are mainly available on a national scale only. A study in 2009/2010 shows that 42.4% of residential buildings in Germany have insulated outer walls, 64.6% of buildings have an insulated roof, and 37.1% have an insulated basement ceiling or ground plate (IWU and BEI, 2010). Given that the year 1995 is considered as the starting point for the introduction of heat protection glass, about 54% of residential buildings contain windows that are energetically advanced (IWU and BEI, 2010). Heating sources in residential buildings are mainly gas (~52%) and oil (~33%) (IWU and BEI, 2010). About 6% of all residential buildings are exclusively using renewable energy for space heating, and 13% use renewables to provide a share of their demand for heating energy (BMUB, 2012). In 2013, about 15% of final energy consumption for heating and cooling was provided by renewables, mainly biogenic solid fuels (~83% of renewable heating energy), solar heat (~8%) and heat pumps (~9%) (BMWi, 2015). Central heating systems are the main heating system type in residential buildings (~84%), followed by apartment (~5%) and room (~7%) heating systems, and district heating (~4%). The analysis of apartments reveals a higher relevance for district heating (~12 %), indicating a higher application of this heating system type in multi-family houses.

The stakeholder analysis resulted in a selection of stakeholders comprising owners of residential properties (ranging from individual homeowners to large housing corporations), public and private energy consultants, municipal energy suppliers, funding agencies (e.g., local banks, public funding bodies), local authorities, lobbying and representative associations (e.g., professional associations, property owner associations, tenant associations), and crafts enterprises. Owners of residential properties were found to have a particularly important role in the system, as they are the ones who take the final decision on energetic refurbishment measures. The case study includes interviews with a high number of experts (i.e., who provided an overview of potential issues and innovations) as well as property owners who decided for an energy efficiency measure. Property owners, local authorities and organizations representing local interests were found to be most important in providing case-specific information. Other actors were considered to have a more general perspective on barriers to and drivers of energetic refurbishments. If establishing contacts with these expert actors in the case study region turned out to be problematic, actors in other regions were approached (in the regions of Münster, Osnabrück and Hannover). These actors included energy consultants, public funding organizations, banks, energy suppliers and crafts enterprises. Some actors were not interested in an interview, including the KFW (Promotional bank of the Federal Republic of Germany; in German: Kreditanstalt für Wiederaufbau) and producers of insulation material and heating systems. Due to the importance of these actors to the research topic, future studies should include these actors where possible. Nevertheless, interviews were conducted with diverse actor groups so that the study includes various perspectives on energetic refurbishment in the Ruhr region.

4.3.2 Analysis of stakeholder-based learning factors in the German case study

As a general impeding factor to energetic refurbishments, stakeholders mentioned construction-related limitations and monument protection that can constrain opportunities for energetic refurbishment. All other factors are sorted according to their respective learning contexts as described below.

Learning objects in the *individual learning context* address awareness of energy topics and sustainable consumer behavior, as well as aspects that are considered by individual owners of residential property (professional real estate companies are allocated to the organizational learning context category) in their decision for or against energetic refurbishment. “Conscious energy use and awareness about energy topics” (learning object no. 1) can be fostered by consumer education. However, changes in unsustainable user behavior (e.g., fresh air ventilation even though an automatic ventilation system is installed) are considered to be hard to accomplish as it is a widespread habit in Germany (i.e., awareness of the problem might be low). Another learning object can be the lack of "knowledge about refurbishment options by owners of residential property (learning object no. 2). Supportive learning factors are considered to be opportunities for self-information (e.g., via the internet), independent advisory services and information campaigns, and a nuanced discussion in the media. However, one stakeholder also pointed to the danger of excessive information which might confuse home owners. "Aesthetic demands" (learning object no. 3) can be another issue (e.g., with respect to insulation of the building envelope or solar panels), which can be addressed by casting a positive or even a prestigious societal image on energetic refurbishment. The "unsettledness of home owners" (learning object no. 4) can be caused by the complexity of the topic, short cycles of innovations (i.e., knowledge is quickly outdated) or the advanced age of the property owner (which can be the reason for more risk-averse behavior). To address this issue, simple energy efficiency measures and financing options and a single contact person (who provides information and supervises the implementation process) can be supportive factors as these measures reduce complexity. Further supportive factors are independent and customized advisory services, positive examples in the neighborhood or personal environment, and a feeling of responsibility by the property owner. Another learning object is the "high cost of energetic refurbishment" (learning object no. 5). Financing options are mentioned as supportive factors, such as tax incentives, loans, allowances and own capital. Stakeholders proposed tax incentives and allowances in particular due to their more direct benefits. In addition, measures are proposed that reduce investment cost such as simple energetic refurbishment options (e.g., sensors for temperature regulation) in combination with standard retrofitting measures (e.g., in case the replacement of an outdated heating system is necessary). However, stakeholders mentioned that such simple measures are impeded by loan programs that require a high standard for energetic refurbishment. General supportive factors to address cost issues (i.e., learning object 5) are rising energy prices, low interest rates, and a positive societal image of energetic refurbishment, which can provide a sense of prestige and increase the value of real estate. Regulations that restrict opportunities to apportion costs of refurbishment to tenants and low purchasing power in a region can be impeding factors though. A "dialogue between landlord and tenant" (learning object no. 6) may be required to reduce potential conflicts before, during and after the implementation phase (e.g., related to rent abatements and rent increases). A modernization agreements between landlord and tenants, which is explicitly mentioned in the German Civil Code (§ 555f BGB), can help to reduce conflict from the outset. Further issues are "high time requirements and efforts" (learning object no. 7), which can be addressed by asking others for help (e.g., friend or family members) or energy consultants who accomplish the planning and supervision of implementation. Another issue from an energetic point of view that was mentioned was a "large living space per person" (learning object no. 8). Stakeholders proposed the widespread development of shared flats, even for seniors. In addition, a sufficiency strategy was proposed, i.e., that encourages people to be content with a smaller living space.

In the *group learning context*, learning objects address dialogues and cooperation within homeowner associations (dt. "Eigentümergemeinschaft"). The first learning object relates to the lack of “cooperation within homeowner associations” (learning object no. 9) that can constrain energetic refurbishment. Finance schemes tailored to homeowner associations and supported by independent advisory services are proposed by stakeholders to address this issue. Given the “high cost of energetic refurbishment” (learning object no. 10), homeowner associations face similar challenges compared with the individual learning context. Thus, financing opportunities, the current renovation requirements of the building and expectations of future benefits influence the decision-making process.

Several learning objects are related to the *organizational learning context*, which address professional actors, such as housing corporations, energy consultants, craftsmen, architects, and producers of insulation material. “Limited skills of craftsmen, energy consultants, and architects” (learning object no. 11) can cause failures in the design and implementation of energetic refurbishments. Stakeholders proposed the improvement of current training curricula and the offering of more advanced training. Further supportive factors include better advertising of apprenticeships in order to promote interest among a higher number of qualified prospective applicants. Other solutions are the training of specialists, such as company-internal energy managers and a stronger focus on simple energetic refurbishment options rather than picking up every innovation. Further issues are the lack of “environmentally friendly and affordable options for thermal insulation of the building envelope” (learning object no. 12). Since conventional materials are often seen as unsustainable and have a poor image, a wider use and production of sustainable insulation materials is required, which can be supported by incentive and research programs and increasing pressure for alternative approaches. The “gap between calculated energy savings and actual savings” (learning object no. 13) can be addressed through better monitoring of the results of energetic refurbishment measures and penalties for noncompliance with targeted energy savings. Supportive factors that address the “profitability of energetic refurbishment” (learning object no. 14) include available options for financing, demand by tenants, age of the heating system and building envelope, regulations regarding standards and cost allocation, and expected profits.

In the *policy learning context*, the “provision of affordable living space” (learning object no. 15) can be accomplished with more investment in public housing, or introduction of regulations such as a ‘climate bonus’ that links housing allowances to energetic quality criteria, or a temporal limitation of cost allocation linked to energetic refurbishments. A sufficiency strategy (i.e., being content with smaller living space) can also address this learning object. Another learning object that was mentioned by stakeholders is related to “current regulations and financing schemes” (learning object no. 16) that set high hurdles for simple measures. A low refurbishment rate below politically-set targets can induce a rethinking which might be detrimental to the interests of some actors (e.g., producers of insulation material) and could have detrimental side effects such as replacing ambitious energetic refurbishments with less-efficient measures (dt.: “Breiten- vs- Tiefensanierung”).

4.3.3 Comparison of stakeholder-based and literature-based learning factors in the German case study

Across all learning contexts, case study and review results demonstrate the importance of physical resources (I-9; G-9; O-15; P-15; see Appendix 1 for factor identifiers). The general impeding factor related to constructional limitations for energetic refurbishment is specific for the case study topic though. More context-specific results (i.e., factors that are not included in all contexts) are presented below.

Supportive learning factors that are consistent between case study and review results linked to the *individual learning context* are the existence of a disturbance or crisis (e.g., rising energy prices or financial crisis) (I-1), sustainability-related values (e.g., valuing thermal insulation of a building) (I-2), a relation to everyday life (I-3), human aspirations (e.g., feeling of responsibility) (I-4), a critical mindset (e.g., people who take action to get informed) (I-5), and inspiration from others (e.g., neighbors) (I-6). Further supportive factors that were consistent include monitoring and evaluation of energetic refurbishment measures (e.g., smart meters) (I-7.2), low financial risks (I-7.3), availability of physical resources (including own capital, help from others (I-9.2) and special funding schemes (I-9.3)). A constructive dialogue between landlords and tenants is a further supportive factor (I-8.1) that should be accomplished in an honest way (I-8.2). Finally, exchange and integration of information and knowledge (I-10.2; I-10.3) is included in the stakeholder-based as well as review-based factor list. The list of review-based factors does not reveal major gaps in the stakeholder-based factor list. Several case-specific factors are included in the factor list though (see Appendix 4). Thus, widespread habits with regard to energy use and ventilation are assessed as an impeding factor that can limit the motivation of actors to adopt new behavior. In addition, risk-adverse behavior and the complexity of measures (e.g., due to short innovation cycles) can be important impeding factors. The expectation of gaining prestige and profits can be a motivational factor that has not been included in the general factor list yet. Trust (e.g., in information and consultants), sustainability-oriented institutions, and the ability to collaborate can be additional supportive learning factors in the individual learning context.

In the *group learning context*, a number of learning factor comply across stakeholder-based and review-based factors, comprising an economic crisis (G-1), a prestigious topic (G-3.2) and low risk measures (G-5.3). Further consistent factors are a collaborative discussion of rules (G-7.1), provision of physical resources (G-9.1), as well as knowledge exchange (G-10.1) and integration (G-10.2). Several gaps between the stakeholder-based and review-based results point to further important factors. Thus, homeowner organizations (e.g., “Haus und Grund”) can consolidate experiences from various projects (G-6.6). Leadership (G-8) and trust (G-11) within a homeowner association are further potentially important factors. Case-specific factors (which can potentially be included in the review-based factor list) relate to impacts of legislation as well as expectations of prestige and profit.

Consistent factors in the *organizational learning context* relate to an economic crisis (O-1), societal values (e.g., a generally favorable perception of energetic refurbishment) (O-2), sustainability-oriented legislation (e.g., EnEV) (O-3), prospects of future profits (O-3.1), low-risk measures (O-10.3), process monitoring (O-13.7), effective communication and networking skills (O-11.3; O-11.4), as well as the availability of physical resources (O-15.1; O.15.2) and knowledge exchange (O-16.1). Further factors from the review-based factor list can play an important role in the German case study. Thus, externalities (O-4) can be an impeding factor to sustainability-oriented learning as disposal costs are not included in the price of insulation materials. Another relevant factor can be the existence of forerunners (O-9) such as real estate companies that advertise a high energetic standard for their buildings. Finally, leadership (O-14) and trust (O-17) can be critical factors in cooperation with tenants or professional actors such as architects or craftsmen. Case-specific factors that support learning are deterrents where negative side-effects of a technical option become apparent. Impeding case-specific factors are short innovation cycles that impede the development of skills, as well as legislative and economic factors that constrain the profitability of investments.

In the *policy learning context*, the following learning factors are consistent across stakeholder-based and review-based factors. Thus, societal values (P-3) (e.g., greater acknowledgement of sufficiency strategies) can be a supportive factor. Further factors are visionary leadership (P-7), active influence of the context of firms and other actors (P-11.1), and leadership by providing public housing (P-14). Impeding factors can be entrenched power structures and actor networks which can constrain policy learning (P-10.5). The comparison also revealed several gaps in the stakeholder–based factor list. Thus, forerunners and prime movers (P-8) can provide new impulses that can be supported by the development of innovation networks (P-9.5). Further relevant supportive factors are vertical and horizontal dialogues (P-10.3) (e.g., between local and national policy actors), the acknowledgement of a diversity of refurbishment approaches (P-10.7) (e.g., considering technical and behavioral measures), and transdisciplinary research processes (P-11.4) that provide tangible and integrated findings (P-16.2). Finally, the development of trust (P-17) and the explicit tackling of power imbalances (13.4) can be further important factors. Case-specific learning factors are not included in the policy learning context.

4.3.4. Analysis and design of a transition governance process in the German case study

Figure 11 shows the result of the structural analysis of interactions between learning contexts (i.e., structural inter-context analysis). Individual learning is included in an overall action situation addressing the "*sustainable living*" of householders (e.g., learning about sustainable energy consumption behavior). This overall action situation can be influenced by the policy learning context through education/awareness-raising programs (e.g., in schools or public information campaigns), as well as by interactions between tenants and owners of residential properties. The overall action situation "*effective energetic refurbishment measures*" contains individual, group and organizational learning, i.e., all building owners, such as individual property owners, homeowner associations, housing corporations and public housing (public housing is related to organizational learning, as this action situation is linked to facility management instead of public policy). Learning in this action situation can be influenced by tenants (i.e., individual learning context) that have sustainable values, preferences (e.g., demand for energetically refurbished apartments) and energy consumption practices, and are open to cooperation with landlords who plan a redevelopment measure (e.g., through a modernization agreement). Further supportive learning factors stem from the policy learning context including legislation (e.g., tenancy law) and funds (e.g., tax exemptions). Funds can also be provided by public organizations (e.g., KFW or the Federal Office for Economic Affairs and Export Control (BAFA)). Additional learning factors are integrated knowledge (e.g., from advisory services), sustainable energetic refurbishment options (e.g., cost-effective and sustainable insulation materials) and monitoring systems (e.g., smart meters) which can be provided by several organizational actors, such as architects, energy consultants, and craftsmen amongst others.

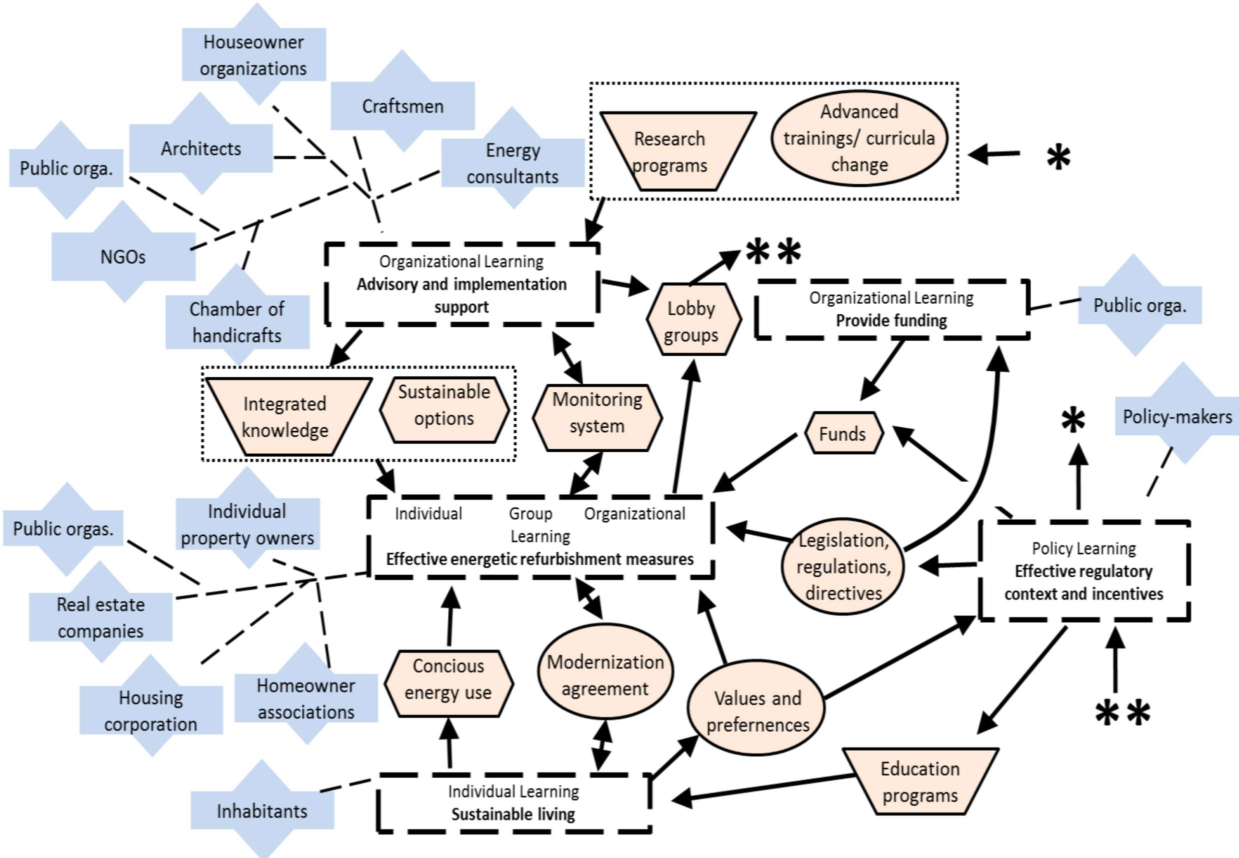

Figure 11: Inter-context analysis for the German case study. See Figure 7 on page 52 for a legend of the geometric forms.

The overall action situation "*advisory and implementation support*" (see Figure 11) includes professional actors that provide practical advice and services to owners of residential property. Learning in this context can be supported by research programs and frameworks for advanced training and curricula change from the policy learning context. Monitoring of completed energetic refurbishments can be another factor that supports reflection and evaluation. The overall action situation "*provide funding*" is also related to the organizational learning context (involving public organizations) which can be influenced by legislation, regulations and directives from the policy learning context. The policy learning context is finally included through an overall action situation that is aimed at "*effective regulatory context and incentives*". Supportive learning factors can be value and preference changes of residents (i.e., individual learning context) as well as lobbying activities of organizational actors.

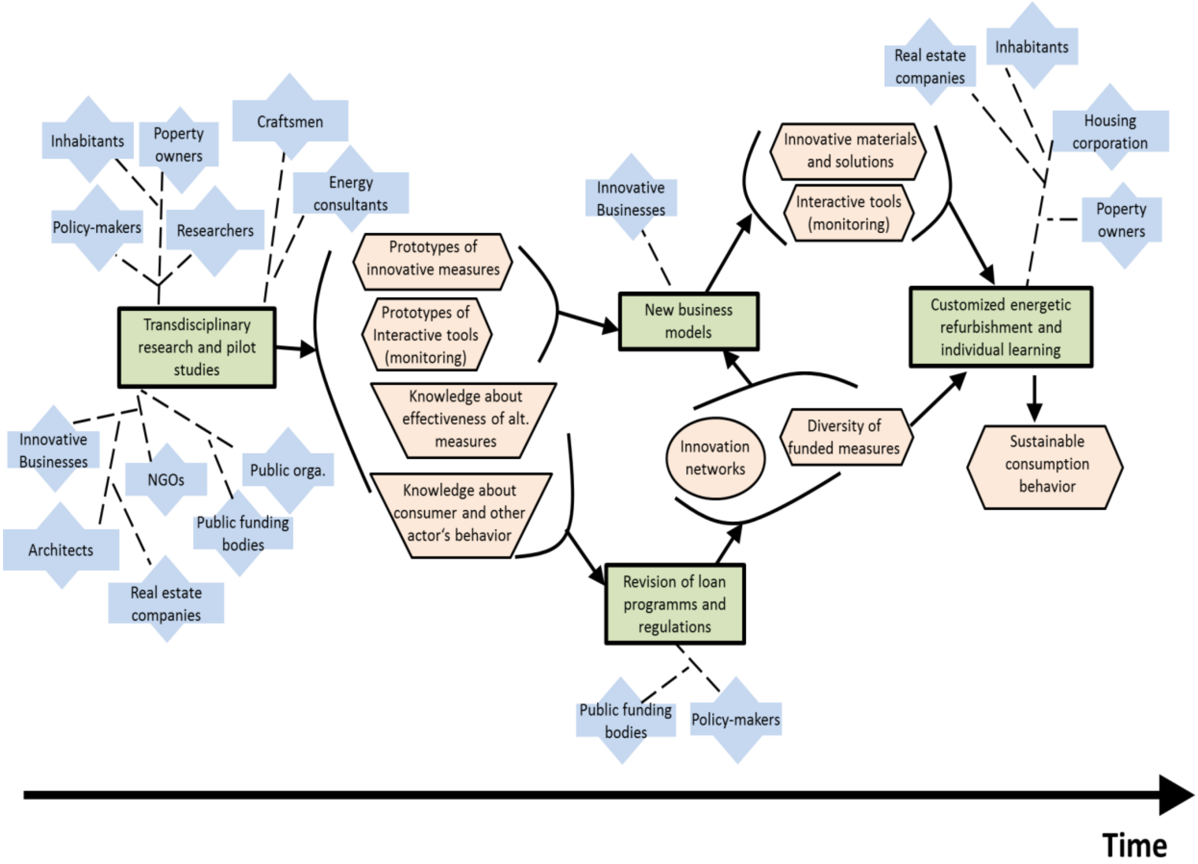

Figure 12: Example of a transition pathway for the German case study. See Figure 7 on page 52 for a legend of the geometric forms.

Figure 12 provides an example of the pathway of a transition towards a more sustainable housing system with significantly reduced energy needs. At the outset of the process, a continuation of transdisciplinary research projects, such as the EnerTransRuhr Project, can bring together various actors in the housing system, including residents, owners of residential property, advisory and funding organizations, as well as planners, manufacturers and craftsmen. As a result, the project could analyze the decision-making behavior of different types of residential owners (e.g., individual owners, corporations, public housing organizations) (cf. Albrecht and Zundel, 2010; Weiß and Vogelpohl, 2010; Friege and Chappin, 2014) and an integrated assessment of various measures (e.g., Soukup et al., 2012) and their effects in specific regional or urban contexts (cf. Großmann et al., 2014), including simple and low price options that affect the behavior of residents (e.g., products that provide feedback to users, cf. Laschke et al., 2011; Jensen et al., 2015). The findings could be considered in a revision of funding programs and regulations in order to make energetic refurbishment attractive to various different types of owners. This can result in revised funding structures and regulations that foster a higher diversity of energy efficiency measures while still assuring a high ambition of energetic refurbishments. Thus, support programs should still promote the combination of age-related maintenance and repairs of the building fabric with energetic refurbishment measures. Nevertheless, additional, relatively low-cost measures could be supplementary approaches for residents and property owners. In particular, devices for monitoring energy consumption behavior, such as smart meters, can be a key approach for inducing low-cost experimentation and learning (Wood and Newborough, 2003). Innovation networks could be established around promising sets of technical and social innovations in order to analyze side-effects as well as develop standards and regulatory structures for a market launch. Transdisciplinary research projects can also support the development of innovative measures and products for energetic refurbishment (e.g., innovative isolation materials) as well as prototypes of interaction tools (e.g., sensors and displays). Based upon these outcomes as well as favorable context conditions through innovation networks and new regulations, new business models in the energetic refurbishment sector can flourish. Innovative materials and technical solutions can enter the market allowing energetic refurbishments that are more customized. Interactive tools can furthermore stimulate the learning of sustainable consumption behavior, and, eventually, substantially reduce energy consumption in the housing sector.

4.4 Synthesis

Table 4 provides an overview of the case study results, including the number of learning objects and factors across learning contexts. Most learning objects in the Canadian and Cypriot case studies are related to the organizational learning context, while the German case study includes most learning objects in the context of individual learning. Given that learning objects are linked to sustainability issues and thus represent a learning requirement (cf. Halbe et al., 2015a), sustainability transitions in the food system in Ontario and the WEF nexus in Cyprus have to predominantly foster learning in organizations, including farming businesses, processing and distribution facilities and public organizations. In the case study on the refurbishment of space heating systems in Germany, learning is mainly required in the individual context, i.e., individual owners of residential property (e.g., with respect to deciding for or against an energetic refurbishment) and residents (e.g., with respect to energy consumption practices). However, the results for each case study reveal that there are learning objects in all learning contexts, which underscores the importance of multi-level learning in sustainability transitions, comprising the individual, group, organizational and policy levels.

Learning factors can be physical objects (e.g., infrastructure, funds), knowledge and institutions (e.g., a piece of legislation) that address learning objects, and thus are ‘working points’ for approaching sustainability issues. Similar to learning objects, the case study results reveal learning factors in all learning contexts (see Table 4). The largest number of learning factors were identified in the Canadian case study and are related to the organizational learning context. In the Cyprus case, the individual and organizational learning contexts display the largest number of learning factors, while the German case reveals that most learning factors are in the individual learning context. Thus, the numbers of learning factors generally correspond to the number of learning objects (i.e., a large number of learning objects implies a large number of learning factors).

Table 4: Overview of case study results comprising (1) an analysis of the number of learning objects, learning factors and roles across case studies, and (2) main factor categories across case studies (Grey scale in the numerical results section reflects the ranks of categories ranging from largest number (dark grey and bold font) to the second rank (medium grey scale), third rank (light grey) and fourth rank (white). In the main factor categories section below this, green boxes denote main factor categories within learning contexts that are consistent across all case studies. Crossed boxes indicate main factor categories that are not included in the respective learning context according to the systematic review).

	Canada				Cyprus				Germany			
Learning Contexts[10]	**I**	**G**	**O**	**P**	**I**	**G**	**O**	**P**	**I**	**G**	**O**	**P**
Numerical results												
Learning Objects	3 (15%)	5 (25%)	**7 (35%)**	5 (25%)	4 (24%)	3 (18%)	**6 (35%)**	4 (24%)	**8 (50%)**	2 (13%)	4 (25%)	2 (13%)
Learning factors	12 (21%)	11 (20%)	**18 (32%)**	15 (27%)	**15 (30%)**	6 (12%)	**15 (30%)**	14 (28%)	**44 (44%)**	18 (18%)	30 (30%)	8 (8%)
Role in implementation process of learning factors	16 (33%)	29 (60%)	**40** (83%)	27 (56%)	17 (34%)	21 (42%)	**43 (86%)**	33 (66%)	34 (39%)	14 (16%)	**58 (66%)**	46 (52%)
Case-specific factors	1	0	8	0	1	0	2	0	15	6	7	0
Main factor categories												
Disturbance or crisis	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	
Change of government				✓								
Societal values that favor sustainability	✓								✓			✓
Sustainability-oriented institutions			✓				✓	✓			✓	
Topic-arousing attention and motivation		✓					✓		✓	✓	✓	
Provision of a leading sust. vision	✓			✓				✓	✓			✓
Commitment (awaren.+ responsibility)						✓					✓	
Existence of forerunners	✓				✓		✓		✓			
Externalities and lock-in effects												
Planning/implement. of experiments			✓	✓	✓		✓	✓	✓	✓	✓	
Structures that support participation			✓	✓							✓	✓
Policy instruments				✓				✓				✓
Design of participatory processes	✓	✓		✓								
Process facilitation		✓				✓		✓		✓	✓	
Leadership												✓
Physical resources	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Information and knowledge	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	
Trust								✓				

[10] I := Individual learning context; G := Group learning context; O := Organizational learning context; P := Policy learning context

In addition, Table 4 shows the roles in the implementation process denoting whether individuals, groups, organizations or policy actors are involved in the implementation of learning factors. As actors from various learning contexts can be required to interact in the implementation of a learning factor (i.e., multiple selections per learning factor are possible), the number of roles is generally larger than the number of learning factors. In fact, most of the learning factors (i.e., ~ 69%) require cooperation across learning contexts during the implementation process (see Appendixes 2-4). Across all case studies, organizations have the largest role in the realization of learning factors. In the Cyprus and German cases, policy-makers come second, while in the Canadian case group actors' roles are slightly more in number than policy actors' roles. Individuals have a smaller role in the implementation of learning factors in the Canada and Cyprus case; in the German case, individuals come are in third place. Nevertheless, individuals are involved in the implementation of more than 30% of learning factors in all case studies, which shows that individual actions still have an important role. Group activities play the largest role in the Canadian case (linked to 60% of learning factors), followed by the Cypriot case (42%) and the German case (16%). These results suggest that stakeholders in the Canadian case study perceive a major role for community action (e.g., to share equipment, seeds and knowledge in a local food system). The low proportion of group activities in the German case study can be explained by the important role of private property in energetic refurbishments that might limit the opportunity of community processes. The role of organizations and policy-makers in the implementation of learning factors show similar levels in the Cyprus and Canadian cases. Thus, organizations are related to the implementation of more than 80% of learning factors and policy actors are related to about 60% of learning factors. The German case involves a slightly lower relevance of roles related to organizations (66%) and policy actors (52%).

The comparison of learning objects, learning factors and roles leads to interesting findings with respect to sustainability issues and learning requirements (i.e., learning objects), potential intervention points (i.e., learning factors) and the agency in the implementation process of interventions (i.e., roles). In the Canadian case, the organizational learning context shows the largest number of objects, factors and roles. This can be interpreted as an advantageous situation for learning, as problems, solutions and agency are positioned on the same societal level. Nevertheless, a more detailed look at the case study results (see Appendix 3) reveal that an individualistic mindset among farmers constrains cooperation between organizations, which, in order to address, requires changes in deeply-held paradigms. Furthermore, the Canadian case study results show a relatively low number of learning factors in the group learning context, while the number of roles is relatively high for this context. This suggests that groups play an important part in inter-context processes (e.g., collaborative actions of the farm community to provide knowledge to farm businesses). The Cyprus case also shows the largest number of objects, factors and roles in the organizational learning context. Similar to the Canadian case, organizational learning plays an important role in a sustainability transition, comprising farming businesses, operators of desalination plants, and public organizations. The individual learning context in the Cyprus case includes a large number of learning objects and factors, reflecting several sustainability issues (e.g., consumer preferences) as well as intervention points (e.g., consumer education). The role of individuals in the implementation process is relatively low though, which indicates that inter-context processes are important for fostering individual learning. The German case provides a similar picture with respect to the dependence of individual learning upon agency of context-external actors (e.g., knowledge and advice through an energy consultant). The individual learning context contains the largest number of learning objects and factors, but only comes third with respect to roles in the implementation process. In particular, organizational and policy actors play a key role in implementing learning factors.

Table 5: Linkages between roles in the implementation of learning factors (i.e., the origin of action) and the learning context in which learning factors and objects are located (i.e., impact or target of actions).

Role → Learning factor	**Canada**	**Cyprus**	**Germany**
I	**8**	**11**	**25**
I → G	1	4	4
I → O	6	1	4
I → P	1	1	1
G	**9**	5	5
G → I	8	**11**	**8**
G → O	5	4	1
G → P	7	1	0
O	**15**	13	20
O → I	7	12	**25**
O → G	9	4	11
O → P	9	**14**	2
P	**11**	**14**	4
P → I	5	9	**18**
P → G	5	2	8
P → O	6	8	16

Table 5 provides more detail on the various interactions between learning contexts, i.e., the link between the origin of actions (i.e., the learning context in which the role of implementing a learning factors is contained) and the impact of actions (i.e., the learning context in which a learning factor is implemented). Thus, individual actions mainly focus on sustainability issues within the individual learning context (e.g., lead by example) and less at the policy context (e.g., through voting). Group action is mainly related to issues in the individual context (e.g., educate consumers in community gardens) or the group context itself (e.g., share equipment and knowledge). Organizational action shows a non-uniform picture across the case studies with most actions being related to the organizational context itself (e.g., improving organizational practices and strategies). Action by policy actors has a heterogeneous pattern as well; while the Canadian and Cypriot cases include most actions within the policy learning contexts, the German case study includes the lowest number of actions within this context. In general, Table 5 demonstrates that actors have various opportunities to actively facilitate societal transformations towards sustainable development either directly through actions at the particular societal level at which they operate (i.e., context-internal learning) or indirectly through actions that influence learning at other societal levels.

In general, the Canadian and Cyprus case studies show several similarities in the distribution of learning objects, factors and roles across learning context. The German case differs though with respect to the relatively high number of learning objects and factors in the individual learning context, and comparatively low number of learning objects and factors in the policy context. This can be explained through the already high level of effort in and commitment of policy-actors in Germany to energy transition. Thus, requirements for learning and interventions in the policy learning contexts are relatively low as perceived by stakeholders in the German case study. In contrast, the sustainability transitions in Cyprus and Canada are fostered more by bottom-up processes, and thus require more substantial changes at the policy level.

Of the 206 factors identified by stakeholders, 40 factors are case-specific and not contained in the general, review-based factor list. This underscores the value of participatory research, as general, top-down analyses might have overlooked these case-specific factors. Some of these factors are rather specific for the study topic, such as community-supported agriculture as a specific financing and distribution approach. Other factors suggest that there is, in general, relevance beyond the specific case study topic, and thus point to potential gaps in the literature-based factors list. For instance, 'trust in information and consultants' was mentioned as a learning factor in the individual learning context of the German case study. Just as 'trust' is a learning factor in the group, organizational and policy learning context, the factor could also be generally relevant for individual learning. Most of the case-specific factors are related to the individual and organizational learning contexts (~42.5% each), followed by the group learning context (~15%). In the policy context, no additional factors were identified, which suggests a higher level of completeness of the learning factors list in this context. This can be explained by the relatively large number of publications on which the systematic review of factors in the policy context builds (i.e., factors in the policy context based upon 38 publications compared with 18 in the organizational, 16 in the group and 6 in the individual learning context). By contrast, learning factors related to the individual context stem from only six publications, so that gaps in the literature-based factor list can be expected.

Table 4 also presents the coverage of main learning factor categories across the case studies. Green boxes denote main factor categories within learning contexts that are consistent across all case studies. Grey boxes indicate main factor categories that are not included in the respective learning context according to the systematic review (e.g., 'externalities' and 'lock-in effects' are only included in the organizational learning context; thus, this factor category is marked in grey for all other learning contexts).

'*Physical resources'* is the only learning factor that has been identified in all contexts and case studies. The coverage of sub-categories, such as '*support programs'* and '*infrastructure*', differs across learning contexts and case studies however. The existence of a '*disturbance or crisis'*, such as climate change or a financial crisis, was found in nearly all learning contexts across case studies, except for the policy learning context in the German case study. Similarly, '*information and knowledge'* is included in all contexts across cases except for the policy learning context in the German case study. '*Knowledge exchange'* is predominantly mentioned as a sub-category, followed by methods and infrastructure for '*knowledge integration'*.

Besides these generally relevant factors, further factors are more context-specific. In the **individual learning context**, the '*existence of forerunners*' was mentioned as a supportive factor across all cases. In addition, this factor was included in the organizational learning context in the Cyprus case. '*Process facilitation*' has been identified as a supportive learning factor in the **group learning context** across all case studies. The Cypriot case study also adds this factor to the policy learning context, while the German case study also mentions this factor in the organizational learning context. 'Sustainability-oriented institutions' were identified as a supportive learning factor in all **organizational learning contexts**, as well as in the policy learning context in the Cyprus case. The '*planning and implementation of multiple experiments'* was also found to be relevant in the organizational learning context across all case studies. This factor is also mentioned in the policy learning context in the Canadian case study, in the individual and policy contexts in the Cyprus case, and the individual and group contexts in the German case study. The opportunity to conduct '*low regret experiments*' was repeatedly mentioned as a sub-category. In the **policy learning context**, the 'provision of a leading sustainability vision' was included in all case studies. Furthermore, this factor was mentioned in the individual context in the Canadian and German case studies. 'Policy instruments' are also found to be relevant in all policy learning contexts across case studies. In particular, the '*influence of contextual forces of companies and initiatives*' was mentioned as a key policy instrument in all case studies.

Some other factors were mentioned broadly across learning contexts and cases. A '*topic that arouses attention and motivation*' was identified in the individual, group and organizational learning contexts in the German case study. In other cases, this factor was only sporadically mentioned (i.e., group context in the Canada case; organizational learning in the Cyprus case). '*Structures that support participation*' are included in the organizational and policy learning contexts in the Canada and German case studies, while this factor is missing in the Cypriot case study.

5 Discussion and Conclusions

In this chapter, the three research questions of this doctoral research (see Section 1.2) are addressed. For each research question, a general discussion and a succinct summary of key conclusions is provided. In the following section, each research question and related research objective are stated and subsequently discussed based upon conceptual and methodological contributions (see Chapter 2 and 3) as well as findings from case study research (see Chapter 4). Finally, a critical reflection of conceptual and methodological contributions is provided, as well as a discussion of promising future research avenues.

5.1 Research Question 1: How can multi-level learning in transformation governance processes be conceptualized?

The first research question, how can multi-level learning in transformation governance processes be conceptualized?, is linked to Objective 1: "Develop and apply a conceptual framework to understand societal transformations towards sustainable water, energy and food systems as multi-level learning processes". This research question and objective are mainly related to the development of the conceptual multi-level learning framework in Section 2.2. In addition to these theoretical considerations, the case study results in Chapter 4 provide some empirical findings for responding to the research question.

The multi-level learning framework presented in Section 2.2 specifies different aspects of learning in sustainability transitions. Building upon prior synthesis efforts (e.g., Bennett and Howlett, 1992; van de Kerkhof and Wieczorek, 2005), the framework differentiates between learning contexts, processes, intensity, objects, outcomes, subjects and factors. Thus, the multi-level learning framework addresses a current gap in transition research (cf. Beers et al., 2014; van Mierlo et al., 2010) with respect to a detailed conceptual understanding of learning in sustainability transitions. This framework should not be considered a new theory, but more as an approach to systematize and consolidate available findings in order to guide the analysis and design of transition governance processes (i.e., processes that aim at the pro-facilitation of sustainability transitions).

In the conceptual framework, each societal level is related to a different learning context, which is defined by a sustainability issue (i.e., a 'learning object') and the social unit that takes action to address this issue. Individual action with respect to a sustainability issue is related to the individual learning context; group actions are linked to the group learning context; organizational actions belong to the organizational learning context; and actions of policy actors are related to the policy learning context. The conceptualization of a learning context for each societal level allowed for an analysis of processes within learning contexts (i.e., intra-context analysis) and between learning contexts (i.e., inter-context analysis). Thus, several social units can play a role in the implementation of learning factors that address a specific learning object. While endogenous factors allow for self-reliant facilitation of learning within each context (i.e., the learning context for the social unit that implements a factor and the learning object is the same), exogenous factors point to aspects that cannot addressed in the respective context due to exogenous events (e.g., a natural disaster) or interdependencies between learning contexts (i.e., social units in another context have to provide a learning factor). Thus, social units can actively influence learning within their own context as well as across other learning contexts. As an example, policy-makers can shape the contexts of entrepreneurial activities (Cramer and Loeber, 2004) through sustainability-oriented legislation (van Mierlo et al., 2013). Thus, the results point to the importance of addressing these inter-context linkages in the design of transition governance processes (e.g., by developing communicative interfaces, cf. Adomßent, 2013).

Linkages between learning contexts can be of different types. First, these interactions can be process-related, i.e., an action situation is located between learning contexts. For instance, a transdisciplinary research process can be organized in such a way that it purposefully links actors from different learning contexts. Second, learning contexts can be linked through learning factors that represent operational aspects (e.g., funds). For instance, policy-makers can develop funding schemes for sustainability innovations that support innovative businesses in the organizational learning context. Third, institutions can also link learning contexts, such as citizens who use their voting rights to support political actors who stand for sustainable development topics. Fourth, knowledge exchange between learning contexts can link learning processes at different societal levels. For instance, the development of consumer knowledge (individual learning context) can influence their purchasing choices in favor of sustainable products, which in the end influences the producers of these products (organizational learning context).

The conceptual multi-level learning framework allowed for the development of a methodology for the analysis and design of linkages between learning contexts (see Section 3.3) that was applied in three case studies. All case studies show the high relevance of inter-context linkages through operational aspects, institutions, knowledge and action situations. The synthesis of case study results (Section 4.4) showed that all learning contexts and their linkages are relevant in the case studies. The specific importance of learning contexts varies between case studies though. The results suggest that transition governance processes should actively foster synergistic linkages between learning contexts (i.e., supportive learning factors) and avoid potentially adverse linkages (i.e., impeding learning factors).

The systematic review of general learning factors (Section 3.2) points to some factors that support learning across learning contexts. Thus, these factors can be critical for foster learning at multiple societal levels. Table 2 in Section 3.2 provides a summary of the results of the review with regard to the main categories of factors. The factor categories that were found to be relevant in all learning contexts include: a significant social, economic or environmental crisis in society; choosing a topic that arouses attention and motivates; planning and implementation of multiple experiments, the design of participatory processes, physical resources, as well as information and knowledge. Except for a disturbance or societal crisis, all factors can be actively addressed in transition governance processes. The case study results confirm the importance of several factor categories and suggest that the review-based factor list can be complemented and specified through empirical research.

In a nutshell, the multi-level learning framework conceptualizes learning at different societal levels as specific learning contexts comprising the individual, group, organizational and policy contexts. The conceptual framework further differentiates between learning processes, intensity, objects, outcomes and subjects, allowing for a more detailed analysis of learning within and across learning contexts. Thus, learning contexts can be linked by processes that involve actors from different learning contexts (e.g., community groups and policy-makers), as well as exchanges of operational aspects, institutions and knowledge (in the form of 'learning factors'). A methodology has been developed based upon the conceptual framework that allows for the analysis and design of multi-level learning processes in specific case studies. In addition, the multi-level learning framework structured a systematic literature review that identified several factors that can support and impede learning across contexts.

5.2 Research Question 2: How can actors actively facilitate societal transformations towards sustainable development in specific regional contexts?

The research question, how can actors actively facilitate societal transformations towards sustainable development in specific regional contexts?, is linked to Objective 2: "Develop and apply a methodological framework to analyze and actively facilitate transition governance processes". Research Question 2 and Objective 2 are mainly related to the methodology presented in Chapter 3. The methodology consists of a participatory modeling approach, a systematic review of factors that support and impede learning, and a process analysis and design approach. Perceptions and knowledge of stakeholders as well as available scientific knowledge are integrated into the analysis and design of case-specific transition governance processes.

Governance of transformation processes can be understood as facilitation and synchronization of learning processes at different societal levels. The utilization of synergies of multi-level learning processes requires that interactions can be analyzed. The conceptual framework and methodology developed address this requirement. Beginning from a set of specific sustainability innovations, the participatory modeling method allows for the identification of tangible issues linked to the implementation of innovations (i.e., 'learning objects'), promising interventions to overcome these issues (i.e., 'supportive learning factors'), implementation barriers (i.e., 'impeding learning factors') as well as specification of roles in the implementation process. The results of the systematic review of learning factors complement the measures identified by stakeholders, and provided further measures that were found promising for inducing transformative change. Gaps in the stakeholder-based list of learning factors can refer to factors that are ignored or belong to the tacit knowledge of stakeholders. Thus, the comparison of review-based and stakeholder-based factors can support reflection and reframing by stakeholders. Endogenous learning factors can be implemented in a self-reliant way in the learning contexts. Exogenous factors include landscape pressures, such as climate change or a financial crisis, which cannot be reversed or resolved in the short term. Most exogenous factors, however, point to requirements for cooperation between actors from different learning contexts (i.e., inter-context linkages). Intra-context and inter-context analysis methods ultimately allowed for a systematic analysis, visualization and design of interactions between different societal levels. In particular, the methodology for temporal analysis of governance processes can be used as a collaborative tool that allows for a context-specific design of transition pathways.

Despite the variety of case study topics, all societal levels are involved in the implementation process of learning factors across the case studies. These learning factors provide opportunities for the active facilitation of sustainability transitions in the case study regions. As shown in Table 4, individuals are related to the implementation of more than 30% of learning factors in all case studies (Canada: 33%; Cyprus: 34%: Germany: 39%). The role of groups is more heterogeneous across cases, ranging from 14% in the German case study to 42% in the Cypriot case and 60% in the Canadian case study. Public and private organizations have the highest number of assigned learning factors, ranging from 66% in the German case, to 83% in the Canadian case and 86% in the Cypriot case. Policy actors also play a major role with a proportion above 50% across case studies (Canada: 56%; Cyprus: 66%: Germany: 52%).

The case study results do not provide any ‘silver bullets’ for facilitating sustainability transitions. Instead various issues (i.e., learning objects) need to be addressed through a large number of measures (i.e., learning factors) that often require agency from several actors. The results of the systematic review also provide a long list of supportive and impeding learning factors that can complement stakeholder-based factors. In the end, a compromise needs to be found between simplistic analyses that only provide a broad overview of a topic without allowing for practical recommendations, and highly detailed analyses that entail the danger of getting lost in the complexity of an issue. The methods presented are flexible enough to develop a compromise between these two extremes in order to obtain a systemic and comprehensive overview of sustainability topics as well as being applicable in practice. The participatory modelling method (see Section 3.1) permits stakeholders to choose the abstraction level that they find to be appropriate. In addition, the MTF that was applied for the analysis and design of transition governance processes (see Section 3.3) allows for highly detailed analysis of governance systems (see Sendzimir et al., 2010) as well as a more general overview of these systems (see Halbe et al., 2013)

From the literature and case study research, three general approaches have been identified for actively influencing sustainability transitions. First, bottom-up processes initiated by concerned citizens and community groups are an important option. The case study results showed several opportunities for communities and individuals to become active in implementing innovative sustainability initiatives (e.g. a community garden) or actively fostering change in other learning contexts (e.g., through consumer choice or political activism). Second, professional engagement in the organizational or policy contexts is another key avenue for facilitating sustainability transitions (e.g., by producing sustainable products or developing support programs). Third, a synchronization of multi-level processes is required to foster the analysis, assessment and implementation of sustainability innovations. Networks processes can play a key role in fostering exchange and cooperation of individuals, groups, organizations and policy actors (cf. Bingham et al., 2005). Transdisciplinary research processes are another promising approach for engaging actors from different contexts, integrating local and scientific knowledge, and coordinating engagement at different societal levels. The methodology developed in this doctoral research project contributed particularly to the third approach by systematically analyzing opportunities for facilitating sustainability innovations at different societal levels, and integrating local knowledge from stakeholders with scientific knowledge from a literature review. However, the methodology can also be applied in the scope of bottom-up movements as well as collaborative processes at the organizational and policy levels.

In sum, the methodology presented in this dissertation allows for the identification and analysis of case-specific intervention points for sustainability transitions at multiple societal levels. The methodology furthermore permits the analysis of interplay between individual, group, organizational and policy actions, which is a first step towards their coordination. The focus on sustainability innovations links the broad topic of sustainability transitions to a set of opportunities for practical interventions. The results demonstrate that all societal levels play an important role in sustainability transitions. Individuals, groups, organizations and policy actors can support sustainability transitions in a self-reliant way (i.e., endogenous factors). Most learning factors however require cooperation between actors from different societal levels. The methodology presented allows for the analysis and design of these interlinkages between learning contexts. While the methodology cannot provide any 'silver bullets' for inducing sustainability transitions, it is flexible enough to identify an appropriate abstraction level for analyzing and designing transition governance processes.

5.3 Research Question 3: What role can modeling play in the governance of transition processes?

This research question, what role can modeling play in the governance of transition processes?, is linked to Objective 3: "Analyze the opportunities of a modeling approach to be applied in transition governance processes". In this research, a classification of model uses was developed that differentiates between modeling for 'understanding transitions', 'providing case-specific policy advice' and 'facilitating stakeholder processes' (see Section 2.3.1). Model uses differ with respect to model purposes, application contexts and epistemological foundations. Participatory modeling for the facilitation of stakeholder processes was found to be particularly relevant for all phases in transition governance processes (see Section 2.3.2) (see Section 2.3.3). Until now, only a few participatory modeling studies have been conducted with an explicit linkage to sustainability transitions (cf. Halbe and Ruutu, 2015) despite significant potential in transition research to explore this link (Holtz et al., 2015). In addition, participatory modeling can also be applied in university education in the teaching of concepts and methods for the facilitation of stakeholder processes and reflection on paradigms in sustainability issues (Halbe et al., 2015b).

Participatory model building using CLDs has been applied in this research to investigate the barriers to and drivers of innovations, and, based upon this, to propose case-specific designs of transition governance processes. The systematic review revealed some factors that point to requirements and application areas for participatory methods (in the following section, factor identifiers are provided which relate to learning factors in Appendix 1). Thus, flexible and adaptive applications of reflexive methods (I-7.1; G-7.5; O-13.3; P-13.5; see Appendix 1 for factor identifiers) are required to be able to respond to surprises, opportunities and demands of stakeholders. In addition, methods should avoid technical language (P-13.6) and require limited resources to support capacity building and continuity of participatory processes (P-13.12) even without the involvement of researchers and research funding. Participatory methods can also facilitate both knowledge exchange between stakeholders (I-10.2; G-10.1; O-16.1; P-16.1) and knowledge integration (G-10.2; O-16.2; P-16.2). The participatory modeling method applied in this doctoral dissertation addresses these factors from the systematic review. The method is flexible with regard to the topic and degree of detail. In addition, the method only requires moderate resources (an interview lasted for about 1.5 hours, and material costs have been minimal) and was found to be intuitive for most stakeholders. The method was highly useful for structuring the interview and fostered a stepwise visualization of the stakeholder's perspective in the form of a CLD (see a description of methodological steps in Section 3.1.2). The method encouraged interviewees to take a holistic viewpoint by asking for multiple causal relationships and feedback processes. The construction of a CLD nevertheless requires that stakeholder get involved into an unusual way of thinking (i.e., thinking about feedbacks as well as indirect causes and effects). Thus, a few interviewees were not responsive to the participatory modeling method, which is reflected in some simple CLDs.

The review of participatory methods (cf. Section 2.3.2) points to the relevance of various participatory modeling methods in transition governance processes, which are partly also reflected in the results of the systematic review. In **Phase 1**, the participatory modeling method can be applied in group processes (Vennix 1999; van den Belt, 2004) to create a shared and integrated problem perspective (see learning factors G-7.7, O-13.4 and P-13.9 in Appendix 1). Participants explain the concepts and rationales underlying variables, which reduce linguistic uncertainty (Brugnach et al., 2008) and facilitate the emergence of a common language (G-7.2 and P-13.6). In **Phase 2** of a transition governance process, a purposeful stakeholder selection (G-6.1, O-12.1 and P-12.2) and the development of an involvement strategy (G-6.2, O-12.2 and P-12.3) can be supported by a participatory social network analysis (see Section 2.3.2, and Halbe and Ruutu, 2015). In **Phase 3** of a transition governance process, participatory modeling can foster the development and analysis of sustainability visions (G-7.8; O-13.5; P-13.10). Halbe and Ruutu (2015) proposed various methods that can be chosen depending on the context of a specific collaborative process, such as the availability of resources and expertise. Methods range from non-technical methods, such as written vision statements (e.g., Auvinen et al., 2015), to conceptual frameworks or reference scenarios (cf. Elle 1992).

Qualitative and quantitative modeling approaches, such as CLDs (Halbe et al., 2015a) or system dynamics modeling (Iwaniec et al., 2014) are further promising methods for developing and assessing sustainability visions (in Phase 3) as well as developing a strategy towards its realization in **Phase 4**. Participatory planning tools can support the coordination of actions in **Phase 5**, and a continuous monitoring and evaluation process (I-7.2; G-7.4; O-13.7; P-13.11) in **Phase 6** of a transition governance process. Halbe and Ruutu (2015) highlight the need for frameworks that help to identify key elements of transition governance processes, including events, responsibilities and expected outcomes. In particular, the application of the MTF for process planning was proposed by Halbe and Ruutu (2015). The method for analysis and design of transition governance processes (see section 3.3) follows this research direction. In particular, the temporal analysis and design approach allows for the specification of a potential transition pathway, including key action situations, participating actors and expected outcomes, which can support the planning, monitoring and evaluation of transition governance processes.

In sum, this research has provided a classification of model uses in transition research (Halbe et al., 2015c) that supports a purposeful discussion of the opportunities of modeling and promising future research directions. A review was conducted to identify experiences from other research fields that can be picked up by transition researchers. It was found that participatory modeling approaches are rarely applied by transition researchers (Halbe et al., 2015c; Holtz et al., 2015) despite their high potential of in the governance of transition processes. Halbe and Ruutu (2015) identify various participatory modeling methods that can be applied in the different phases of transition governance processes. The methodology developed in this doctoral research provides several contributions for the development of participatory modeling methods in transition research. Thus, the method supports an integrated analysis of problems as well as barriers and drivers of sustainability innovations. The temporal analysis and design of transition governance processes can also be applied in a participatory setting, which supports the proactive planning as well as monitoring of transition processes.

5.4 Limitations of conceptual and methodological contributions

As already mentioned in section 5.1, the conceptual multi-level learning framework should not be considered as a meta-theory of multi-level learning, but more as an approach to systematize and consolidate learning concepts and guide transition governance processes in its attempts to organize effective interventions. Due to the more integrative nature of the framework, some aspects can be further specified and included in more detail in future research. The confinement to four learning contexts can be considered as a simplification that requires further specification in the future. For instance, the organizational learning context could be further specified by differentiating between public and private organizations. Educational organizations, such as schools and universities, can be added as specific learning contexts. As with the specification of learning contexts, further research on learning objects would be worthwhile. Several learning objects were identified in the systematic review and are related to three learning intensities (i.e., routine learning, reframing and paradigm change). This list of learning objects cannot be considered exhaustive and requires more detailed research to arrive at a more all-encompassing list of learning objects.

The bridging and consolidating function of the framework allowed the development of a list of specific factors that supportive and impeding factors of learning by means of a systematic review. However, this list cannot be considered exhaustive and requires refinement through future research as well. The highest number of publications are related to the policy learning context (see Table 2), which reflects a focus of the transition literature on policy processes (with emphasis on the role of policy networks). The low number of references related to the individual context however reveals that more research on the role of individuals might be fruitful. Furthermore, the low number of impeding factors to learning (9% of the total number of factors) suggests a bias towards reporting of successful case studies within the scientific literature. Thus, future research on transition governance should also give more consideration to stalled or failed processes. In addition to a potential bias in the underlying empirical literature, the application of the conceptual framework for structuring the literature review also has to be critically reflected upon. The extraction of data from articles often requires some interpretation, particularly as key terms such as ‘supportive learning factor’ or ‘learning contexts’ usually are not explicitly mentioned. A systematic review approach was, however, found to be helpful to reduce personal bias, compared with a narrative review approach. Several measures were undertaken to reduce personal bias, as described in Halbe et al. (submitted). For instance, three articles were jointly reviewed and subsequently discussed by the review team at the outset of the review process. In addition, several group and bilateral meetings were organized to assure a common understanding of categories of the conceptual framework as well as the review process.

With regard to the case study analysis, it has to be noted that the use of concepts from the multi-level learning framework for analyzing CLDs has a strong interpretative component. Sustainability issues identified by stakeholders are interpreted as ‘learning objects’, and solutions and barriers as ‘supportive and impeding factors’. Thereby, a strong action-orientation is chosen, as learning connotes the opportunity to actively address perceived problems. The researcher has to keep the interpretative framing in mind while identifying learning objects and learning factors in CLDs. In order to make this interpretative step explicit, it is helpful to relate case-specific learning objects in CLDs to the general learning objects that were identified in the systematic review (see Table 1). This analytical step has been conducted in all case studies, as can be seen in Appendices 3, 4 and 5 (see second column).

The case study results demonstrate the applicability of the methodology, but do not represent a comprehensive analysis of the topic (i.e., local/organic food systems in Ontario, WEF nexus in Cyprus, energetic refurbishment in the Ruhr region). In the end, a comprehensive analysis of all sustainability innovations as well as related stakeholders, barriers and drivers was beyond the scope of a single doctoral dissertation. For instance, more advanced methods could be applied for the selection of stakeholders (e.g., social network analysis) in future research. A higher number stakeholder interviews might also be required to comprehensively analyze the case study topic. In this dissertation, the sustainability-related benefits of innovations were analyzed based upon a literature analysis and information from stakeholders. A more systematic and thorough assessment of sustainability-enhancing innovations is another important research topic for future research to assure that the "right set" of innovations are supported. An integrated assessment (e.g., using system dynamics modeling) should verify the sustainability benefits of innovations and potential trade-offs in their application.

Another limitation of this research is the qualitative nature of case study results which do not allow for a priorization of measures or an assessment of the effectiveness of interventions. The purpose of the methodology developed is a comprehensive analysis of relevant issues, solutions and roles in the governance of transition processes, rather than providing a specific recommendation of a strategy. As mentioned in Section 5.3, further quantitative modeling methods might be required to complement the explorative character of the proposed methodology. The participation of stakeholders in the final design of a transition pathway can also foster a priorization of interventions based upon local or expert knowledge. As the methodology was iteratively developed in this research, continuous stakeholder participation in the comparison of stakeholder-based and literature-based learning factors (step 2 of the methodology), as well as analysis and design of transition governance processes (step 2 of the methodology) was not possible beyond a small group workshop in the Canadian case study and bilateral exchanges with selected stakeholders.

While the Cypriot and Canadian case studies addressed quite innovative topics that have not been high on the agenda of research organizations and political authorities in the case study regions (i.e., the WEF nexus in Cyprus, and local food systems in Canada), the German case study on energetic refurbishment can be related to various studies and political programs. Most measures that are proposed in the climate protection plan NRW (LANUV, 2015) are also included in the case study results (see Section 4.3). This comprises the improvement of public support programs including support of simple energy efficiency measures and provision of allowances instead of loans. In addition, the intensification and improvement of consultation services are planned with the intention of developing a targeted refurbishment strategy that takes the individual situation of property owners into account (e.g., tailored to elderly people). Further measures in the Climate Protection Plan NRW that are also included in the case study results comprise technological innovation, revision and coordination of regulations, monitoring of energetic refurbishments, investments in public housing, intensification of professional training programs, and promotion of sustainable building materials. The large overlap of case study results and the climate protection plan NRW underscore the ability of the proposed methodology to consolidate findings on sustainability transitions, despite the limitation of a single doctoral research project in terms of time and funding. This observation suggests that the case study results, despite the aforementioned limitations, provide a good overview of sustainability challenges of and opportunities to proactively facilitate sustainability transitions.

5.5 Future research opportunities

The previous section already mentioned some promising future research directions, which are summarized and complemented in the following. First, this doctoral research project was able to iteratively develop, test and refine the aforementioned conceptual and methodological frameworks. However, a larger research project is required to conduct a comprehensive analysis, including an in-depth stakeholder analysis, an integrated assessment of sustainability innovations (also their interactions, i.e., modeling of visionary system designs for supply systems) and a broader interview process. As already proposed in Section 5.3, participatory social network analysis can be a promising approach for purposefully selecting stakeholders by drawing upon local and scientific knowledge. The analysis of sustainability visions is a particularly promising research area that can include several modeling approaches, such as fuzzy cognitive mapping (e.g., Olazabal and Pascual, in press; Weide, 2015), multi-criteria analysis (e.g., Trutnevyte et al., 2012) or system dynamics modeling (e.g., Iwaniec et al., 2014). Future research could analyze the synergies and trade-offs between different sets of sustainability innovations for a specific case study.

Second, future research should also closely involve stakeholders in the analysis and design of transition governance processes. Structural and temporal governance analyses presented in this dissertation were constructed without strong involvement of stakeholders, but mostly based upon the results of the participatory modeling process. By actively involving stakeholders in the structural and temporal analysis of transition governance processes in future research, the methods developed can be used as reflexive methods to analyze and coordinate actions across learning contexts.

Third, the temporal analysis and design method can also provide the basis for process evaluation. The evaluation of participatory processes and methods is generally challenged by the uniqueness of complex problem situations (cf. Checkland and Holwell, 1998). Furthermore, sustainability transition is characterized by a long time scale and broad thematic coverage (cf. Holtz, 2011) which impedes process monitoring and evaluation. The temporal analysis and design method can support process evaluation by specifying the various process steps, expected results and theoretical assumptions at the beginning of the process. After the participatory process, experiences and actual process results can be reviewed, drawing upon observations, interviews and questionnaires (cf. Jones et al., 2009). CLDs can also be applied to investigate if participants changed their problem perspectives during the process (Scholz et al., 2015). Thus, the empirical basis of transition governance processes should be broadened by using the developed conceptual and methodological frameworks for process design and evaluation. Based upon a broader empirical basis, the conceptual framework and general learning factors from literature review should be refined and complemented.

Finally, even though the analysis is considered as a good compromise between complexity and simplicity (as simple as possible, but as complex as needed), further visualization methods might be needed to support its widespread application. Process designs (e.g., Figure 7 in Section 4.1) were developed with Microsoft PowerPoint which requires considerable time and the diagrams can quickly become unwieldy. Other visualization tools might simplify the construction of process designs. In particular, online tools can be a fruitful approach to allow the participatory development of CLDs and process designs.

5.6 Final remarks

The concepts and methods developed in this research project allow for reflection on transition governance processes from a systemic viewpoint. This includes an analysis of opportunities and constraints for pro-active facilitation of sustainability transitions, as well as design of transition governance processes that embrace multiple societal levels. In all case studies, a large variety of sustainability innovations exist that are partly hidden from the general public (such as aquaponics systems at a household level) and in part well-known (such as labeled organic food or energetic refurbishment measures). This diversity of available solutions, even though they are mostly residing at a niche level today, can be an important asset in coping with future challenges and surprises (cf. Johnson et al., 2011; van Mierlo et al., 2010).

Governance of sustainability transformations requires an acknowledgment of this diversity as well as a dialogue and cooperation between actors at various societal levels. In recent years, several research concepts and approaches have been developed that reflect this need for exchange and cooperation, such as boundary work (e.g., Zietsma and Lawrence, 2010; Clark et al., 2011), transdisciplinary research (e.g., Bergmann et al., 2010; Lang et al., 2012), transformative science (e.g., Schneidewind und Singer-Brodowski 2014; Schneidewind, 2015) and citizens science (e.g., Irwin, 1995; Hand, 2010). Several social and technical innovations have been developed that address key learning factors as identified in the systematic review. For instance, the rapid development of internet-based technologies and the proliferation of smart phones allow for various crowdsourcing activities such as the provision of information and knowledge (Wechsler, 2014) (cf. learning factor 'knowledge exchange'). Crowdfunding can be an important supportive factor in the activities of entrepreneurs and other actors (Belleflamme et al., 2014) (cf. learning factor 'physical resources'). Transformative research can play a key role in the governance of sustainability transitions by guiding knowledge exchange, coordinating multiple experiments and cooperation among multiple actors, and integrating knowledge about problem situations.

Despite substantial differences in the geographic location, culture and topics addressed, all case studies include promising sustainability innovations and the engagement of multiple actors in their implementation. The stakeholders generally exhibited a strong interest in the study and provided multifaceted support (e.g., by taking part in the participatory modeling process, establishing contacts to further actors, and offering site visits to innovative developments promoting sustainability). What is also striking about the case studies is not only their relative success under often challenging conditions, but the fact that they are taking place in diverse countries and are representative of a multitude of initiatives taking place around the globe. Thus, this doctoral research provides an optimistic outlook on future opportunities for large-scale sustainability transitions.

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Appendix 1: General factors from literature review

Appendix 1.1: Individual learning context

Supportive (Sup) and impeding (Imp) factors of learning in sustainability transition processes related to an individual learning context. Similar factors in other learning contexts are provided by using factor identifiers. Endogenous factors (N) can be implemented in the scope of an individual learning process, while exogenous factors (X) cannot be addressed directly (N/X denotes an ambiguous factor).

Individual learning context (I)					
Factor group	**Description of supportive/impeding factor**	**Sup/ Imp**	**Similar factors**	**References; theoretical (T) / empirical (E)**	**Exog. (X) / Endog. (N)**
Motivation	**1 Disturbance or crisis (e.g., social, economic or environmental crisis)**	**Sup**	**G-1; O-1; P-1**	**E: Leitgeb et al., 2014; T/E: Reed et al., 2013**	**X**
	2 Environmental values based upon a deep understanding of environmental interactions	**Sup**	**O2; P3**	**E: Leitgeb et al., 2014**	**N**
	3 Relation of experiment or innovation to everyday life	**Sup**	**G-3.4; O-6.3; P-5.1**	**T/E: Kemp et al., 2007** **E: Fam and Mitchell 2013; Leitgeb et al., 2014**	**N**
	4 Aspirations (clear vision and goals)		**O-8; P-7**	**T/E: Reed et al., 2013** **E: Leitgeb et al., 2014**	**N**
	5 Curious and critical mindset (i.e.,, question others and one's own assumptions)	**Sup**		**E: Leitgeb et al., 2014;**	**N**
	6 Inspirations from others to become pro-active (e.g., organizations, family, colleagues)	**Sup**	**O-9; P-8**	**T/E: Reed et al., 2013** **E: Leitgeb et al., 2014**	**X**
Experimental process	**7 Application of experimental method**	**Sup**	**G-5; O-10; P-9**	**E: Leitgeb et al., 2014**	N/X
	7.1 Flexible and adaptive application of experimental and reflexive methods	Sup	G-7.5; O-13.3; P-13.5	E: Leitgeb et al., 2014	N
	7.2 A continuous process monitoring and evaluation, and reflection on outcomes and process	Sup	G-7.4; O-	E: Leitgeb et al., 2014	N

			13.7; P-13.11		
	7.3 Possibility of no-regret experimentation (i.e., reduce the risk of failure)	Sup	G-5.3; O-10.4; P-9.4	T/E: Reed et al., 2013 (Inv) E: Leitgeb et al., 2014	N/X
Social Interaction Process	**8 Engagement of affected actors/users**	**Sup**		**E: Lopes et al., 2012**	N/X
	8.1 Interactive concepts to inform all stakeholders, and foster learning	Sup		T/E: Kemp et al., 2007 E: Lopes et al., 2012	N/X
	8.2 Simplicity and honesty of the message without a bargaining mentality attached	Sup		E: Lopes et al., 2012; Fam and Mitchell 2013 (Inv)	N
Resources	**9 Physical resources (e.g. funding, materials)**	**Sup**	**G-9; O-15; P-15**	**T/E: Reed et al., 2013** **E: Leitgeb et al., 2014**	N/X
	9.1 Creative usage of what is available (e.g., recycle material)	Sup		E: Leitgeb et al., 2014	N
	9.2 Ability to ask others for help	Sup		T/E: Marschke and Sinclair, 2009 E: Leitgeb et al., 2014	N/X
	9.3 Support from individuals, organizations or programs (e.g. governmental agencies, universities and other intellectual entrepreneurs)	Sup	G-9.1; O-15.1; P-15.1	T/E: Reed et al., 2013 E: Fam and Mitchell 2013; Leitgeb et al., 2014	N/X
	9.4 Natural capital	Sup		T/E: Reed et al., 2013	X
	10 Knowledge and information	**Sup**	**G-10; O-16; P-16**		N/X
	10.1 Availability of local or traditional knowledge	Sup	G-10.3	E: Leitgeb et al., 2014	X
	10.2 Measures and infrastructure for knowledge exchange (between practitioners, scientists, ...)	Sup	G-10.1; O-16.1; P-16.1;	T/E: Reed et al., 2013 E: Leitgeb et al., 2014	
	10.3 Measures and infrastructure for knowledge integration (between practitioners, scientists, ...)	Sup	G-10.2; O-16.2; P-16.2	T/E: Reed et al., 2013 E: Leitgeb et al., 2014	N/X

Appendix 1.2: Group learning context

Supportive (Sup) and impeding (Imp) factors of learning in sustainability transition processes related to a group learning context. Similar factors in other learning contexts are provided by using factor identifiers. Endogenous factors (N) can be implemented in the scope of a group learning process, while exogenous factors (X) cannot be addressed directly (N/X denotes an ambiguous factor).

Group learning context (G)						
		Description of supportive/impeding factor	**Sup/ Imp**	**Similar factors**	**References; theoretical (T) / empirical (E)**	**Exog. (X) / Endog. (N)**
Motivation	**1**	**Disturbance or crisis (e.g., social, economic or environmental crisis)**	**Sup**	**I-1: O-1; P-1**	**E: Seyfangd and Longhurst, 2013**	**X**
	2	**Change of government**	**Sup**	**P-2**	**T/E: Marschke and Sinclair, 2009**	**X**
	3	**Choose topic that arouses attention and motivation**	**Sup**	**O-6; P-5**	**T/E: Brown et al., 2003**	N/X
	3.1	Topic that involves a sense of urgency and can be addressed by the group	Sup	O-6.2; P-5.1; P-5.2	T/E: Brown et al., 2003 (Inv); Brown and Vergragt, 2008; Marschke and Sinclair, 2009 (Inv)	N
	3.2	Topic that arouse public expectations in order to induce reputational and prestige risks for the participants	Sup		T/E: Brown et al., 2003	N/X
	3.3	Include innovative and novel topic (too radical innovations might face resistance though)	Sup	O-6.1	T/E: Brown et al., 2003 E: Beers et al., 2014	N
	3.4	Relation to everyday life by choosing a tangible topic	Sup	I-3; O-6.3; P-5.1	T/E: Brown et al., 2003; Brown and Vergragt, 2008; Marschke and Sinclair, 2009; Seyfang and Haxeline, 2012; Davies and Doyle, 2015 E: Alvial-Palacino et al., 2011	N
	4	**Commitment due to self-awareness and a feeling of responsibility**	**Sup**	**O-7; P-6**	**T/E: Brown et al., 2003 (Inv); Manring, 2014; Schneider and Rist, 2014**	**N**

Experimental Process	**5 Purposeful planning and implementation of multiple experiments**	**Sup**	**I-7; O-10; P-9**	**T/E: Brown et al., 2003; Brown and Vergragt, 2008**	N/X
	5.1 Separation of viable from less viable design ideas, e.g. through reality checks	Sup		T/E: Brown et al., 2003 (Inv); Brown and Vergragt, 2008	N
	5.2 Complexity of experiments can overwhelm the project members (i.e., no time to consider group external processes)	Imp		E: Beers et al., 2014	N
	5.3 Enable learning from failures through low-risk experiments	Sup	I-7.3; O-10.4; P-9.4	T/E: Brown and Vergragt, 2008 E: Seyfangd and Longhurst, 2013	N/X
	5.4 Early implementation of prototypes and engagement tools	Sup	O-10.3; P-9.2	T/E: Lopes et al., 2012	N/X
Social Interaction Process	**6 Purposeful and pro-active design of participatory processes**		**O-12; P-12**	**E: Beers et al., 2014**	N/X
	6.1 Purposeful stakeholder selection to achieve vertical and horizontal integration within the process	Sup	O-12.1; P-12.2;	T/E: Brown and Vergragt, 2008; Marschke and Sinclair, 2009; Schneider and Rist, 2014 E: Di Iacovo et al., 2014	N
	6.2 Establish an involvement strategy that defines the engagement of stakeholders to various degrees at different stages of the process (e.g., start with a small homogenous group and bring include further actors later)	Sup	O-12.2: P-12.3;	T/E: Brown and Vergragt, 2008; Schneider and Rist, 2014 (Inv)	N
	6.3 Develop conflict mediation and resolution mechanisms	Sup	O-12.4; P-12.5	T/E: Marschke and Sinclair, 2009 (Inv); Espinosa and Porter, 2011; Beers et al., 2014 (Inv)	N
	6.4 Effective networking with group-external actors (to receive support)	Sup	O-12.5; P-12.6	T/E: Lopes et al. 2012 E: Seyfangd and Longhurst, 2013	N/X
	6.5 Being outwardly oriented and intellectually entrepreneurial by observing related processes (e.g., experiments), bringing in innovative solutions by "outsiders"	Sup	O-11.4; O-12.5; P-10.1	T/E: Brown et al., 2003; Espinosa and Porter, 2011; Lopes et al., 2012 E: Seyfang and Longhurst (Inv), 2013; Beers et al., 2014	N
	6.6 Representatives that can speak for a field (e.g., national networking organizations) and consolidate findings	Sup	O-12.6; P-12.7	E: Seyfangd and Longhurst, 2013	N/X
	7 Process facilitation		**O-13; P-13**		N/X

	7.1 Discuss process design and rules with participants	Sup	O-13.1; P-13.1	T/E: Marschke and Sinclair, 2009; Lopes et al., 2012; Manring, 2014 (Inv); Schneider and Rist, 2014	N
	7.2 Facilitating the emergence of a common language	Sup	P-13.6	T/E: Brown and Vergragt, 2008; Schneider and Rist, 2014 (Inv)	N
	7.3 Address power asymmetries	Sup	P-13.4	T/E: Manring, 2014 (Inv)	N/X
	7.4 A continuous process monitoring and evaluation, and reflection on outcomes and process	Sup	I-7.2; O-13.7; P-13.11	T/E: Brown et al., 2003; Brown and Vergragt, 2008; Marschke and Sinclair, 2009; Espinosa and Porter, 2011; Lopes et al., 2012;	N
	7.5 Flexible and adaptive application of reflexive methods	Sup	I-7.1; O-13.3; P-13.5	E: Alvial-Palacino et al., 2011	N
	7.6 Open discussion on limitations and potentials of scientific methods (truly deliberative dialogue)	Sup		T/E: Schneider and Rist, 2014	N
	7.7 Creating shared and integrated problem perspective	Sup	O-13.4; P-13.9	T/E: Brown et al., 2003 (Inv); Brown and Vergragt, 2008; Seyfang and Haxeline, 2012; Manring, 2014; Schneider and Rist, 2014	N/X
	7.8 Develop a vision of a desirable future	Sup	O-13.5; P-13.10	T/E: Brown et al., 2003 (Inv); Brown and Vergragt, 2008; Espinosa and Porter, 2011; Seyfang and Haxeline, 2012; Davies and Doyle, 2015 E: Seyfangd and Longhurst, 2013 (Inv)	N
	7.9 Clarify expectations of participants	Sup	O-13.6; P-13.8	T/E: Brown et al., 2003 E: Seyfangd and Longhurst, 2013; Beers et al., 2014	N
	7.10 Attempt of powerful actors to exploit participatory processes for their individual interests	Imp		T/E: Rist et al., 2007	N/X
	7.11 Maintain momentum through continuous interactions in regular meetings	Sup	P-13.12	T/E: Schneider and Rist, 2014	N/X

	7.12 Take into account needs and interest of all participants	Sup	P-13.3	T/E: Schneider and Rist, 2014	N
	8 Leadership	**Sup**	**O-14; P-14**	**T/E: Marschke and Sinclair, 2009 (Inv); Manring, 2014**	N/X
	8.1 Unwillingness to take risks	Imp		T/E: Marschke and Sinclair, 2009; E: Brown et al., 2003	N/X
	8.2 Representatives of organizations can show risk-avoiding behavior, if they do not have a string backing by their organization	Imp		E: Brown et al., 2003	N/X
Resources	**9 Physical resources (e.g. funding, materials)**	**Sup**	**I-9; O-15; P-15**	**T/E: Rist et al., 2007; Brown and Vergragt, 2008; Seyfang et al., 2014** **E: Seyfangd and Longhurst, 2013;**	N/X
	9.1 Support from individuals, organizations or programs (e.g. governmental agencies, universities and other intellectual entrepreneurs)	Sup	I-9.3; O-15.1; P-15.1	T/E: Brown et al., 2003; Marschke and Sinclair, 2009	N/X
	10 Knowledge and information	**Sup**	**I-10; O-16; P-16**	**E: Bos et al., 2013**	N/X
	10.1 Creation of a knowledge infrastructure and interfaces to enable knowledge exchange (e.g., media reports, key publications, conferences and workshops, lecture tours,...)	Sup	I-10.2; O-16.1; P-16.1;	T/E: Rist et al., 2007; Marschke and Sinclair, 2009; Espinosa and Porter, 2011; Lopes et al., 2012; Seyfang et al., 2014; E: Seyfangd and Longhurst, 2013;	N
	10.2 Measures and infrastructure for knowledge integration (between practitioners, scientists), e.g. through online resources	Sup	O-16.2; P-16.2	T/E: Seyfang and Haxeline, 2012; Manring, 2014 ; Schneider and Rist, 2014 E: Seyfangd and Longhurst, 2013	N/X
	10.3 Availability of local or traditional knowledge	Sup	I-10.1;	T/E: Marschke and Sinclair, 2009;	X
	10.4 Lessons and best practices from other projects and initiatives	Sup		T/E: Brown et al., 2003; Seyfang and Haxeline, 2012	X
	11 Trust between and legitimacy of stakeholders (e.g., based upon previous collaboration)	**Sup**	**O-17; P-17**	**T/E: Marschke and Sinclair, 2009; Manring, 2014 (Inv)**	N/X

Appendix 1.3: Organizational learning context

Supportive (Sup) and impeding (Imp) factors of learning in sustainability transition processes related to an organizational learning context. Similar factors in other learning contexts are provided by using factor identifiers. Endogenous factors (N) can be implemented in the scope of an organizational learning process, while exogenous factors (X) cannot be addressed directly (N/X denotes an ambiguous factor).

Organizational learning context (O)						
		Description of supportive/impeding factor	**Sup/ Imp**	**Similar factors**	**References; theoretical (T) / empirical (E)**	**Exog. (X) / Endog. (N)**
Motivation	1	**Disturbance or crisis (e.g., social, economic or environmental crisis)**	**Sup**	**I-1: G-1; P-1**	**T/E: Suurs and Hekkert, 2009; Mitchell, 2013; Karadzic et al., 2014; T: Edwards, 2009**	**X**
	2	**Societal values that favor sustainability (e.g., general perception that sustainability characteristics are an important product characteristic)**	**Sup**	**I-2; P-3**	**T/E: Cramer and Loeber, 2004; Kemp et al., 2007; Suurs and Hekkert, 2009; Johnson et al., 2011; Grin, 2012; Mitchell, 2013; Waltz and Köhler, 2014;**	**X**
	3	**Sustainability-oriented institutions, formal laws, regulations, and norms**	**Sup**	**P-4**	**T/E: Cramer and Loeber, 2004; Kemp et al., 2007; Suurs and Hekkert, 2009; Johnson et al., 2011; Grin, 2012; van Mierlo et al., 2013; Karadzic et al., 2014 (Inv); Waltz and Köhler, 2014,**	**X**
	4	**Externalities (undesired effects are not included in market price)**	**Imp**		**T/E: van Mierlo et al., 2013**	**X**
	5	**Lock in into an overly specialized industry with high investments, competition and government support**	**Imp**		**T/E: van Mierlo et al., 2013; Karadzic et al., 2014;**	**N/X**
	6	**Choose topic that arouses attention and motivation**	**Sup**	**G-3; P-5**		**N/X**

	6.1 Innovation that is likely to be applied widely (e.g., in further countries) (i.e., prospect of future profits)	Sup	G-3.3	T/E: Johnson et al., 2011; Waltz and Köhler, 2014	X
	6.2 Consider technological capability and expertise of organization	Sup	G-3.1; P-5.1; P-5.2	T/E: Waltz and Köhler, 2014	N
	6.3 Ensure motivation within organization, e.g. through providing tangible benefits (e.g., getting started with small but concrete sub-projects), or translating insights gained to current practices and cultures	Sup	**I-3; G-3.4; P-5.1**	T/E: Cramer and Loeber, 2004; Espinosa and Porter, 2011; Molla, 2013	N/X
	6.4 Provide motivation for networking, e.g. through highlighting common interest or tangible benefits	Sup	P-5.2	T/E: Karadzic et al., 2014;	N/X
	7 Commitment due to self-awareness and a feeling of responsibility	**Sup**	**G-4; P-6**	**T/E: Wooltorton, 2004; Molla, 2013; Karadzic et al., 2014 (Inv)**	**N/X**
	7.1 Communicate and discuss problems within organization i.e. explain the complexity of issues	Sup		T/E: Karadzic et al., 2014	N
	7.2 Ability of critical self-reflection (by members of organization)	Sup	I-5; G-4; P-6	T/E: Wooltorton, 2004	N/X
	7.3 Widely applied practices that are not put into question	Imp		T/E: van Mierlo et al., 2013	N/X
	8 Setting a sustainability vision for the organization by top management	**Sup**	**I-4; P-7**	**T/E: Espinosa and Porter, 2011** **E: Young, 2010** **T: Edwards, 2009**	**N**
	9 Existence of forerunners	**Sup**	**I-6; P-8**	**T/E: Grin, 2012**	**X**
Experimental Process	**10 Purposeful planning and implementation of multiple experiments (practical and organizational)**	**Sup**	**I-7; G-5; P-9**	**T/E: Suurs and Hekkert, 2009; Espinosa and Porter, 2011; Karadzic et al., 2014**	**N/X**
	10.1 Being open towards different technical solutions	Sup		T/E: Johnson et al., 2011; Waltz and Köhler, 2014;	N
	10.2 Creation of partially protected socio-technical experiments in which various actors exchange knowledge, information and experience	Sup	P-9.3; P-9.5	T/E: Espinosa and Porter, 2011; Bos et al., 2013; Ceschin, 2013	N/X
	10.3 Engage stakeholders (e.g., users) in experiments	Sup	G-5.4; P-9.2	T/E: Alvial-Palacino et al., 2011; Espinosa and Porter, 2011; Bos et al., 2013	N/X

	10.4 Low regret experiments (e.g., due to low-tech characteristics of technology)	Sup	I-7.3; G-5.3; P-9.4	T/E: Suurs and Hekkert, 2009	N/X
Social Interaction Process	**11 Organizational structures that support participation**				**N/X**
	11.1 Interactive culture within organizations that cuts across horizontal and vertical structures of the organization	Sup	P-10.3	T/E: Wooltorton, 2004; Mitchell, 2013	N/X
	11.2 Linking bottom-up process and top down ratification and dissemination of the most promising innovations (i.e., use synergies between command and control and a more participatory network approach)	Sup	P-12.4	T/E: Espinosa and Porter, 2011 E: Young, 2010	N/X
	11.3 Skills for active networking and collaboration (e.g., effective communication skills)	Sup	P-10.6	E: Young, 2010 T/E: Karadzic et al., 2014 (Inv)	N
	11.4 Actively engage in networking activities (other actors in the value chain, consumers, government,…)	Sup	P-10.1	T/E: Cramer and Loeber, 2004; van Mierlo et al., 2013	N
	12 Purposeful and pro-active design of participatory processes (for collaboration and networking)	**Sup**	**G-6; P-12**	T/**E:** Cramer and Loeber, 2004; **Espinosa and Porter, 2011; Johnson et al., 2011; Ceschin, 2013; van Mierlo et al., 2013; Karadzic et al., 2014; Waltz and Köhler, 2014** **E: Young, 2010; Ornetzeder and Rohracher, 2013**	**N/X**
	12.1 Careful selection of actors for participation/collaboration/networking through an analysis of actors and innovations	Sup	G-6.1; P-12.2	T/E: Ceschin, 2013	N
	12.2 Establish an involvement strategy that defines the engagement of stakeholders to various degrees at different stages of the process	Sup	G-6.2; P-12.3	T/E: Wooltorton, 2004; Alvial-Palacino et al., 2011	N
	12.3 Actively look for events in the landscape, and align/link the process and innovations	Sup		T/E: Ceschin, 2013	N
	12.4 Develop conflict mediation and resolution mechanisms	Sup	G-6.3; P-12.5	T/E: Wooltorton, 2004; Karadzic et al., 2014	N

	12.5 Limited opportunities to influence actors beyond organization	Imp	G-6.4; P-12.6	T/E: Mitchell, 2013	X
	12.6 Forming of organizations to coordinate networking and consolidate findings		G-6.6; P-12.7	T/E: Suurs and Hekkert, 2009; Bos et al., 2013 E: Ornetzeder and Rohracher, 2013	N/X
	13 Process facilitation		**G-7; P-13**		N/X
	13.1 Discuss process design and rules with participants	Sup	G-7.1; P-13.1	T/E: Karadzic et al., 2014;	N
	13.2 Informal meetings and networks	Sup	P-13.2	E: Young, 2010; Ornetzeder and Rohracher, 2013	N
	13.3 Flexible and adaptive application of reflexive methods	Sup	I-8.1; G-7.5; P-13.5	T/E: Ceschin, 2013; T: Edwards, 2009	N
	13.4 Creating shared and integrated problem perspective	Sup	G-7.7; P-13.9	T/E: Ceschin, 2013; Karadzic et al., 2014;	N/X
	13.5 Collaborative vision development	Sup	G-7.8; P-13.10	T/E: Alvial-Palacino et al., 2011; Ceschin, 2013	N
	13.6 Clarify expectations of participants	Sup	G-7.9; P-13.8	T/E: Ceschin, 2013	N
	13.7 A continuous process monitoring and evaluation, and reflection on outcomes and process	Sup	I-7.2; G-7.4; P-13.11	T/E: Alvial-Palacino et al., 2011; Espinoa and Porter, 2011; Bos et al., 2013; Ceschin, 2013	N
	14 Leadership (democratic leadership, problem-solving attitude, readiness to assume risks, capacity to network and negotiate; communication skills, listening capacity; an interest in change and the ability to foresee, understanding of complex patterns)	**Sup**	**G-8; P-14**	**T/E: Molla, 2013; Karadzic et al., 2014 (Inv); Wooltorton, 2004 (Inv)** **E: Young, 2010**	N/X
	14.1 Defensive type of leadership: articulate (too) many problems to manage and for which they can offer no practical solutions	Imp		T/E: Karadzic et al., 2014	N/X
	14.2 Actively nurture and highlight importance of bottom-up initiative development	Sup		T/E: Espinosa and Porter, 2011	N

	14.3 Rhetoric-reality gap: sustainability is supported by management but practical support is low	Imp		T/E: Wooltorton, 2004	N/X
Resources	**15 Physical resources (e.g. funding, materials)**	**Sup**	**I-9; G-9; P-15**	**T/E: Cramer and Loeber, 2004, Wooltorton, 2004 (Inv); Espinosa and Porter, 2011; Bos et al., 2013;** **E: Young, 2010 (Inv)**	N/X
	15.1 Support from individuals, organizations or programs (e.g. governmental agencies, universities and other intellectual entrepreneurs)	Sup	I-9.3; G-9.1; P-15.1	T/E: Suurs and Hekkert, 2009; Grin, 2012; Ceschin, 2013	N/X
	15.2 Own financial resources of an organization	Sup		T/E: Suurs and Hekkert, 2009	N/X
	15.3 Infrastructure (roads, cyber infrastructure)	Sup	P-15.2	T/E: van Mierlo et al., 2013	X
	16 Knowledge and information	**Sup**	**I-10; G-10; P-16**	T/**E: Ceschin, 2013; Molla, 2013** E: **Ornetzeder and Rohracher, 2013**	N/X
	16.1 Creation of a knowledge infrastructure and interfaces to enable knowledge exchange (e.g., conferences, seminars, workshops, …)	Sup	I-10.2; G-10.1; P-16.1	T/E: Suurs and Hekkert, 2009; Espinosa and Porter, 2011; van Mierlo et al., 2013 E: Young, 2010	N
	16.2 Methods and infrastructure for knowledge integration (between practitioners, scientists, ...)	Sup	G-10.2; P-16.2	van Mierlo et al., 2013	N/X
	16.3 Lack of metrics that measure progress toward sustainability	Imp	P-16.3	E: Young, 2010	N/X
	17 Trust between and legitimacy of stakeholders	**Sup**	**G-8; P-14**	**T/E: Alvial-Palacino et al., 2011; Karadzic et al., 2014;**	N/X

Appendix 1.4: Policy learning context

Supportive (Sup) and impeding (Imp) factors of learning in sustainability transition processes related to a policy learning context. Similar factors in other learning contexts are provided by using factor identifiers. Endogenous factors (N) can be implemented in the scope of a policy learning process, while exogenous factors (X) cannot be addressed directly (N/X denotes an ambiguous factor).

Policy learning context (P)						
Factor groups		**Description of supportive/impeding factor**	**Sup/ Imp**	**Similar factors**	**References; theoretical (T) / empirical (E)**	**Exog. (X) / Endog. (N)**
Motivation	**1**	**Disturbance or crisis (e.g.,** social, economic or environmental crisis**)**	**Sup**	**I-1; G-1; O-1**	**T/E: Chapin et al., 2006; Kemp et al., 2007; Suurs and Hekkert, 2009; van Mierlo et al., 2010; Quist et al., 2011**	X
	2	**Change of government**	**Sup/Imp**	**G-1**	**T/E: Ison and Watson, 2007; Kemp et al., 2007 (Imp); Nevens et al., 2013 (Imp); Colvin et al., 2014; Hoppmann et al., 2014; Di Iacovo et al., 2014 (Imp)**	N/X
	3	**Societal values and trends that favor sustainability**	**Sup**	**I-2; O-2**	**T/E: Kemp et al., 2007; Johnson et al., 2011; Grin, 2012**	X
	4	**Legislation that prescribes a participatory approach (e.g. WFD) and allows flexibility (i.e., regarding decision-making)**	**Sup**	**O-3**	**T/E: Diduck and Mitchell, 2003; Ison and Watson, 2007; Dedeurwaerdere, 2009; Suurs and Hekkert, 2009; Johnson et al., 2011; Herrfahrdt-Pähle and Pahl-Wostl, 2012 ; Colvin et al., 2014;**	N/X
	5	**Choose topic that arouses attention and motivation**	**Sup**	**G-3; O-6**	**E: Olsson et al., 2004b**	N/X
	5.1	Relation to a pressing problem that stakeholders face in everyday life by choosing a tangible topic	Sup	I-3; G-3.1; G-3.4; O-6.3	T/E: Ison and Watson, 2007; Kemp et al., 2007; de Bruijne et al., 2010; van Mierlo et al., 2010 E: Bos and Brown, 2012; Evans and Karvonen, 2014	N/X
	5.2	Action orientation and tangible impacts of participation	Sup	G-3.1; G-5.4; O-6.2;	T/E: Diduck and Mitchell, 2003 (inv); Cramer and Loeber, 2004; Marschke and Sinclair, 2009 (inv); E: Nevens and Roorda, 2014	N

	5.3 Lack of knowledge about a topic by the public	Imp		T/E: Einsiedel et al., 2013	N/X
	6 Commitment due to self-awareness, openness to other perspectives, and a feeling of responsibility and interdependency	**Sup**	**G-4; O-7;**	**T/E: van Mierlo et al., 2010; van Mierlo et al., 2013** **E: Nevens and Roorda, 2014;**	N/X
	7 Motivate stakeholders through visionary and strategic leadership	**Sup**	**I-4; O-8**	**T/E: Quist et al., 2011; Bos and Brown, 2012; Nevens et al., 2013; van Mierlo et al., 2013** **E: Olsson et al., 2004b**	**N**
	8 Existence of forerunners and prime movers	**Sup**	**I-6; O-9**	**T/E: van Mierlo et al., 2010; Grin, 2012; Di Iacovo et al., 2014; van Mierlo et al., 2013;**	X
Experimental Process	**9 Purposeful planning and implementation of multiple experiments**	**Sup**	**I-7; G-5; O-10**	**E: Nevens and Roorda, 2014;**	**N/X**
	9.1 Flexibility regarding outcomes (i.e., being not too goal but process oriented)	Sup		T/E: Herrfahrdt-Pähle and Pahl-Wostl, 2012	N
	9.2 Limited view/ focus on technical experimentation	Imp	G-5.4; O-10.3	T/E: Bos and Brown, 2012; Hoppmann et al., 2014	N
	9.3 Learning and coordination between the experiments/projects, (e.g. through case study comparison to define lessons learnt and scientific evaluation of previous failed programs)	Sup	O-10.2	E: Olsson et al., 2004b; Bos and Brown, 2012 T/E: Albert and Vargas-Moreno, 2010; Farrelly and Brown, 2011 (Inv)	N/X
	9.4 Low regret experiments (allow for failures)	Sup	I-7.3; G-5.3; O-10.4	T/E: Kemp et al., 2007; Nevens et al., 2013 E: Nevens and Roorda, 2014;	N/X
	9.5 Development of innovation networks around a societal problem through the design of innovation experiments (technical, but also management and governance)	Sup	O-10.2	T/E: Chapin et al., 2006; Voß et al., 2009; Bos and Brown, 2012; Nevens et al., 2013	N/X
	9.6 Linking experiences from different levels, such as local groups with national and international lobbying efforts	Sup		T/E: Chapin et al., 2006; Bos and Brown, 2012;	N/X
Social Interaction Process	**10 Political structures that support participation**: consideration of various interest and values	**Sup**			**N/X**
	10.1 Policy entrepreneurs who act in a more strategical and instrumental way	Sup	G-6.5; O-11.4	T/E:; Suurs and Hekkert, 2009 T: Brundiers et al., 2013 E: Pahl-Wostl et al., 2013; Nevens and Roorda, 2014;	N/X

	10.2	Consider policies as social innovation processes	Sup		T/E: Voß et al., 2009	N
	10.3	Multi-level (vertical) and multi-sectoral (horizontal) dialogue between policy implementers and policy makers	Sup	O-11.1;	T/E: Colvin et al., 2014; Di Iacovo et al., 2014 E: Olsson et al., 2004b	N/X
	10.4	Dominance of command-and-control or market paradigms	Imp		T/E: Dedeurwaerdere, 2009; Farrelly and Brown, 2011; Colvin et al., 2014; Nevens et al., 2013; E: Nevens and Roorda, 2014;	N/X
	10.5	Lock-in effects through encrusted power structures and actor networks	Imp		T/E: Herrfahrdt-Pähle and Pahl-Wostl, 2012; Di Iacovo et al., 2014; Colvin et al., 2014 T: Pahl-Wostl et al., 2007;	N/X
	10.6	Skills for active networking and collaboration (e.g., within network)	Sup	O-11.3	T/E: von Malmborg, 2007; van Mierlo et al., 2010; Wittmayer and Schäpke, 2014; Di Iacovo et al., 2014; Goldstein et al., 2015 T: Brundiers et al., 2013	N/X
	10.7	Acknowledge diversity (institutions, economy, lifestyles, culture, perspectives) to deal with uncertainty and change	Sup		T/E: Chapin et al., 2006; van Mierlo et al., 2010; Johnson et al., 2011; Grin, 2012	N
	11	**Policy Instruments**				**N/X**
	11.1	Influence the contextual forces that may affect firms' strategies and initiatives;	Sup		T/E: Cramer and Loeber, 2004; van Mierlo et al., 2013	N/X
	11.2	Influence public opinion, e.g., by involving local media	Sup		T/E: Suurs and Hekkert, 2009 E: Olsson et al., 2004b	N/X
	11.3	Broad and early stakeholder participation to broaden and link networks and assure transparency and democratic legitimacy	Sup		T/E: Chapin et al., 2006; von Malmborg, 2007; Voß et al., 2009; van Mierlo et al., 2010; Farrelly and Brown, 2011; Quist et al., 2011 (also inverse); Bos and Brown, 2012; Grin, 2012; Herrfahrdt-Pähle and Pahl-Wostl, 2012; Bos et al., 2013 (Inv); van Mierlo et al., 2013 E: Pahl-Wostl et al., 2013 (Inv); Evans and Karvonen 2014; Nevens and Roorda, 2014 T: Brundiers et al., 2013	N

	11.4 Foster transdisciplinary research processes to include actors from science and practice	Sup		T/E: Albert and Vargas-Moreno, 2010; Johnson et al., 2011; Bos and Brown, 2012; Nevens et al., 2013; Wittmayer and Schäpke, 2014; Di Iacovo et al., 2014 E: Olsson et al., 2004b; Evans and Karvonen, 2014 T: Adomßent, 2012; Kueffer et al., 2012; Brundiers et al., 2013;	N
	12 Purposeful and pro-active design of participatory processes		**I-8; G-6; O-12**		**N/X**
	12.1 Responsibility for the design and implementation of public involvement programs by a neutral party (i.e., avoidance of tailoring the process to service special interest)	Sup		T/E: Diduck and Mitchell, 2003; Marschke and Sinclair, 2009 (inv); van Mierlo et al., 2010; Di Iacovo et al., 2014; T: Voß and Bornemann, 2011; Brundiers et al., 2013	N/X
	12.2 Purposeful selection of stakeholders (e.g., innovative 'regime' actors and frontrunners from 'niche' contexts)	Sup	G-6.1; O-12.1	T/E: Voß et al., 2009; Bos and Brown, 2012; Bos et al., 2013; van Mierlo et al., 2013; Nevens et al., 2013; Di Iacovo et al., 2014 E: Olsson et al., 2004b; Nevens and Roorda, 2014	N
	12.3 Establish an involvement strategy that defines the engagement of stakeholders to various degrees at different stages of the process (e.g., start with a homogenous group of stakeholders)	Sup	G-6.2; O-12.2	T/E: Bos and Brown, 2012; Nevens et al., 2013; van Mierlo et al., 2013; Di Iacovo et al., 2014; E: Nevens and Roorda, 2014 (Inv)	N
	12.4 Striking a balance between orchestrated and self-organized action (e.g., informal processes) and ensure their linkage	Sup	O-11.2	T/E: Nevens et al., 2013; Colvin et al., 2014 E: Pahl-Wostl et al., 2013 (Inv)	N
	12.5 Develop conflict mediation and resolution mechanisms	Sup	G-6.3; O-12.4	T/E: Diduck and Mitchell, 2004; Albert and Vargas-Moreno, 2010; Nevens et al., 2013; Di Iacovo et al., 2014 (Inv); Wittmayer and Schäpke, 2014 E: Olsson et al., 2004b; T: Voß and Bornemann, 2011; Brundiers et al., 2013	N
	12.6 Collaborating with national and international non-governmental organizations	Sup	G-6.4; O-12.5	E: Olsson et al., 2004b	N/X
	12.7 Include 'boundary spanners' and bridging organizations that connect groups, centers and levels	Sup	G-6.6; O-12.6	T/E: Cramer and Loeber, 2004; Bos and Brown, 2012 E: Olsson et al., 2004b; Pahl-Wostl et al., 2013 T: Brundiers et al., 2013	N/X
	13 Process facilitation	**Sup**	**G-7; O-13**	**T/E: Wittmayer and Schäpke, 2014**	N/X

	13.1 Discuss process design and rules with participants	Sup	G-7.1; O-13.1	T/E: Diduck and Mitchell, 2003; Cramer and Loeber, 2004; van Mierlo et al., 2010; Wittmayer and Schäpke, 2014 E: Olsson et al., 2004b; Evans and Karvonen, 2014 T: Voß and Bornemann, 2011	N
	13.2 Informal meetings and networks	Sup	O-13.2	T/E: Cramer and Loeber, 2004; Ison and Watson, 2007; Bos and Brown, 2012; Colvin et al., 2014 E: Pahl-Wostl et al., 2013	N
	13.3 Explicitly address alternative framings from all stakeholders during participation processes	Sup	G-7.12	T/E: Cramer and Loeber, 2004; de Bruijne et al., 2010 (inv); van Mierlo et al., 2010; E: Evans and Karvonen, 2014 (inv)	N
	13.4 Address power asymmetries	Sup	G-7.3	T/E: Diduck and Mitchell, 2003 (inv); Voß et al., 2009 (inv); de Bruijne et al., 2010 (inv); Colvin et al., 2014 T: Voß and Bornemann, 2011 (also inverse); Brundiers et al., 2013	N/X
	13.5 Flexible and adaptive application of reflexive methods	Sup	I-7.1; G-7.5; O-13.3	T/E: Diduck and Mitchell, 2003; Cramer and Loeber, 2004; Chapin et al., 2006; Kemp et al., 2007; de Bruijne et al., 2010; Einsiedel et al., 2013; van Mierlo et al., 2013; T: Pahl-Wostl et al., 2007	N/X
	13.6 Facilitating the emergence of a common language (i.e., avoidance of technical language and methods)	Sup	G-7.2;	T/E: Diduck and Mitchell, 2003 (inv); van Mierlo et al., 2010 (inv)	N
	13.7 Continuously adaptation of the process design (e.g., activities, stakeholder selection, methods…)	Sup		T/E: Kemp et al., 2007; Bos et al., 2013; Einsiedel et al., 2013; Nevens et al., 2013 E: Nevens and Roorda, 2014;	N
	13.8 Clarify expectations of participants and goals of the process	Sup	G-7.9; O-13.6	T/E: Einsiedel et al., 2013 E: Olsson et al., 2004b	N
	13.9 Creating shared and holistic problem perspective	Sup	G-7.7; O-13.4	T/E: Grin, 2012; Nevens et al., 2013	N/X
	13.10 Collaborative vision development	Sup	G-7.8; O-13.5	T/E: ; Johnson et al., 2011; Quist et al., 2011 (also inverse); Frantzeskaki et al., 2012; Nevens et al., 2013; van Mierlo et al., 2013; Di Iacovo et al., 2014 E: Nevens and Roorda, 2014; Goldstein et al., 2015	N

	13.11 A continuous process monitoring and evaluation, and reflection on outcomes and process	Sup	I-7.2; G-7.4; O-13.7; P-13.11	T/E: Chapin et al., 2006; Dedeurwaerdere, 2009; Albert and Vargas-Moreno, 2010; de Bruijne et al., 2010; Nevens et al., 2013; van Mierlo et al., 2013; Hoppmann et al., 2014; Wittmayer and Schäpke, 2014 E: Olsson et al., 2004b; Nevens and Roorda, 2014	N
	13.12 Continuity of participatory process, e.g. through institutionalization of learning process and capacity building within participating organizations	Sup	G-7.7	T/E: Kemp et al., 2007; von Malmborg, 2007 (inv); Farrelly and Brown, 2011; Quist et al., 2011 (also inverse); Herrfahrdt-Pähle and Pahl-Wostl, 2012; Einsiedel et al., 2013; van Mierlo et al., 2013 (Inv); Colvin et al., 2014; Wittmayer and Schäpke, 2014	N/X
	14 Leadership (e.g., by champions / key stakeholders)	**Sup**	**G-8; O-14**	**T/E: von Malmborg, 2007; Farrelly and Brown, 2011; Quist et al., 2011 (also inverse)** **E: Olsson et al., 2004b; Bos and Brown, 2012**	**N/X**
	14.1 Facilitating information flows between different levels of governance	Sup		E: Olsson et al., 2004b; Bos and Brown, 2012	N
	14.2 Mobilizing funding when needed	Sup	P-9.6; P-10.3	E: Olsson et al., 2004b	N/X
Resources	**15 Physical resources (e.g. funding, materials)**	**Sup**	**I-9; G-9; O-15**	**T/E: von Malmborg, 2007; Quist et al., 2011 (also inverse); Bos and Brown, 2012; Bos et al., 2013; Nevens et al., 2013 (Inv)** **E: Olsson et al., 2004b**	N/X
	15.1 Support from individuals, organizations or programs (e.g. governmental agencies, universities and other intellectual entrepreneurs)	Sup	I-9.3; G-9.1; O-15.1	T/E: Cramer and Loeber, 2004; Quist et al., 2011; Hoppmann et al., 2014; Colvin et al., 2014 (inv) E: Nevens and Roorda, 2014	N/X
	15.2 Modern infrastructure (roads, cyber infrastructure)	Sup	O-15.3	T/E: Chapin et al., 2006; van Mierlo et al., 2013 E: Evans and Karvonen, 2014 (inv)	N/X
	15.3 Participant funding mechanisms to redress the resource imbalance	Sup		T/E: Diduck and Mitchell, 2003	N/X
	16 Information and knowledge	**Sup**	**I-10; G-10; O-16**	**T/E: Suurs and Hekkert, 2009; Einsiedel et al., 2013 (inv)**	N/X

	16.1 Creation of a knowledge infrastructure and interfaces to enable knowledge exchange (e.g., media reports, key publications, conferences and workshops, lecture tours,...)	Sup	I-10.2; G-10.1; O-16.1	T/E: Cramer and Loeber, 2004; Chapin et al., 2006; Ison and Watson, 2007; von Malmborg, 2007; Albert and Vargas-Moreno, 2010; de Bruijne et al., 2010; Johnson et al., 2011; Bos and Brown, 2012; Einsiedel et al., 2013; Nevens et al., 2013; Colvin et al., 2014; Wittmayer and Schäpke, 2014 E: Olsson et al., 2004b T: Kueffer et al., 2012	N
	16.2 Methods and infrastructure for knowledge integration (between practitioners, scientists, ...)	Sup	G-10.2; O-16.2;	T/E: ; Albert and Vargas-Moreno, 2010; Johnson et al., 2011; Nevens et al., 2013; van Mierlo et al., 2013; Di Iacovo et al., 2014 E: Olsson et al., 2004b; Nevens and Roorda, 2014 T: Pahl-Wostl et al., 2007; Adomßent, 2012; Brundiers et al., 2013	N/X
	16.3 Definition of useful sustainability indicators		O-16.3	T/E: Suurs and Hekkert, 2009; Albert and Vargas-Moreno, 2010	N/X
	17 Trust (between and legitimacy of stakeholders and institutions)	**Sup**	**G-11; O-17**	**T/E: Cramer and Loeber, 2004; van Mierlo et al., 2010; Bos et al., 2013; Einsiedel et al., 2013; Nevens et al., 2013** **E: Olsson et al., 2004b; Nevens and Roorda, 2014** **T: Pahl-Wostl et al., 2007**	N/X

Appendix 2: Learning factors in the Canada case study

Stakeholder-based learning objects, supportive factors and roles for a transition towards a sustainable food system in Southwestern Ontario. Stakeholder-based learning factors are compared to literature-based learning factors (see factor identifiers in Appendix 2 and Halbe et al., submitted). Learning factors that are not included in the list of literature-based factors are marked in green.

Learning Contexts	**Learning Objects**	**Learning Intensity** I: Routine learning II: Reframing III: Paradigm change [specification of underlying learning object]	**Supportive/impeding learning factors (Solutions/barriers to solutions)**	**Comparison to learning factors from systematic review, cf. Halbe et al. (submitted)**	**Links to other learning contexts**	**Roles in the implementation of learning factors**	**Endogenous (N) / Exogenous (X) / Ambiguous (N/X)**
All			Crisis of conventional agriculture	I-1; G-1; O-1; P-1			
			Rising food demand of the world population (Imp)				
Individual Context	Consumer preferences and values (e.g., food has to be cheap and look perfect) *(Learning object no. 1)*	III [Consumer preferences and values]	Rise public attention about organic products through media (eg TV, papers, social media)	I-6; I-8.1	I, G, O	Farmer community; NGOs; journalists	N/X
			Lead by example (e.g., healthy diet; buy local/organic products, become active)	I-6	I	Citizens	N
			Regain connectedness to nature and place	I-2	I, G	Citizens, community groups; farmer community	N/X
			Clear labeling of food products		G, O, P	Policy-makers; farmers community	X

	Knowledge of food and agriculture *(Learning object no. 2)*	II *[Food-related nowledge to allow reframing]*	Education of consumers, esp. children and youth (e.g., about farming approaches; health impacts of diet; use of fresh produce; preservation of food)	I-10.2	I, G, O, P	Schools; parents; NGOs; farming community; Agricultural enterprise; citizens	N/X
			Spread the word about alternatives and healthy nutrition	I-10.2	I, G	Citizens; citizen groups	N
			Community gardens and urban farms as educational facilities (e.g., farming skills)	I-6	I, G, O	community groups; farmers; farmer community	X
			Translation of research findings about sustainable agriculture to the wider public	I-10.2	I, G, O, P	Researchers; public organizations; policy-maker (funding requirement)	X
	Resistance of people to take action (e.g., getting informed; develop new habits) *(Learning object no. 3)*	III *[Change people's mindset with regards to taking action]*	Clear goals and vision of a desirable future	I-4	I, G, O, P	Citizens; Researchers; NGOs; Public organizations; policy-makers	N/X
			Leadership of public organizations, e.g., demanding local food for cafeterias	I-6; I-9.3	O, P	Public organizations; policy-makers	X
Group context	Cooperation within the farmers community *(Learning object no. 4)*	III *[Change of mindset]*	Joint action that yields visible results that are helpful in the farmer's practice (e.g., famer research center; alliance to educate the public)	G-3.1; G3.4	G, O	Farmer community	N
			Programs that connect young farmers to share knowledge	G-10.1	G, O, P	Farmer community; NGOs; Public organizations	N/X
			Develop a positive reputation of local farmers (e.g., stewards of the land)	G-7.8	G, O, P	farmers; farmer community; media	N/X
	Lack of seed	III	Regional seed saving network	G-3.1; G-3.4;	G, O	Farmer community;	N/X

	saving infrastructure *(Learning object no. 5)*	*[Paradigm change from buying seeds towards seed saving]*		G-6.4		NGOs	
	Farming knowledge and equipment availability *(Learning object no. 6)*	III *[New cooperative paradigms for knowledge and equipment management]*	Cooperation to share equiment	G9	G, O	Farmer community; NGOs; Public organizations	N
			(Online) bridging technology for exchange and coordination	G-10.1	G, O, P	Farmer community; NGOs; Public organizations	N/X
			Farmer Research Center (Research and extension for small, diversified farms; topics: equipment; pest mgmt)	G-10.1; G-10.2	G, O, P	Farmer community; NGOs; Public organizations; policy-maker	N
	Fertility management (group) *(Learning object no. 7)*	III *[New paradigms for Fertility mgmt]*	Cooperation of neighbouring farms	G9	G, O	Agricultural enterprise; Farmer community	N
	Lack of skilled labor in the agriculture sector *(Learning object no. 8)*	II *[New strategies for to find skilled labor]*	Marketing that help people to find ways to contribute to a local food system	G-6.4	I, G, O, P	Farmer community; NGOs; Public organizations; citizens;	N/X
Organizational context	Hart to start with farming (expensive/low revenues) *(Learning object no. 9)*	II *[Strategies to deal with start-up phase]*	Training programs for new farmers (e.g., understanding of standards; farming + business skills...)	O-16.1	G, O, P	Farmer community; NGOs; Public organizations; policy-maker (e.g., funding)	X
			Programs/Subsidies for small-scale farmers (costs of	O-3; O-15.1	O, P	NGOs; Public	X

			buying a farm)			organizations; policy-maker	
			Reduce financial risks (e.g., minimalization of production costs)	O-10.4	O	Agricultural enterprise	N
	Increase/assure customer base despite higher prices compared to conventional products *(Learning object no. 10)*	II *[New marketing strategies]*	Production of high-quality premium products for customers who accept higher prices		I, O	Agricultural enterprise, Consumers	N/X
			Develop tight connections to consumers	O-11.4	I, O	Agricultural enterprise; Consumers	N/X
			Upscaling of organics to decrease price difference		O	Agricultural enterprise	N
			Consumer education	O-16.1; O-2	I, G, O, P	Schools; parents; NGOs; farming community; Agricultural enterprise; citizens	N/X
			Willingness of Stores/Restaurants to take Produce		I, O	restaurants; retailers, customers (demand)	N/X
	Work and equipment requirements on farm *(Learning object no. 11)*	III *[New planting strategies]*	Planting of perennial crops that require less cultivation and use of equipment		O	Agricultural enterprise	N
	Fertility management (on-farm) *(Learning object no. 12)*	III *[New paradigms for fertility mgmt]*	Integrating lifestock on farms		O	Agricultural enterprise	N
			Increase crop rotation		O	Agricultural enterprise	N

	Lack of proper distribution system for local food (accessibility for consumers needs to be increased) *(Learning object no. 13)*	III *[New strategies and paradigms for food distribution]*	Practical marketing models that improve access to local food (community-supported agriculture; small super fresh markets; farmers markets; wholesale)		I, G, O	Agricultural enterprise; Farmer community, retailers; consumers	N/X
			Programs that teach business and marketing skills	O-15.1; O-16.1	G, O, P	Farmer community; NGOs; Public organizations	X
	Lack/vanishing of regional processing facilities (e.g., abattoirs) + storage facilities *(Learning object no. 14)*	II *[New business models for regional processing facilities]*	Legislation that supports local food systems (e.g., food safety)	O-3	P	Policy-makers	X
	Limited financing opportunities *(Learning object no. 15)*	III *[New financing strategies and paradigms]*	Increased grants and microloans tailored to SC farming	O-15; O-15.1	O, P	NGOs; Public organizations; financial organization; policy-maker	X
			Community-supported agriculture		I, G, O	Agricultural enterprise; Farmer community; Citizens	N/X
Policy context	Availability of affordable land for farming *(Learning object no. 16)*	III *[New land planning paradigm that considers arable land]*	Rezoning of urban + suburban lands for small-scale production (e.g., through "small farm enterprise zone")	P-7; P-10.7; P-11.1	O, P	Policy-makers; urban planners	N
			Protection of agricultural land from construction into residential areas	P-7; P-11.1	O, P	Policy-makers; urban planners	N

			Land planning by landscape design to achieve productive ecosystems that do only require limited external input	P-16.2	O, P	Policy-makers; urban planners; landscape designers, researchers	N/X
	Power of regime actors from conventional agriculture (with respect to distribution infrastructure, legislation, funding opportunities) that constrain niches, such as local food systems *(Learning object no. 17)*	III *[New power structures that involve local, organic food actors]*	Government subsidies to diversified, organic farmers (esp. young farmers; help with transition towards organic; land purchase) or payments for ecosystem services	P-7; P-10.7; P-11.1	P	Policy-makers	N
			Subsidization of organic food	P-7; P-11.1	P	Policy-makers	N
			Organizations that lobby for local, organic food	P-12.6	G, O	Farmers community; NGOs	X
			Legislation that supports small scale, organic farming (e.g., quota exemptions; on-farm housing regulation)	P-7; P-10.7; P-11.1	P	Policy-makers	N
			Practice democracy: Vote for people who support sustainable agriculture; write to representative (e.g., ministers)	P-2	I, G	Citizens; citizen groups	X
	Lack of research regarding local food systems, as research/funding is more focusing on conventional agriculture *(Learning object no. 18)*	II *[Reframing of research agenda]*	Research on organic, small-scale farming / local food systems (potential research topics: fertility mgmt; processing/distribution infrastructure; pest mgmt; risk mgmt)	P-7; P-10.7; P-11.1; P-16	G, O, P	Researchers; Farmers community; NGOs; Public organizations; policy-maker (funding)	N/X

	Integration of knowledge and management levels to find best practices for specific locations *(Learning object no. 19)*	II *[Integration of frames towards an encompassing frame]*	Integrated assessment of solutions (e.g., combination of conventional and organic systems to utilize both advantages)	P-16.2; P-10.7	G, O, P	Researchers; NGOs; Public organizations; Farmer community; policy-maker (funding)	N/X
			university research on sustainable agriculture (eg on soil fertility, distribution systems; water use)	P-16	G, O, P	Researchers; policy-maker (funding); Farmer community;	N/X
	Lack of dialogue between regime (conventional agriculture) and niche actors (e.g., organic, local agriculture) *(Learning object no. 20)*	III *[Acceptance of alternative worldviews and willingness to start dialogue]*	Research on (a mix of) alternative farming approaches and education of farmers	P-7; P-16.1; P-10.7	G, O, P	Researchers; NGOs; Public organizations, policy-maker (funding); Farmer community;	N/X
			Knowledge sharing between countries	P-9.6	G, O, P	Researchers; NGOs; Public organizations; policy-maker (funding); Farmer community	N/X

Appendix 3: Learning factors in the Cyprus case study

Stakeholder-based learning objects, supportive factors and roles for a transition towards a sustainable food system in Cyprus. Stakeholder-based learning factors are compared to literature-based learning factors (see factor identifiers in Appendix 2 and Halbe et al., submitted). Learning factors that are not included in the list of literature-based factors are marked in green.

Learning Contexts	**Learning Objects (problems/barriers)**	**Learning Intensity** I: Routine learning II: Reframing III: Paradigm change [specification of underlying learning object	**Supportive factors of learning (Solutions)**	**Comparison to learning factors from systematic review, cf. Halbe et al. (submitted)**	**Links to other learning contexts**	**Roles in the implementation of learning factors**	**Endogenous (N) / Exogenous (X) / Ambiguous (-)**
All			Economic crisis; fossil fuel scarcity	I-1; G-1; O-1; P-1		-	
Individual Context	Environmental awareness and conscious resource use practices for energy, water, food and housing *(Learning object no. 1)*	III *[Consumer preferences and values]*	Lead by example (e.g., eat less meat)	I-6	I, G, O, P	Schools; parents; public organizations; polic ymaker	-
			Consumer education	I-10.2	I, G, O, P	Schools; parents; NGOs; citizens; media, polcy-maker	X
			Water demand management (e.g., water pricing)	Institutions	O, P	Policy-maker; public organizations	X
	Self-sufficiency at a personal level *(Learning object*		Education programs (e.g., from the government or community)	I-9.3; I-10.2	I, G, O, P	Schools, community; public organizations; policy-maker	X
			Startup support (e.g., allowances)	I-9.3	O, P	NGOs, public organizations; policy-maker	X

	no. 2)	III *[Consumer preferences and values]*	Conduct experiments	I–7	I, G, O	Citizens, community; businesses	N
			Willingness to invest some money	I–9 (Own resources)	I	Citizens	N
			Information gathering and exchange on the internet (facebook; youtube)	I-9.3; (Cyber infrastructure)	I, G, O, P	Citizens; media; NGOs, community; public organizations: policy-maker	N
			Ownership of resources, like inherited land	I–9 (Own resources)	I, G	Citizens; community	X
			Learn basic farming and craftsman skills	I–10 (skills)	I, G, O, P	Schools, community, NGOs, public organizations, policy-maker	-
	Low number of customers for local, organic food *(Learning object no. 3)*	III *[Change of consumer preferences]*	New tourism strategy: Organic Destination	I-6 (Visions set by others)	G, O, P	Actors from tourism sector, public organizations, farmers' community	-
			Explain benefits of local, organic and traditional farming	I-10.2	I, G, O	Farming businesses, part-time farmers	N
			Explore new distribution strategies	I–9 (infrastructure)	G, O	Farming businesses, part-time farmers	N
	Self-motivation to get informed and active *(Learning object no. 4)*	III *[General mindset with regards to taking action]*	Open access to data and information	I–10	I, G, O, P	Citizens; media; NGOs, community; public organizations; policy-maker	X
			Develop a hobby about sustainable practices (e.g., urban gardening)	I-5 (Hobby)	I	Citizens	N
Group context	Cooperation in community to become more	III *[Cooperative mindset]*	Participation of individuals in community activities	G-4	I	Citizens	X

	self-sufficient *(Learning object no. 5)*		Exchange of seeds, knowledge, skills and products (food + tools)	G-10.1; G-9 (exchange of resources)	I, G, O, P	Community; public organizations, policy-makers	N
	Development of stable networks (e.g., for learning or exchange) *(Learning object no. 6)*	III *[Cooperative mindset]*	Funds for community projects	G-9; G-9.1	I, G, O, P	Citizens, community, NGOs, public organizations, policy-makers	X
		II *[Develop skills for cooperation]*	Develop clear structures for community projects	G-7.1	G	Community	N
	Cooperation of farmers in the local, organic food sector *(Learning object no. 7)*	III *[Cooperative mindset]*	Joint workshops	G-10.1	G, O	Farming businesses, part-time farmers	N
			Seed exchange	G-9 (exchange of resources)	I, G, O	Farming businesses, part-time farmers; citizens	N
	High water consumption for outside facilities and golf courses *(Learning object no. 8)*	II *[Water saving strategies]*	Xeriscaping in public gardens / outside facilities	O-9 (Actors who set a good example)	O, P	Public organizations; policy-makers	N
			Policy that constricts golf course development	O-3	P	Policy-makers	X
	Mass tourism *(Learning object no. 9)*	II *[New tourism strategies]*	New tourism strategy: Organic Destination	O-3 (publicly shared visions)	G, O, P	Actors from tourism sector, public organizations; policy-makers	-

Organizational learning context	High energy requirements of desalination plants *(Learning object no. 10)*	II *[Alternative approaches for water supply]*	Optimize desalination (renewable energy, brine outflow, contracts)	O-10 (Experiment to improve environmental performance)	O, P	Operators, policy-makers	-
			Research on innovative desalination methods, such as cogeneration of electricity and desalinated seawater	O-16; O-15.1	O, P	Operators, research organizations; policy-makers	-
	High hurdles for start of a new organic farming business *(Learning object no. 11)*	II *[Strategies to deal with start-up phase]*	Startup support (e.g., demand for organic products, loans, knowledge, subsidies, land)	O-15.1	I, G, O, P	Farmers' community, NGOs, policy-makers, public organizations, citizens	X
			Cooperation of producers, e.g., to improve know-how (e.g., apprenticeships, workshops…)	O-16.1	G, O	Farmers' community	N
			Conduct market studies to learn about customer demands and develop viable business plan	O-16	G, O	Farming businesses; Farmers' community	N
	Fertility Management *(Learning object no. 12)*	III *[New paradigms for fertility mgmt]*	Farming in closed loops (permaculture)		O	Farming businesses	N
			Composting (worms)		O	Farming businesses	N

	Affordable land, energy, and water supply for organic, local farms *(Learning object no. 13)*	*II [Sustainable strategies for water, energy and land supply]*	Implement technologies that support self-sufficiency: rainwater harvesting, solar panels	O-10 (Experiment to improve environmental performance)	O	Farming businesses	N
			Use plants and animals that are adapted to the climate (e.g., low water requirements)	O-16 (local knowledge); O-10 (Experiment to improve environmental performance)	O	Farming businesses	N
			Policies to promote water-efficient crops	O-3	P	Policy-makers	X
			Apply advanced technologies (e.g., hydroponics) / precision agriculture	O-10 (Experiment to improve environmental performance); O-6.1	O	Farming businesses	N
			Land availability (being an island; division of the island)		O, P	Public organizations; policy-makers	X

Policy learning context	Improvement of current water resources management *(Learning object no. 14)*	*II [Consider alternative water management options]*	Consider environmental flows and ecosystem services in water management	P-16.2; P-4 (EU regulations)	O, P	policy-makers, public organizations	N
			Increase groundwater recharge (dams; check dams)	P-9	O, P	policy-makers, public organizations	N
			Study of agricultural water use and options for groundwater recharge	P-16	O, P	Research organizations, policy-makers (funding)	X
			Increase rainwater harvesting (e.g., install collection system)	P-9	O, P	policy-makers, public organizations	N
			Foster the use of treated wastewater for irrigation and groundwater recharge (needs to be closely monitored)	P-9; P-13.11	O, P	policy-makers, public organizations, Research organizations	N
			Implement EU water regulations and policies	P-4	O, P	policy-makers, public organizations,	N
			Increase transparency and accountability	P-17 (transparency and accountability)	O, P	policy-makers, public organizations,	N
			Water demand management (Water Pricing / Water conservation)	P-11.1	O, P	policy-makers, public organizations	N
	Leakage of water infrastructure *(Learning object no. 15)*	I *[Improvement of water infrastructure]*	Provide sufficient funding for investments in infrastructure (e.g., maintenance of water pipes)	P-15	O, P	policy-makers, public organizations	N

	Investments and development of the grid for decentralized, renewable energy *(Learning object no. 16)*	*II [Consider alternative energy supply options]*	CO2 certificates	P-11.1; P-4	O, P	Policy-makers, public organizations	X
			Long-term vision of a decentralized, renewable energy system	P-7	I, G, O, P	NGOs, policy-makers, public organizations, communities, citizens	X
			Development of regulatory framework to allow steering of decentralized, renewable energy system (building and operation)	P-11.1	O, P	policy-makers, public organizations	X
	Knowledge and design of integrated local/regional energy system (electricity, heat, mobility) *(Learning object no. 17)*	*II [Consider alternative energy management options]*	Research on decentralized renewable energy systems and electric mobility	P-16; P-15.1	O, P	Research organizations, policy-makers (funding)	X
			Pilot projects and upscaling	P-9	O, P	Research organizations, policy-makers, public organizations, companies	-

Appendix 4: Learning factors in the German case study

Stakeholder-based learning objects, supportive factors and roles for a transition towards a sustainable food system in Germany. Stakeholder-based learning factors are compared to literature-based learning factors (see factor identifiers in Appendix 2 and Halbe et al., submitted). Learning factors that are not included in the list of literature-based factors are marked in green.

Learning Contexts	**Learning Objects**	**Learning Intensity** I: Routine learning II: Reframing III: Paradigm change [specification of underlying learning object]	**Supportive/impeding learning factors (Solutions/barriers to solutions)**	**Comparison to learning factors from systematic review, cf. Halbe et al., in review**	**Links to other learning contexts**	**Roles in the implementation of learning factors** (Actor list is not comprehensive)	**Endogenous (N) / Exogenous (X) / Ambiguous (N/X)**
All			<u>Impeding factor</u>: Constructional limitations for energetic refurbishment (e.g., lack of space for solar panels,…) or monument protection (“Denkmalschutz”)			-	X
Individual Context	Conscious energy use (e.g., heating behavior) and awareness about energy topics *(Learning object no. 1)*	III [Consumer preferences and values]	Consumer education	I-9.3; I-10.2	I, G, O, P	Schools; parents; NGOs; citizens; media; policy-maker	N/X
			Leading by example	I-6	I, G, O, P	citizens; parents; Public organizations; NGOs; policy-maker	N
			<u>Impeding factor</u>: bad habits with regard to energy use and ventilation	Similar to factor O-7.1: widely	I	parents; citizens	N/X

				applied practices that are not put into question			
	Knowledge about refurbishment options *(Learning object no. 2)*	I-II *[Knowledge that allows reframing or choice of optimal strategy]*	Discussions in society through differentiated coverage of refurbishment topics in the media	I–5, I-10.2	I, G, O, P	Media; owners of residential property; policy makers that foster public discussion	X
			Self-information via the internet	I–5, I-10.2	I	Owners of residential property, citizens	N
			Independent advisory services and information campaigns (<u>impeding or supporting</u>?: only one interviewee saw this factor as impeding! mostly supporting)	I-9.3; I-10.2	I, O, P	Energy consultants; NGOs; public organizations; owners of residential property	N/X
	Aesthetic demands (e.g., insulation of building envelope can impair the visual attractiveness of a building) *(Learning object no. 3)*	II-III [House owner's preferences and values / acknowledgement of importance of energetic refurbishment]	Positive societal image of energetic refurbishment	I-2: Shared societal values	I, G, O, P	Citizens; friends, neighborhood; actors in the implementation process; policy makers (e.g., through providing future visions)	X
			Linking of energetic refurbishment with comfort (e.g., interior climate) and prestige	New factor: Prestige, similar to G-3.2	I, O	Owners of residential property; Energy consultants; architects; media	N/X

	Unsettledness of home owners *(Learning object no. 4)*	II [New knowledge and information to make a deliberate choice]	Simple refurbishment options (e.g., hydronic balancing; sensors for heating regulations)	I-7.3	O	Energy consultants; NGOs; building companies; architects	X
			Independent advisory services and information campaigns; thermography; solutions tailored to individual situations	I-9.3; I-10.2	I, O, P	Energy consultants; NGOs; public organizations; Owners of residential property	N/X
			Simple financing models (e.g., allowances rather than loans)	I-9.3; Low complexity of measures	O, P	Private banks, KFW	X
			Positive examples in the neighborhood or personal environment	I-6	I, G, O	Owners of residential property, neighborhood; organizations that were involved in implementation	X
			A single contact person	I-10.3; Low complexity of measures	O	Energy consultants; NGOs; public organizations; architects	X
			Feeling of responsibility; lead-by-example	I-4	I	Owners of residential property	N

			Trust in information and consultants	Trust	I, G, O	Owners of residential property; friends, and other people; energy consultants	N/X
			<u>Impeding factor</u>: cycles of innovation are getting shorter	Complexity of measures (imp)	O, P	Policy-maker; research institutes; lobbyists	X
			<u>Impeding factor</u>: Age of home owner (risk aversion)	Risk aversion (imp)	I	Owners of residential property	X
			Strict and clear regulations that demand energetic refurbishment (e.g., renting is forbidden, if certain minimum standards are not met); ENEV	Sustainability-related legislation	P	Policy-maker	X
	High costs of energetic refurbishment / profitability *(Learning object no. 5)*	I [Find optimal strategy]	Tax incentives (<u>ineffective according to some stakeholders</u>)	I-9.3	P	Policy-maker	X
			Opportunities for loan financing (<u>ineffective according to some stakeholders</u>)	I-9.3	O, P	Policy-maker; banks; public organizations	X
			Allowances rather than loans (simpler financing options)	I-9.3; Low complexity of measures	O, P	Policy-maker; public organizations	X
			Simple energetic refurbishment options (e.g., hydronic balancing; sensors for heating regulations)	I-7.3; Low complexity of measures	O	Energy consultants; NGOs; building companies; architects; industry	X

			<u>Impeding factor</u>: High standards for energetic refurbishment in order to qualify for loan programs	Complexity of measures + high costs (imp)	O, P	Policy-maker; banks; public organizations	X
			Rising energy prices and fear of financial breakdown (Euro crisis)	I-1		-	X
			Combination of standard retrofitting measures (e.g., senior friendly homes; replacement of outdated heating system; renovation works at the face of the building, …) and energetic refurbishment	I-7.3	I, O	Owners of residential property; architects	N/X
			Monitoring of results of energetic refurbishment measures	I-7.2	I, O, P	Energy consultants; architects; policy-maker (who sets the regulation); owners of residential property	N/X
			Rising value of real estate, supported by energy efficiency labels (e.g., KFW Effizienzhaus; Energieausweis)	Expectations of profits	O, P	KFW; Policy-maker; NGOs;	X
			Linking of energetic refurbishment with comfort (e.g., interior climate) and prestige	Expectation of prestige and comfort	I, O	Owners of residential property; media; architects	N/X
			Positive societal image of energetic refurbishment (demand of tenants)	I-2: Shared societal values; Expectations of profits	I, O, P	Tenants; media; policy-makers	X

			Home owner accomplishes some refurbishment work by her/himself	Could be related to: Skills (I-9; I-10)	I	Owners of residential property	N/X
			Own funds	I-9	I	Owners of residential property	N/X
			<u>Impeding factor</u>: Limited opportunities to apportion costs to tenants	Expectations of profits (inv)	P	Policy-maker	X
			<u>Impeding factor</u>: Limited opportunities for tenants to pay higher rents	Expectations of profits (inv)	I	Tenants	X
			Age of heating system and building envelope	I-7.3		-	X
			Low interest rates (energetic refurbishment as capital investment)	Opportunity costs (I-9)	O	Banks	X
			Anticipation of self-use of flat by landlord (or other family members)	I-3	I	Owners of residential property	N
	High time requirements and effort for energetic refurbishment *(Learning object no. 6)*	I [Optimize use of resources]	Service of an independent energy consultant for planning and supervision of implementation	I–10; I-10.3	O	Energy consultants; NGOs; public organizations	N/X
			Opportunity to get help from others (friends, family, ….)	I-9.2	I, G	Owners of residential property, living environment	N/X

	Dialogue between landlord and tenant *(Learning object no. 7)*	II-III [Cooperative mindset]	Modernization agreements between landlord and tenants	G-7.1	I	Landlord; tenants	N
	Large living space per person (in particular, an issue for many seniors) *(Learning object no. 8)*	II [Consider an alternative approach]	Creation of shared flats	Ability to collaborate	I, G	Housing owners; tenants	N/X
			Incentive programs for portioning of large living spaces into smaller households, or moving into a smaller apartment (e.g., reduction of real estate transfer tax)	I–9.3	O, P	KFW; Policy-maker; NGOs;	X
			Being content with smaller living space	I-2 (sufficiency values)	I	Owners of residential property; tenants	N
Group context	Cooperation within homeowner associations *(Learning object no. 9)*	II-III [Cooperative mindset]	Finance schemes tailored to homeowner associations	G-9.1	O, P	KFW; Policy-maker	X
			Independent advisory services and information campaigns; thermography; solutions tailored to individual situations	G-10	I, G, O, P	Energy consultants; NGOs; public organizations; owners of residential property	N/X
			A single contact person	G-10.2; Low complexity of measures	O	Energy consultants; NGOs; public organizations; architects	X
	High costs of energetic refurbishment / profitability *(Learning object no. 10)*	I [Find optimal strategy]	Finance schemes tailored to homeowner associations	G-9.1	O, P	KFW; Policy-maker	X
			Own funds	G-9	I, G	Owners of residential property	N/X

			Simple energetic refurbishment options (e.g., hydronic balancing; sensors for heating regulations) ("Breitensanierung")	G-5.3	O	Energy consultants; NGOs; building companies; architects	N/X
			Impeding factor: High standards for energetic refurbishment in order to qualify for loan programs		O, P	Policy-maker; banks (KFW); public organizations	X
			Rising energy prices and fear of financial breakdown (Euro crisis)	G-1		-	X
			Combination of standard retrofitting measures (e.g., replacement of outdated heating system; renovation works at the face of the building, …) and energetic refurbishment	G-5.3	G, O	Owners of residential property; architects	N/X
			Rising value of real estate, supported by energy efficiency labels (e.g., KFW Effizienzhaus)	Expectation of prestige / profit	O, P	KFW; Policy-maker; NGOs;	X
			Linking of energetic refurbishment with comfort (e.g., interior climate) and prestige	G-3.2	G, O	Owners of residential property; media; architects	N/X
			Image of energetic refurbishment (demand of tenants)	Societal values	I, G, O, P	Tenants; media	X
			Strict and clear regulations that demand energetic refurbishment (e.g., renting is forbidden, if certain minimum standards are not met); ENEV	Sustainability-related legislation	P	Policy-maker	X
			Low interest rates	Opportunity costs (G-9)	O	Banks	X
			Impeding factor: Limited opportunities to apportion costs to tenants		P	Policy-maker	X
			Impeding factor: Limited opportunities for		I	Tenants	X

			tenants to pay higher rents				
			Age of heating system and building envelope	G-5.3		-	X
Organizational context	Limited skills of craftsmen, energy consultants, and architects *(Learning object no. 11)*	II [Development of new skills]	Advanced training	O-16	O, P	Chamber of handicrafts; Policy-maker	N/X
			Advertising of apprenticeships	O-11.3; O-11.4	O, P	Chamber of handicrafts; NGOs; media; crafts enterprises	N/X
			Simple energetic refurbishment options (e.g., hydronic balancing; sensors for heating regulations)	O-10.4	O	Energy consultants; NGOs; building companies; architects	N/X
			Improvement of curricula (e.g., for craftsmen; architects, energy consultants)	O-16	O, P	Chamber of handicrafts; universities: policy-maker	N/X
			Company-internal energy managers	O-16	O	Larger housing companies	N
			Impeding factor: cycles of innovation are getting shorter	Complexity of measures; Short 'half-life' of knowledge (imp)	O, P	Policy-maker; research institutes; lobbyists	X
	Environmentally friendly and affordable options for thermal insulation of the building envelope *(Learning object no. 12)*	II [Development of new alternatives]	Research and sale of innovative insulation materials	O-15.1; O-16.1	O, P	Universities and other research organizations; building material manufacturers	N/X
			Incentive programs for ecological building	O-15.1	P	Policy-maker	X

			materials				
			Bad examples that cause a bad image for energetic refurbishment (e.g., mold formation, …	O-1 (Crisis of a particular technical option)	O	Media; crafts enterprise; Energy consultants; architects	X
	Gap between calculations of energy savings and actual savings *(Learning object no. 13)*	I-II [Improve calculation and implementation strategy]	Monitoring of results of energetic refurbishment measures	O-10 (Monitoring is only linked to technical measure not social process); O-13.7	O, P	Energy consultants; architects; policy-maker (who sets the regulation)	N
			Penalties for noncompliance to targeted energy savings	O-3	P	Policy-maker	X
			Impeding factor: bad habits with regard to energy use and ventilation	O-7.3	I	Tenant	N/X
			Consumer education	O-16.1	I, G, O, P	Schools; parents; NGOs; citizens; media; policy-maker	N/X
	Profitability of energetic refurbishment	I [Find optimal strategy]	Tax incentives	O-3	P	Policy-maker	X
			Opportunities for loan financing	O-15.1	O, P	Policy-maker; banks; public organizations	X
			Own funds	O-15.2	O	Organizations (e.g., real estate companies)	N/X
			Simple energetic refurbishment options (e.g., hydronic balancing; sensors for heating regulations) (“Breitensanierung”)	O-10.4	O	Energy consultants; NGOs; industry;	N/X

	(Learning object no. 14)				architects	
		<u>Impeding factor</u>: High standards for energetic refurbishment in order to qualify for loan programs	High costs (imp)	O, P	Policy-maker; banks (KFW); public organizations	X
		Rising energy prices and fear of financial breakdown (Euro crisis)	O-1		-	X
		Combination of standard retrofitting measures (e.g., replacement of outdated heating system; renovation works at the face of the building, …) and energetic refurbishment	O-10.4	O	Owners of residential property; architects	N/X
		Rising value of real estate, supported by energy efficiency labels (e.g., KFW Effizienzhaus; Energieausweis)	O-6.1	O, P	KFW; Policy-maker; NGOs;	X
		Linking of energetic refurbishment with comfort (e.g., interior climate) and prestige	O-6.1 (Prospects of future profits?); Prestige of ogrganization?	O, P	Owners of residential property; media; architects	N/X
		Image of energetic refurbishment (demand of tenants)	O-6.1 (Prospects of future profits?); Prestige of organization?; O-2	I, O, P	Tenants; media; policy-makers	X
		Strict and clear regulations that demand energetic refurbishment (e.g., renting is forbidden, if certain minimum standards are not met); ENEV	O-3	O	Policy-maker	X

			Low interest rates	O-15	O	Banks	X
			Impeding factor: Limited opportunities to apport costs to tenants	Expectations of profits (inv)	P	Policy-maker	X
			Impeding factor: Limited opportunities for tenants to pay higher rents	Expectations of profits (inv)	I	Tenants	X
			Age of heating system and building envelope	O-10.4		-	X
Policy context	Provision of affordable living space *(Learning object no. 15)*	II [Consider alternative approaches]	Climate bonus: linking of housing allowances to energetic quality criteria (Hartz IV)	P-11.1	P	Policy-maker	N
			Temporal Limitation of modernization allocation	P-11.1	P	Policy-maker	N
			Public housing	P-14; P-15 (Public actors take leadership)	O, P	Policy-maker; public organizations	N
			Being content with smaller living space	P-3	I	Owners of residential property; tenants	N/X
	Current regulations and financing schemes that set high hurdles for simple measures *(Learning object no. 16)*		Low refurbishment rate	P-7 (i.e., refurbishment rate is lower than envisioned)		-	N/X
			Political goals for sustainable development	P-7	P	Policy-maker	N
			Impeding factor: Lobbyism (e.g., producers of insulation material)	P-10.5	O	Lobyists	N/X

Appendix 5: Questionnaires in Canada case study

Sustainable Agriculture Survey

Section 1 – Food Supply Systems

1.1 Farming Approaches

In our research, we are looking at the following approaches to farming:

1) Large/medium-scale conventional agriculture
2) Large/medium-scale, certified organic agriculture
3) Rural, small-scale, diversified, organic agriculture
4) Urban, small-scale, diversified, organic agriculture

Can you think of further farming approaches that are relevant for the food system today or a sustainable food system in the future?

5) ____
____

6) ____
____

1.2 Towards a sustainable food production system

How would you assess the importance of each of the farming approaches defined above in Ontario's food production system? Please use a scale from 10 (very high importance) to 0 (negligible)

Today	2020	Your Ideal
Vision		
1) ____	1) ____	1) ____
2) ____	2) ____	2) ____
3) ____	3) ____	3) ____
4) ____	4) ____	4) ____
5) ____ (if applicable)	5) ____ (if applicable)	5) ____ (if applicable)
6) ____ (if applicable)	6) ____ (if applicable)	6) ____ (if applicable)

Section 2 – Transition towards a sustainable food system

Do you think that we need a transition of our agriculture system? Why?

____
____
____

What would you say are the most challenging issues for a transformation towards a sustainable food system?

What do you think are the next steps that need to be done to achieve a sustainable food system?

What is your role in this transition process? What can you do out of your profession or as a citizen?

What role do you see for small-scale, organic farming in the future?

Is there anything else you would like to share about the challenges and opportunities of farming?

Thank you very much for your participation

Sustainable Agriculture Survey
- Farmers -

Section 1 – Food Supply Systems

1.1 Farming Approaches

In our research, we are looking at the following approaches to farming:

1) Large/medium-scale conventional agriculture
2) Large/medium-scale, certified organic agriculture
3) Rural, small-scale, diversified, organic agriculture
4) Urban, small-scale, diversified, organic agriculture

Can you think of further farming approaches that are relevant for the food system today or a sustainable food system in the future?

5) ____
____

6) ____
____

1.2 Towards a sustainable food production system

How would you assess the importance of each of the farming approaches defined above in Ontario's food production system? Please use a scale from 10 (very high importance) to 0 (negligible)

Today	2020	Your Ideal
Vision		
1) ____	1) ____	1) ____
2) ____	2) ____	2) ____
3) ____	3) ____	3) ____
4) ____	4) ____	4) ____
5) ____ (if applicable)	5) ____ (if applicable)	5) ____ (if applicable)
6) ____ (if applicable)	6) ____ (if applicable)	6) ____ (if applicable)

Section 2 – Farm information

What is the approximate size of land you grow food on?

____

What do you produce on your farm?

____
____

Where is your food distributed?

What distance does your food travel from where it is grown to where it is sold?

How would you describe your farming approach (options in question no. 1.1)?

What would you say are the most challenging issues you face as a farmer (factors that limit the viability of your farm)?

What opportunities do you see to further strengthen your agricultural approach?

- Currently, what allows you to operate viably?

- What further steps can be taken to increase the viability of your farm?

In your opinion, what would be the impact on the region if your approach to farming is not viable?

____
____
____
____

In your opinion, what would be the beneficial impact on the region if your approach to farming remains or becomes more viable?

____
____
____
____

What role do you see for small-scale, organic farming in the future?

____
____
____
____
____

Is there anything else you would like to share about the challenges and opportunities of farming?

____
____
____
____
____
____

Thank you very much for your participation

Articles

This appendix includes the manuscripts of all lead-authored articles that are related to this Ph.D. research:

- **Article 1**: Halbe, J. C. Pahl-Wostl, G. Scholz, H.Thomsen, J. Vincke-de Kruijf and U. Scheidewind, submitted. Learning in the governance of sustainability transitions – A systematic review. Research Policy.

- **Article 2**: Halbe, J., Pahl-Wostl, C., Lange, M. A., and Velonis, C., 2015. Governance of transitions towards sustainable development – the water–energy–food nexus in Cyprus. *Water International* 40(5-6), 877-894.

- **Article 3**: Halbe, J., Pahl-Wostl, C., Sendzimir, J., and Adamowski, J., 2013. Towards adaptive and integrated management paradigms to meet the challenges of water governance. *Water Science and Technology*, *67*(11), 2651–2660.

- **Article 4**: Halbe, J. C. Pahl-Wostl and U. Scheidewind, to be submitted. Analysis and design of case-specific transition governance processes. Ecology & Society.

- **Article 5**: Halbe, J., J. Adamowski and C. Pahl-Wostl, C., 2015. The role of paradigms in engineering practice and education for sustainable development. Journal of Cleaner Production 106, 272-282.

- **Article 6**: Halbe, J., D. E. Reusser, G.Holtz, M. Haasnoot, A. Stosius, W. Avenhaus and J. Kwakkel, 2015. Lessons for model use in transition research: A survey and comparison with other research areas. Environmental Innovation and Societal Transitions 15, 194-210.

- **Article 7**: Halbe, J. and R. Sampsa, R., 2015. Use of participatory modeling in transition governance processes. International Sustainability Transitions Conference 2015, Brighton, UK.

Article 1

Halbe, J. C. Pahl-Wostl, G. Scholz, H.Thomsen, J. Vincke-de Kruijf and U. Scheidewind, submitted. Learning in the governance of sustainability transitions – A systematic review. Research Policy.

Learning in the governance of sustainability transitions - A systematic review

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Abstract

Even though learning is considered as fundamental for innovation and system transformation, a differentiated and comprehensive review of learning concepts in the field of sustainability transitions is currently missing. Different learning concepts have been applied in the transition literature, often without explicitly differentiating between processes, objects and contexts of learning. In this article, we provide a systematic literature review of learning concepts in transition research, and develop a conceptualization of learning in sustainability transitions. Based upon this conceptualization, factors that support and impede learning are identified from the review and related to individual, group, organizational, and policy learning contexts. The results lay the foundation for a more systematic understanding of learning in sustainability transitions and support the evidence-based design of transition governance processes.

Keywords: Sustainability transitions; innovation studies; learning; governance; systematic review

1. Introduction

The effects of human action on the environment have resulted in global problems, such as, accelerating climate change, deforestation or desertification. Instead of incremental innovations, major and system-wide socio–technical changes are required that involve changes in social aims, demands, industrial structures and institutions (van den Bergh et al., 2011). The field of socio-technical transition research has developed to examine such long-term, multi-sectoral, and fundamental transition processes towards sustainable development (Markard et al., 2012). Social-ecological systems research is another research field that deals with transitions in complex systems (e.g., Folke 2006). Learning processes are underlying key dynamics of socio-technical and social ecological transitions, including innovation processes (e.g., Carlsson and Stankiewicz, 1991; Bergek et al., 2008), niche formation and development (e.g., Kemp et al., 1998; Geels 2005), and regime transformation (Pahl-Wostl 2009).

In studies on socio-technical transitions, the concept of learning is often mentioned as being important without being further elaborated (Beers et al., 2014), i.e., the transition literature often does not specify how exactly learning takes place and how learning processes can be supported (van de Kerkhof and Wieczorek, 2005; van Mierlo et al., 2010; Lopes et al., 2012). In the social-ecological systems literature, learning concepts, assumptions and approaches tend to remain unspecific as well (Armitage et al., 2008). I It often remains unclear “if, who, how, when and what type of learning actually occurs” (Armitage et al., 2008, p. 87). This is an important research gap, as a differentiated understanding of learning is needed to govern sustainability transitions in a pro-active way (cf., Voss and Kemp 2006; Loorbach 2007). Van de Kerkhof and Wieczorek (2005) and Armitage et al. (2008) provide narrative reviews that take a first step towards understanding learning in transition governance processes. However, a comprehensive and systematic review of learning in sustainability transitions taking into account the different contexts of learning (such as individual, group, organizational and policy learning) is currently lacking.

In this article, we address this research gap by providing a systematic review of learning in transition research, comprising the fields of socio-technical as well as social-ecological systems research. The goals of this article are (1) to develop a conceptual framework of learning in sustainability transitions, and, based upon this framework, (2) to systematically review the empirical literature for factors that support or impede learning. The overall aim of this article is to identify context-specific factors for actively supporting learning in transition governance processes.

The paper is structured as follows. First, the systematic review method is presented. Next, a conceptual framework is developed that is used to systematically review the literature with respect to factors that support and impede learning in different contexts. Finally, a discussion of the applicability of the results for the practical design of transition governance processes is provided, as well as an outlook to future research.

2. Methodology

A literature review is an accepted and widely used method to screen available scientific evidence about a certain topic and to summarize and synthetize research findings (cf., Petticrew and Roberts, 2006; Liberati et al., 2009). Narrative reviews can be influenced by the researchers’ bias, as the selection, interpretation and synthesis of findings is usually accomplished in an implicit way (Tranfield et al., 2003). Due to this lack of transparency and reproducibility of narrative reviews, guidelines have been developed that support a more systematic review that explicitly explains the rationale, literature selection, risk of bias and synthesis method (cf., Liberati et al., 2009). A systematic review is defined as “a review of a clearly formulated question that uses systematic and explicit methods to identify, select, and critically appraise relevant research, and to collect and analyze data from the studies that are included in the review" (Moher et al., 2009, p. 1).

Due to the complexity of sustainability transitions, a qualitative review and synthesis approach is required for the identification of factors that support and impede learning. A "framework-based synthesis" conforms to these requirements by following two steps (Dixon-Woods 2011; Caroll et al., 2011, 2013). First, a conceptual framework is gradually developed for the review topic based upon the theoretical and empirical literature. Second, the framework's categories are applied to structure a review and synthesis of qualitative evidence. During its application, the framework is revised by including new concepts or themes (Oliver et al., 2008; Caroll et al., 2013).

Figure 1 shows the methodological design of the systematic review that was applied in this article. The first author of this article initially drafted a conceptual framework and a review protocol, and invited fellow researchers to join the review team. The review team members had complementary expertise with regard to the topic of the study, comprising adaptive resource management and governance, social and societal learning, social psychology, policy and knowledge transfer, and socio-technical transition research. The final review protocol was designed by the review team to guide the selection of relevant literature, the review process and synthesis of findings. During the review process, we critically reflected and, if considered necessary, revised the draft conceptual framework. Finally, the categories from the conceptual framework were applied to conduct a review of factors that support of impede learning in sustainability transitions.[11]

[11] The review question was formulated the following way: What are supportive and impeding factors of learning in sustainability transitions?

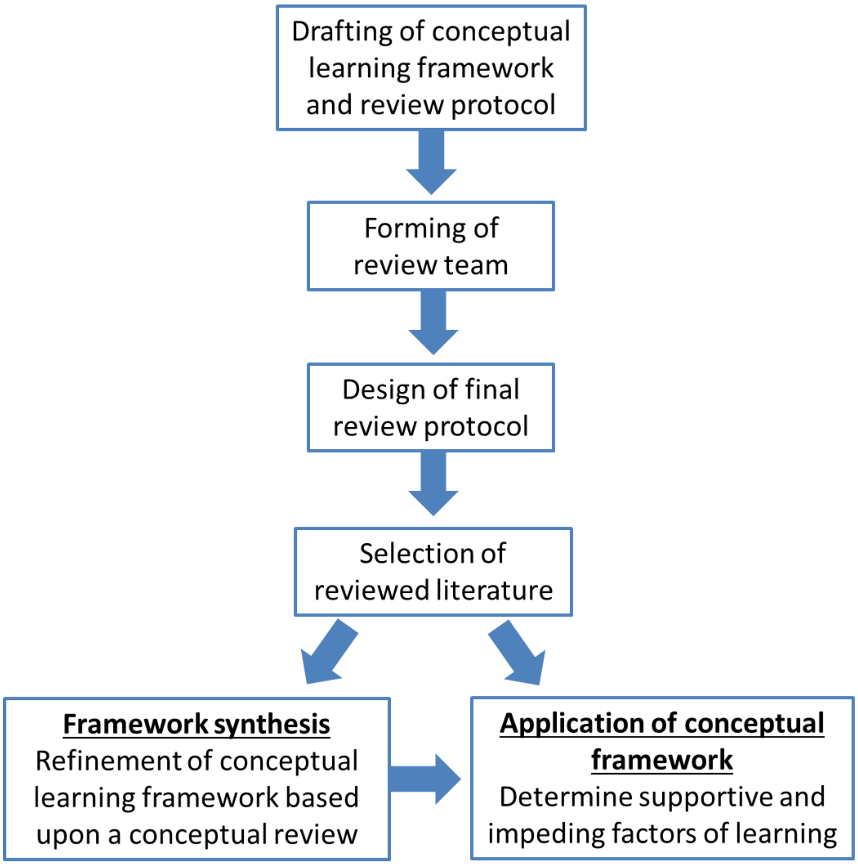

Figure 1: Methodology of the systematic literature review applied in this article.

In our literature review, the database Scopus was used to identify original research articles, reviews and editorials that apply learning concepts in the sustainability transitions literature (date of Scopus query: May 12, 2015). Research on sustainability transitions in the *socio-technical* and *social-ecological* system research fields were considered relevant for our review (cf. Smith and Stirling, 2010; van der Brugge and van Raak, 2007; Foxon et al., 2009). A query was designed to screen titles, abstracts and key words for three aspects:

1) *Sustainable development and learning* (search terms: sustainab* AND learning);

2) *Fundamental societal change* (search terms: transition OR transform* OR "system* innovation" OR "radical innovation");

3) *Key concepts from the research fields of socio-ecological and social technical transitions* (search terms: governance OR "adaptive management" OR "adaptive co-management" OR "social-ecological" OR “socio-technical” OR “strategic niche management” OR “multi-level perspective” OR “innovation system” OR “multi-level framework”).

The query resulted in a list of 132 publications from the social-ecological and socio-technical systems research fields. A potential limitation is the exclusion of conference papers, book chapters, literature without peer review (e.g., grey literature) and literature in a language other than English.

We screened the abstract, introduction and conclusion of all 132 publications using selected search terms ("transition", "transform*" and "learn*") to assure that each article was dealing with learning in sustainability transitions". The full text of the remaining 92 publications was read to finally assess the thematic proximity, conceptual quality and empirical quality of articles. Appendix 1 includes a detailed description of the quality assessment as well as a flow chart that shows the number of articles that were excluded at each step of the selection process. After scanning the full text, 63 publications finally entered the review process.

All empirical information has been sorted into the categories of the conceptual learning framework (see Section 3 and Appendix 2). The review team jointly reviewed three articles to assure a common understanding of categories and the review process. Descriptive coding has been applied to consolidate learning factors at two different levels of abstraction (i.e., main categories and one level of sub-categories). Summative and essence-capturing codes were assigned to synthesize factors with the same or similar meaning (Saldana, 2012). To avoid misinterpretation, the assignment of codes was discussed within the review team. Each factor has been qualified as being a supportive (abbreviation: Sup), impeding (Imp) or ambiguous (Sup/Imp) factor of learning. If different papers included semantically congruent factors but using an inverse formulation (e.g., "monitoring" as a supportive factor and "lack of monitoring" as an impeding factor), references were sorted to the same factor category and marked by the abbreviation "inv". In addition, the factor's susceptibility to purposeful change is rated on an ordinal scale from endogenous (i.e., the factor can be directly influenced by learning processes) to ambiguous (i.e., susceptibility unclear) and exogenous (i.e., factor cannot be influenced).

3 Conceptual framework of learning in sustainability transitions

Several learning concepts are used in the transition literature, including experiential learning (e.g., Geels, 2004; Broto et al., 2014), learning-by-doing (e.g., Kemp and Rotmans, 2004; van den Bergh et al., 2007), learning-by-using (e.g., Geels, 2002), trial-and-error learning (e.g., Garud and Karnøe, 2003), single, double and triple loop learning (e.g., van de Kerkhof and Wieczorek, 2005), higher order learning (e.g., Broto et al., 2014) and social learning (e.g., Geels, 2004; van der Brugge et al., 2005; Loorbach, 2007). Some concepts have substantial similarities with respect to underlying learning processes (e.g., learning-by-doing and learning-by-using), while others differ widely. Furthermore, some learning concepts focus more on the learning process (e.g., social learning) while others focus more on the objects of learning (e.g., higher-order-learning).

In their review of learning concepts, Bennett and Howlett (1992) and van der Kerkhof and Wieczorek (2005) dealt with this conceptual plurality by developing a conceptual framework that distinguishes between the subjects of learning (who learns?), the objects of learning (learns what?), and the results of learning (to what effect?). We follow a similar approach by differentiating between learning concepts that are related to (1) learning intensity, objects and outcomes, and (2) learning processes. Subsequently, we examine the (3) subjects of learning and (4) contexts in which learning takes place.

3.1 Learning intensities, objects and outcomes

Some learning concepts address different levels of learning intensity, such as the low order and high order learning concepts (Brown et al., 2003). Each learning intensity is associated with changes to different objects (i.e., the primary objects of change) and various outcomes (i.e., secondary objects of change that result from a change in primary objects). For instance, learning can change the want structure of individuals (primary learning object), which can result in a new consumption behavior (secondary learning object) (Buenstorf and Cordes, 2008). Pahl-Wostl (2009) presents a triple-loop learning concept to define different levels of learning intensity, building upon previous work from Argyris and Schön (1978), Flood and Romm (1996) and Hargrove (2002). Single loop learning denotes the incremental improvement of strategies without questioning the underlying assumptions, while double loop learning relates to a reframing of a problem conceptualization, which includes a reflection on underlying assumptions. Triple loop learning finally refers to a paradigm change through a reconsideration of values and goals. The triple-loop learning concept points to different primary objects of learning, ranging from incremental refinements of instruments and practices (single loop learning) to reframing (double loop learning), and deep paradigm changes through rethinking of values and goals (cf., van de Kerkhof and Wieczorek, 2005; Pahl-Wostl, 2009).

Broto et al. (2014) point to similarities of the triple-loop learning concept to other classifications from Bateson (1972) and Meadows (1999) that deal with learning intensities. Bateson (1972) defines different types of learning[12]: *Learning I* refers to improving successful responses in a similar context by drawing upon a fixed set of alternatives. *Learning II* denotes the development of the capacity to adapt responses to new contexts based upon prior experiences by changing the set of alternatives. *Learning III* involves an understanding of the learning process and a change in the system that determines the sets of alternatives that are considered. Another classification is provided by Meadows (1999) who lists 12 leverage points to induce effective change in complex systems. Intervention points with low leverage are related to changing parameters and other measures that proceed within the old system structure. Medium leverage is associated with changing information flows and rules. High leverage pertains to paradigm changes that include goals, values and power structures. Broto et al. (2014)

[12] Bateson (1972) also present two further learning levels that are less relevant for an understanding of societal learning processes: Zero Learning is a specific response that is not subject to change (i.e., a kind of reflex action); Learning IV would be a change in Learning III, which “probably does not occur in any adult living organism on this earth” (Bateson, 1972, p. 298).

draw a connection between Meadows' (1999) high leverage points and Bateson's (1978) learning type III. Similarly, Sterling (2000) links Bateson's (1978) learning types to paradigm change (type III), process-oriented, intrinsic learning (type II) and purpose-oriented, instrumental learning (type I). The conceptual framework developed in this article builds upon these conceptualizations. Three learning intensities are distinguished, namely routine learning, reframing and paradigm change. Table 1 shows these learning intensities and related primary learning objects, as well as examples of learning outcomes.

Table 1: Learning intensities, primary learning objects and outcomes.

Learning Intensity	Learning objects	Examples of learning outcomes
I: Routine learning	Iterative improvement of *strategies* (Agyris and Schön, 1978) and *actions* (Sabatier 1988) within current mental models (Sterman, 2000)	Changing *parameters* without changing the system structure (Meadows, 1999), such as: • Increase the heights of dikes to address higher flood levels (Pahl-Wostl et al., 2013). • Solving of merely technical problems in innovation experiments (e.g., Beers et al., 2014)
II: Reframing	Reconsideration and revision of underlying *assumptions* (Agyris and Schön, 1978; Pahl-Wostl, 2009), *fundamental positions* (Sabatier 1988) and *mental models* (Sterman, 2000)	Consider *alternative options* and *viewpoints*: • Allow for river-landscape flows and restoration of the floodplain in flood management (Pahl-Wostl et al., 2013). • Accommodate frames hold by heterogeneous actors in the design process of a sustainable building (Brown and Vergragt, 2008)
III: Paradigm change	Reconsideration and revision of *values and beliefs* (Hargroves, 2002; Flood and Romm, 1996) including *fundamental normative and ontological axioms* (Sabatier 1988)	Change in *rules, goals,* and *mindsets* (Meadows, 1999): • Structural change in water governance and management systems with the ambition to improve overall sustainability (Herrfahrdt-Pähle and Pahl-Wostl, 2012). • Introduction of a culture that promotes experimentation in protected spaces to support active learning in urban water management (Farrelly and Brown, 2011)

3.2 Learning processes in transition research

In addition to concepts that address intensities and objects of learning, other learning concepts focus more on the process of learning, i.e. the specific mechanisms that explain how the objects of learning (e.g., mental models, values) can be altered. Two general types of learning processes can be differentiated. First, learning through interactions with the actual (problem) situation by means of direct *experience and experimentation*. Second, learning about the behavior, values, goals and beliefs of others through *social interactions*. Some learning concepts comprise both types of learning processes. For instance, Wenger's (1998, 2000) concept of communities of practices involves learning through the interplay of socially constructed competence (i.e., learning through social interaction) and experience of a joint enterprise (i.e., learning through experience/experimentation). A similar distinction is made in the transformative learning concept, which distinguishes between learning of instrumental competence (i.e., control and manipulation of the environment) and communicative competence (i.e., communicate in an effective way with others) (Mezirow, 1994, 2009). In the following, we present process-related learning concepts that were identified in the selected sustainability transitions literature in more detail.

Learning through direct experience and active experimentation is described in the *experiential learning* concept (Kolb, 1984). Learning is conceived as a four-step process comprising concrete experience, reflective observation, abstract conceptualization and active experimentation. Transition scholars mainly refer to the experiential learning concept to explain processes of individual learning (e.g., Geels and Raven 2007; Broto et al., 2014). *Instrumental learning* processes involve the empirical testing of assumptions in a transformative learning process (Mezirow, 1994, 2009), which is closely related to an experimental learning approach. The transformative learning concept considers adult learning as a process of critical reflection about reference frames, which cause selective perceptions (Diduck and Mitchell, 2003). Reference frames can become dysfunctional due to a dilemma, major events, or long-lasting problems. *Learning-by-doing* and *doing-by-learning* are further learning concepts that are repeatedly applied by transition scholars (e.g., Seyfang and Longhurst, 2013; Bos et al., 2013). These concepts describe the processes of developing theoretical knowledge and testing it through practical experience (learning-by-doing), and developing empirical knowledge and testing it against a theory (doing-by-learning) (van der Brugge et al., 2005). *Learning-by-using* refers more to learning of customers who gain experience through the utilization of a product (Rosenberg 1982). *Trial-and-error learning* has been used in the transition literature to describe the process of conducting an experiment and optimizing the outcome through iterative revisions (Sosna et al., 2010). Trial-and-error learning can also describe an iterative and incremental learning approach in policy-making due to limited information (e.g., Lindblom, 1979) or endogenous technological change (Hoppmann et al., 2014). *Learning-by-exploring* and *learning-by-searching* are more related to learning processes in research or business organizations (e.g., Hekkert et al., 2007). Learning-by-exploring include basic research activities that are conducted by universities and similar research organizations (Lundvall, 2010). Learning-by-searching describes more profit-oriented learning in the business sector through R&D departments in firms (Lundvall, 2010).

In the transition literature, learning based upon social interactions is often linked to *social learning* concepts (e.g., van den Bergh et al., 2007; Safarzynska et al., 2012; Broto et al., 2014). Various definitions of social learning exist. Reed et al. (2010) reviewed social learning concepts and, based upon this, defined social learning as a "change in understanding that goes beyond the individual to become situated within wider social units or communities of practice through social interactions between actors within social networks". Scholz et al. (2014) add to this definition the convergent character of constructive social learning processes (e.g., development of shared vision), as social interaction processes can also result in increased conflict and stalemate positions (see also van Mierlo et al., 2013; Vinke-de Kruijf et al., 2014; van der Wal et al., 2014). Wenger (1998, 2000) notes the synergies between convergent social learning within a community of practice and more divergent social learning that takes place at the community's boundaries. However, there should be a moderate tension between experience (e.g., of novel aspects or practices) and competence (e.g., actual abilities of an individual or a community of practice) to enable learning. Thus, a close overlap of experience and competence reduce the learning potential, while a wide gap would prevent learning at all (Wenger, 2000). *Learning-by-imitation* is another concept originally proposed by Bandura (1977) under the term 'social learning'. It refers to learning of individuals from the observation and imitation of others. *Communicative learning* is considered as a central learning process for transformative learning. Discourses are needed to critically reflect upon competing viewpoints and develop a collective judgment (Mezirow, 1994, 2009). This conceptualization has been applied in the transition literature to understand how stakeholder participation and interaction can promote fundamental social change (e.g., Marschke and Sinclair, 2009).

As already described for the concepts of transformative learning and communities of practice, learning through experience/experimentation and social interactions are both relevant for addressing broader societal issues. For instance, learning processes in adaptive resource management require the setting of joint goals and visions and the discussion of suitable policies (i.e., social interactions), as well as an experimental mindset to deal with complexity (i.e., direct experience and experimentation) (Pahl-Wostl 2008). Another example is provided by Senge et al. (1994) who present a concept for organizational learning combining direct experience, experiments (e.g., innovations in infrastructure) and social interactions (e.g., discussions on attitudes and beliefs), which was applied by Beers et al. (2014) to understand social learning processes in niche experiments.

3.3 Learning subjects and contexts

The involvement of multiple actors is a characteristic of sustainability transitions (Halbe et al., 2015), which raises the question of how the subjects of learning and their respective learning contexts can be conceptualized. Van de Kerkhof and Wieczorek (2005) distinguish between individual learning processes of stakeholders (e.g., policy makers, scientists, and other stakeholders) and mutual learning processes where stakeholders learn together. Participants of group processes learn individually from others' behaviors and statements. In addition, groups can develop formal and informal rules that affect their group internal as well as external interactions, so that such collective learning processes also become situated beyond the individual (cf., Reed et al., 2010; Vinke-de Kruijf and Pahl-Wostl, 2016). Group processes are a particular context of learning that involves specific learning processes (e.g., social learning) and outcomes (e.g., rules for group discourses). The same is true for organizations, such as firms or public authorities, which form a particular context for (1) individual learning of their members (e.g., employees and directors) (see Kim 1993) and (2) group learning processes (e.g., within task forces) (cf., Wenger 1998). Learning in the context of organizations also comes along with specific learning processes (e.g., learning-by-interacting) and outcomes reflected in organizational structures, culture and rules (cf., Kim 1993). Policy learning is another learning context in which actors involved in public policy making are the subjects of learning, comprising governmental actors as well as non-governmental actors in policy networks (e.g., Pemberton, 2000; Newig et al., 2010). The policy learning context allows for particular learning outcomes, such as transfer payments, pieces of legislations, or directives, amongst others. Sustainable development requires learning ranging from the individual to the policy learning context, as well as the development of communicative interfaces in between (Adomßent, 2013). In this article, an agency-perspective with respect to a specific sustainability issue is applied to define learning contexts (i.e., the following question is asked: What is the social unit that primarily takes agency in a learning process that aims at addressing a sustainability issue?). In the following paragraphs, each learning context and pertinent learning processes are described in detail.

In an *individual learning context*, an individual takes action to tackle a sustainability problem. The individual can belong to a social group (e.g., citizen, employee), but acts on her/his own behalf. Two types of interactions, as defined in Section 3.2, can be distinguished in the individual learning context: First, an experiential learning process through interactions with the environment (e.g., experimentation with certain practices) or exploration of personal motives and genuine aspirations (i.e., a more introspective experiential process), and, second, a learning processes based upon social interactions with other individuals (e.g., to receive resources or inspirations).

In the *group learning context*, a group takes collective action to address a problem. Guzzo and Shea (1992) define a group by having three properties: (1) the group is considered as an entity by its members and by non-members who are familiar with it, (2) group members share some degree of interdependence, and (3) group members have different roles and duties. In contrast to organizations, groups have a low hierarchical differentiation (i.e., a flat hierarchy) and a limited formal cohesion (i.e., there is no formal structure that binds group members; participation is more voluntary and can be stopped without significant consequences). In a group context, two types of interactions proceed to deal with a task or a problem in a collaborative way. First, group members can interact to find common ground for actions (i.e., social interactions) and discuss procedural rules, which can be explained by processes of social learning. Second, the group can interact with its environment, which can include group-external stakeholders (social interactions) or physical aspects (i.e., experimental interactions) (cf. Beers et al., 2014).

In an *organizational learning context*, individuals or groups act as representatives (i.e., they act in their role as employees / members of a particular division) to solve a problem in an organizational structure. Organizations have some form of hierarchical structure, are partitioned in different divisions (e.g., manufacturing, sales department), and members are bound together through formal arrangements (e.g., employment contracts) (see De Wine 2001). Organizations have the function to accomplish a certain task or address a societal issue that requires experiential and social interactions with the environment. For instance, a farming business interacts with the environment (e.g., farmland, livestock) to provide food for his customers (often by way of intermediaries). Learning in organizations involves individual learning (e.g., personal mastery) and group learning (e.g., team learning) processes (Senge, 1990). Furthermore, public or private organizations interact with external individual stakeholders (i.e., social interactions), such as customers or clients, or collective stakeholders, such as action groups. The learning-by-interacting (Lundvall 1988) and social learning (e.g., Beers et al., 2014) concepts can explain such interactions between producers, customers and the wider public. Another interaction process involves interactions between organizations (e.g., Easterby-Smith et al., 2008). The formalization of these interactions can be influenced by legislative demands, contracts or more informal agreements in networks. In the *policy learning context*, state actors can fulfill a public interest through a hierarchical mode of governance (e.g., laws, bureaucracies), cooperation with relevant non-state actors in policy networks, or allowing institutionalized self-regulation, which can be voluntary (e.g., industry-led standardization processes) or commissioned (e.g., labor agreements) (Mayntz, 2004). According to this notion, governmental and non-governmental actors interact in addressing a sustainability issue through public policy making and implementation. The hierarchical governance mode includes regulatory, distributive and redistributive policies (Lowi, 1964), as well as constituent policies (e.g., establishment of a new public organization) (Lowi, 1972). Formal and informal linkages between governmental and other actors in policy networks are becoming increasingly important in public policy-making and implementation (Rhodes 1997; Rhodes, 2007). The purposeful design of participatory processes and development of networks can play an important role in mediating interests and coordinating actions of heterogeneous stakeholders in policy making (Bingham et al., 2005). Network processes involve some form of direct interaction and cooperation between state and private actors (Mayntz, 2006). Delegated self-regulation of a state function to private actors is a more indirect form of cooperation. Mayntz (2006) highlights that the state still has to monitor the effectiveness of these arrangements and to reserve its right to intervene (e.g., in case public interests are not catered to). The policy learning context includes the context of individual learning (e.g., policy makers that make decisions based upon past experiences, e.g., Schneider and Ingram, 1988), group learning (e.g., in meetings of policy networks, e.g., Colvin et al., 2014), as well as organizational learning (e.g., through learning within governmental organizations, such as ministries) (e.g., Grin and Loeber, 2007).

4 Review results: Factors that support and impede learning

For each learning context, our systematic review resulted in a list of factors at two levels of abstraction (i.e., main and sub-categories of factors). The comprehensive list of factors is presented in tabular form in Appendices 2.1 – 2.4. Factors were sorted into four groups to structure their presentation: factors that are related to (1) the motivation of actors to engage in a learning process, (2) experimental processes, (3) social interaction processes, and (4) resources (cf. factor groups in Appendices 2.1 – 2.4).

In the following, Section 4.1 provides an overview on the review results (i.e., main categories) and presents factors that comply across four and three learning contexts (main and sub-categories). Section 4.2 presents more context-specific factors in detail (i.e., factors that are only relevant in one or two learning contexts). All references that are linked to learning factors are provided in the factor list in Appendices 2.1 – 2.4. To improve the readability, we only provide factor identifiers in the following sections that are composed of a capital letter referring to the learning context (i.e., 'I' refers to the individual context; 'G' refers to the group context; 'O' refers to the organizational context; 'P' refers to the policy context) and a factor number, as provided in the factor list in Appendices 2.1 – 2.4.

4.1 General review results

Our review shows that the number of relevant factor categories is increasing from the individual (10 main factor categories / 12 sub-categories) to the group (11/33), organizational (17/37) and policy (17/47) learning contexts (see Appendix 2). This is also representative of the number of publications from which the factors were derived, ranging from six publications in the individual learning context to 16 (group learning), 18 (organizational learning) and 38 publications (policy learning). 66 % of the learning factors were reported as supportive factors in the literature, which reflects a general tendency to report on success factors. 25 % of the supportive factors are backed by references that included these factors in an inverse formulation. Only 9 % of the factors were found to be impeding factors. One factor ("government change") is in some publications reported as a supportive and in others as an impeding factor, which suggests that the influence of this factor depends upon case-specific attributes. Endogenous and exogenous factors were identified in all learning contexts indicating that learning processes can be actively supported by social units, but also depend to some extent on exogenous factors. Across all learning contexts, exogenous factors turned out to have the lowest share (I: 18%; G: 9%; O: 15%; P: 5%), while ambiguous factors (i.e. those that were assessed to be only partly susceptible to context-internal learning) have the highest share (I: 46%; G: 48%; O: 52%; P: 61%). Endogenous factors also have a substantial percentage in all learning contexts (I: 36%; G: 43%; O: 33%; P: 34%).

Table 2 summarizes the review results by providing an overview of main factor categories across learning contexts, and the numbers of underlying references at a scale from low (1-2) to medium (3-5), large (6-10) and very large (>10). In *all learning contexts*, the reviewed literature suggests a disturbance or crisis as a supportive learning factor (I-1; G-1; O-1; P-1). The topic for experiments and participatory processes should furthermore be selected in a way that stakeholders can relate to it and expect tangible impacts (I-3; G-3; O-6; P-5). The 'planning/implementation of multiple experiments' (I-7; G-5; O-10; P-9) should be flexible to be able to react to surprises and opportunities (I-7.1; G-7.5; O-13.3; P-13.5). Low-regret experiments are generally mentioned as particularly important, as they allow learning from failure (I-7.3; G-5.3; O-10.4; P-9.4). Process monitoring, reflection and evaluation are supportive learning factors in experimental as well as social interaction processes (I-7.2; G-7.4; O-13.7; P-13.11). Another supportive factor in all contexts is the 'design of participatory processes' (I-8; G-6; O-12; P-12). The same applies to physical resources (e.g. funding, materials) (I-9; G-9; O-15; P-15) and non-physical resources (e.g., knowledge, information) (I-10; G-10; O-16; P-16). Support programs (e.g. from governmental agencies, universities and other actors) can be instrumental in providing the infrastructure for knowledge exchange as well as start-up funding (e.g., I-10; G-9.1; O-15.1; P-15.1). In addition, measures and infrastructures for knowledge exchange (I-10.2; G-10.1; O-16.1; P-16.1) and integration (I-10.2; G-10.2; O-16.2; P-16.2) are supportive factors in all contexts.

In the *individual, organizational and policy learning contexts*, societal values that favor sustainability (I-2; O2; P3), the setting of a leading sustainability vision (I-4; O-8; P-7) and the existence of forerunners (I-6; O-9; P-8) are mentioned as supportive factors. Supportive learning factors in the *group, organizational and policy learning contexts* comprise a strong commitment of stakeholders, which can be based upon a feeling of responsibility (G-4; O-7; P-6), as well as process facilitation (G-7; O-13; P-13), leadership (G-8; O-14; P-14) and trust (G-8; O-17; P-14). Similar sub-categories of learning factors also appear across the group, organizational and policy learning contexts. A purposeful design of participatory processes includes a purposeful stakeholder selection (G-6.1; O-12.1; P-12.2) and the establishment of an involvement strategy that defines the engagement of stakeholders to various degrees at different stages of the process (G-6.2; O-12.2: P-12.3). For instance, it can be beneficial to start the process with a homogenous group of stakeholders, and broaden the involvement later in the process (e.g., Nevens et al., 2013). Conflict mediation and resolution mechanisms can help to overcome diverging viewpoints and interest (G-6.3; O-12.4; P-12.5). Further supportive factors are an effective networking with group-external actors (G-6.4; O-12.5; P-12.6) inclusion of findings from other related learning processes (G-6.5; O-11.4; P-10.1) and existence of organizations that coordinate processes and consolidate findings (G-6.6; O-12.6; P-12.7). Effective process facilitation includes the discussion of the process design and rules with stakeholders (G-7.1; O-13.1; P-13.1) and clarification of expectations (G-7.9; O-13.6; P-13.8). Further supportive factors are the development of a shared and integrated problem perspective (G-7.7; O-13.4; P-13.9) and vision of a desirable future (G-7.8; O-13.5; P-13.10).

Table 2: Comparison of main categories of learning factors across learning contexts. The number of references are rated using the following scale: low number (o) := 1-2 references; medium number (+) := 3-5 references; large number (++) := 6-10 references; very large number (+++) := >10 references).

	Sup/ Imp	**IDs***	**Individual Context** (Total #: 6)	**Group Context** (Total #: 16)	**Organizational Context** (Total #: 18)	**Policy Context** (Total #: 38)
Disturbance or crisis	Sup	I-1; G-1; O-1; P-1	o	o	+	+
Change of government	Sup/ Imp	G-2; P-2		o		+
Societal values that favor sustainability	Sup	I-2; O-2; P-3	o		++	+
Sustainability oriented institutions	Sup	O-3; P-4			++	++
Choose topic that arouses attention and motivation	Sup	I-3; G-3; O-6; P-5	+	++	++	++
Provision of a leading sustainability vision	Sup	I-4; O-8; P-7	o		+	+
Commitment (awareness and responsibility)	Sup	G-4; O-9; P-6		o	+	+
Existence of forerunners	Sup	I-6; O-9; P-8	+		o	+
Externalities and lock-in effects	Imp	O-4; O-5			o	
Experimental and social interaction process						
Planning/implementation of multiple experiments	Sup	I-7; G-5; O-10; P-9	o	+	++	+++
Structures that support participation	Sup	O-11; P-10			++	+++
Policy instruments	Sup	P-11				+++
Design of participatory processes	Sup	I-8; G-6; O-12; P-12	+	++	+++	+++
Process facilitation	Sup	G-7; O-13; P-13		+++	++	+++
Leadership	Sup	G-8; O-14; P-14		+	+	+++
Resources						
Physical resources	Sup	I-9; G-9; O-15; P-15	+	++	++	+++
Information and knowledge	Sup	I-10; G-10; O-16; P-16	o	+++	++	+++
Trust	Sup	G-11; O-17; P-17		o	o	++

* ID stands for factor identifier, as provided in Appendices 2.1 – 2.4.

4.2 Context-specific review results

In addition to consistent factors across learning contexts, more context-specific factors were identified, which are relevant to one or two learning contexts only. In the *individual learning* context, a curious and critical mindset (I-5) is a learning factor that is related to an actor's motivation for sustainability-related learning. Learning factors in the individual learning context generally focus more on the application of the experimental method for learning (i.e., learning through experience and experimentation; see related factor in Section 4.1). Nevertheless, social interactions are also relevant with regard to engaging affected actors through honest communication processes (I-8). Physical resources can be acquired by individuals through a creative use of available material (I-9.1) or asking others for help (I-9.2). The availability of natural capital (i.e., the capacity of ecosystem to provide goods and services) (I-9.4) and local/traditional knowledge (I-10.1) can be further critical resources for experimental learning.

In the *group* learning context, a change of government is considered as a supportive factor (G-2), if elected officials advance sustainability values. An innovative topic for the group process should be chosen that arouses public expectations and interest (G-3.2). The continuous separation of viable from less viable design ideas, e.g. through reality checks, can support a purposeful experimentation process (G-5.1). The complexity of experiments can overwhelm the project members though, and thus can become an impeding factor of learning about group external processes (as group members do not have time to monitor external processes, such as acceptance of group actions by residents) (G-5.2). With regard to process facilitation, the development of a common language (G-7.2), an active tackling of power asymmetries (G-7.3) and an open discussion on limitations and potentials of scientific methods (G-7.6) are supportive factors. Process facilitators should assure that the momentum is maintained through continuous interactions (G-7.11) and needs of all participants are addressed (G-7.12). An impeding factor can be the influence of powerful actors who try to exploit participatory processes for their individual interests (G-7.10). Effective leadership can be impeded by actors who are unwilling to take risks (G-8.1), which can be particularly problematic in case of group members who are representatives of organizations (G-8.2). In the resource-related factor group, lessons and best practices from other projects (G-10.4) and the availability of local or traditional knowledge are supportive factors for group learning (G-10.3).

In the *organizational learning context*, sustainability-oriented institutions, formal laws, regulations, and norms are included as supportive factors (O-3). The selection of an innovation that is likely to be applied widely (e.g., in further countries) is another supportive factor as it motivates organizations to invest resources into experimentation due to prospects of future profits (O-6.1). The awareness of a sustainability issue can be supported through an active communication within an organization (O-7.1). Widely applied practices are an impeding factor though, as they are not put into question due to the perception of normality (O-7.3). Further impeding factors relate to a low motivation of organizations to engage in a sustainability-related learning process due to the existence of externalities (i.e., undesired effects that are not included in market price) (O-4) and a lock-in into an overly specialized industry with high investments, competition and government support (O-5). Learning through social interactions can be promoted by an interactive culture that cuts across horizontal and vertical structures of the organization (O-11.1), linking of bottom-up and top down processes (O-11.2), availability of skills for active networking and collaboration (O-11.3) and active engagement in networking activities (O-11.4). Those who design social interactions and experimental processes should furthermore actively look for events in the landscape, and align/link the process accordingly (O-12.3). A factor that impedes learning through social interactions is a leadership that articulates (too) many problems to manage (O-14.1) and provides only rhetorical support for sustainable development without practical actions (O-14.3). In the organizational learning context, physical infrastructure (e.g., roads, cyber infrastructure) (O-15.3), the financial resources of an organization (O-15.2) and metrics that measure process towards sustainability (O-16.3) are resource-related factors that support learning.

In the *policy learning context*, a change of government is considered an ambiguous factor (P-2) (i.e., some references mention this factor is supportive, e.g., Colvin et al., 2014, while others regard it as an impeding factor, e.g., Di Iacovo et al., 2014), which depends upon the government's position towards participation and sustainability concerns. Sustainability-oriented institutions (e.g., legislation that demand stakeholder participation) are supportive factors (P-4) in the motivation-related factor group. An impeding factor can be a lack of knowledge about a topic by the public, which might constrain the motivation for participation. Policy experiments should be process-oriented (i.e., being flexible to utilize opportunities and address problems as they arise) (P-9.1) and utilize linkages to local and national initiatives (P-9.6). Sub-categories of learning factors with respect to a participatory approach to policy-making comprise the consideration of policies as social innovation processes (P-10.2), horizontal and vertical integration (P-10.3), collaboration skills (P-10.6), and acknowledgement of diversity (e.g., with regard to lifestyles, culture, perspectives) (P-10.7). Impeding factors are the dominance of command-and-control or market paradigms (P-10.4) and lock-in effects through encrusted power structures and actor networks (P-10.5) that counteract a participatory approach. Several policy instruments have been revealed that can function as supportive factors (i.e., policy instruments can also function as impeding factors, for example, if misinformation is distributed), comprising the use of media to influence public opinion on sustainability issues (P-11.2), addressing the contextual forces that may affect firms' strategies and initiatives (P-11.1), broad and early stakeholder participation to assure transparency and democratic legitimacy (P-11.2), and support of transdisciplinary research processes (P-11.4). With respect to the design of participatory processes, public involvement programs should be led by a neutral party (P-12.1) and balance between orchestrated and self-organized action (e.g., through a mix of formal and informal processes) (P-12.4). Process facilitation should involve informal meetings and networks (P-13.2), explicitly address alternative framings (P-13.3) and power asymmetries (P-13.4), facilitate the emergence of a common language (P-13.6), and allow for a continuous adaptation of the process design (P-13.7). The continuity of a participatory process was mentioned as another supportive factor that can be achieved through institutionalization of a learning process and capacity building within participating organizations (P-13.12). Leadership can support learning by facilitating information flows between different levels of governance (P-14.1). In addition, the definition of useful sustainability indicators is mentioned as a supportive learning factor, as this allows systematic monitoring and knowledge development (P-16.3).

4 Discussion

Framework-based synthesis turned out to be a useful approach to deal with the complexity of learning processes in the scope of sustainability transitions. Without the design of a conceptual framework, a systematic collection of data from the literature would have been hardly possible for such a complex topic. The design of the conceptual framework, including the definition of key concepts, required substantial time and several meetings of the review team. This extra effort in the review process however allowed for the design of a systematic data collection process that guided the review of full papers. By jointly reviewing three articles and continuous personal meetings during the review process (group and bilateral meetings), the review team developed a common language and confidence in the review results. The discussion of marginal cases (e.g., with respect to the quality criteria) supported the reaching of well-grounded decisions and limited personal bias.

The quality check of articles with respect to the conceptual and empirical quality as well as thematic proximity was a critical step in the review process. Several articles were considered as conceptually weak, as learning concepts were only used in a shallow way without providing details or references to theoretical backgrounds. Some papers were excluded due to empirical limitations, such as missing details on methods and data collection. Further papers were excluded due to thematic misfits despite matching search terms from the query (for instance, a paper on the transition of juveniles from education to employment was excluded). In the end, the review team aspired to include only conceptually and empirically rigorous papers that are thematically related to broader societal transitions towards sustainability. Nevertheless, a review of such a complex topic as sustainability transitions prevents absence of any subjective decisions. The extraction of data from articles often required some interpretation, particularly as key terms such as “supportive learning factor” or “learning contexts” usually are not explicitly mentioned. Nevertheless, a systematic review approach was found to be helpful to reduce personal bias, compared to a narrative review approach.

The conceptual framework integrates a range of learning concepts and builds upon prior synthesis efforts (e.g., van de Kerkhof and Wieczorek, 2005). This framework should not be considered as a new theory, but as an approach to systematize and consolidate available learning concepts in order to consolidate findings and guide practice in its attempts to organize effective interventions. The bridging and consolidating function of the framework helped us to develop a list of factors that support or impede learning based upon the scientific literature. The highest number of publications is related to the policy learning context (see Table 2), which reflects a focus of the transition literature on policy processes in which governmental and non-governmental actors interact in the governance of sustainability transitions. The low number of references related to the individual context reveals that more research on the role of individuals might be fruitful. The low number of impeding factors (9% of the total number of factors) suggests a bias towards reporting of successful case studies within the scientific literature. Thus, future research on transition governance should pay more attention to stalled or failed processes.

Several factors comply across learning contexts and thus can play a central role in sustainability transitions (see Table 2). Compliant factors include a crisis, the choice of a motivating topic for experimental and collaborative processes, an experimental approach, purposeful process design as well as physical resources, information and knowledge. The review resulted in a list of learning factors (see Appendix 2) that can be used to design effective learning processes by individuals, groups, organizations and policy-actors. While endogenous factors allow for self-reliant facilitation of learning within each context, exogenous factors point to aspects that cannot be addressed in the respective context due to exogenous events (e.g., a natural disaster) or interdependencies between learning contexts. As an example, policy-makers can shape the contexts of entrepreneurial activities (Cramer and Loeber, 2004) through sustainability-oriented legislation (van Mierlo et al., 2013). Thus, the results point to the importance of addressing these inter-context linkages in the design of transition governance processes (e.g., through developing communicative interfaces, cf. Adomßent, 2013).

The collection of learning factors needs to be tested and verified through further research in the future. Up to now, studies are rarely explicit about the contexts, processes, objects, supportive factors and barriers of learning (cf., van de Kerkhof and Wieczorek, 2005; van Mierlo et al., 2010). Methodologies are needed to systematically analyze the contexts of reflexive governance processes, monitor the processes and evaluate the outcomes (cf., Forrest and Wiek, 2014). Methodological and conceptual frameworks are available that can support the identification of learning processes and their outcomes in singular cases, and allow for the identification of influencing factors through the comparison of multiple case studies (e.g., Pahl-Wostl et al., 2010; Forrest and Wiek, 2014).

5 Conclusions

Pro-active governance of transitions can be a critical approach to deal with contemporary sustainability challenges. Learning is of key importance in transition processes in general, as well as transition governance processes in particular. Despite the importance of learning, learning concepts are often used broadly in the transition literature without specifying the specific objects, processes and contexts of learning.

In this paper, we presented a framework of learning concepts in transition research that differentiates between learning intensity, objects, outcomes, processes, subjects and contexts. The conceptual framework guided a systematic literature review of factors that support and impede learning in sustainability transitions. The results show multiple entry points for interventions and roles of several actors for facilitating sustainability transitions. Learning factors were identified for individual, group, organizational and policy learning contexts. While several learning factors are specific for their respective context, we identified six main factor categories that support learning in all learning contexts and are therefore critical to achieving broad societal learning processes: (1) a disturbance or crisis, (2) a topic that arouses attention and motivation, (3) planning/implementation of multiple experiments, (4) design of participatory processes, (5) physical resources, and (6) information and knowledge.

The list of supportive and impeding factors that resulted from our literature review can be used to guide and improve the organization of learning processes. Transdisciplinary research can play an important role in the design of transition governance processes by analyzing and introducing learning factors that actors can implement in a self-reliant way, as well as factors that require cooperation across learning contexts. The factor list can act as a reference for future empirical work on learning in transition processes and help to consolidate new findings.

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Appendix 1: Literature selection

The query in the Scopus database (see Section 2) resulted in a list of 132 publications. We screened the abstract, introduction and conclusion of all articles with the following questions in mind: (1) Does the article use learning concepts (i.e., we searched for the term "learn" and checked whether learning concepts are applied)?; (2) Is the study related to a transition process (i.e., we searched for the terms 'transition' and 'transform')? Thus, we excluded all publications that only use learning concepts on a superficial level (i.e., learning concepts are not explicitly stated), or articles that are not related to sustainability transitions.

Following, the full text of 92 publications has been read to finally check their eligibility. The conceptual rigor (i.e., are concepts/theories plausible and well-grounded in the literature? Is sufficient detail provided?) and thematic proximity (i.e., is the paper focusing on sustainability transitions, or is it more a side-topic?) were assessed in the full text. In addition, the empirical rigor was assessed (i.e., is the methodological design and results of the empirical study described in a detailed and plausible way?). A weak thematic proximity resulted in the exclusion of the paper from the review process. Papers with a weak conceptual rigor were not considered in the development of the conceptual framework. Papers with a weak empirical rigor were not included in the identification of factors that support and impede learning. In cases where reviewers were uncertain about the quality assessment of specific papers, these papers were discussed in a group meeting or bilateral meetings with the first author to make a final decision. After scanning the full text, 63 publications entered the review process. A flow chart is provided below that shows the number of articles that were identified in each step of the selection process.

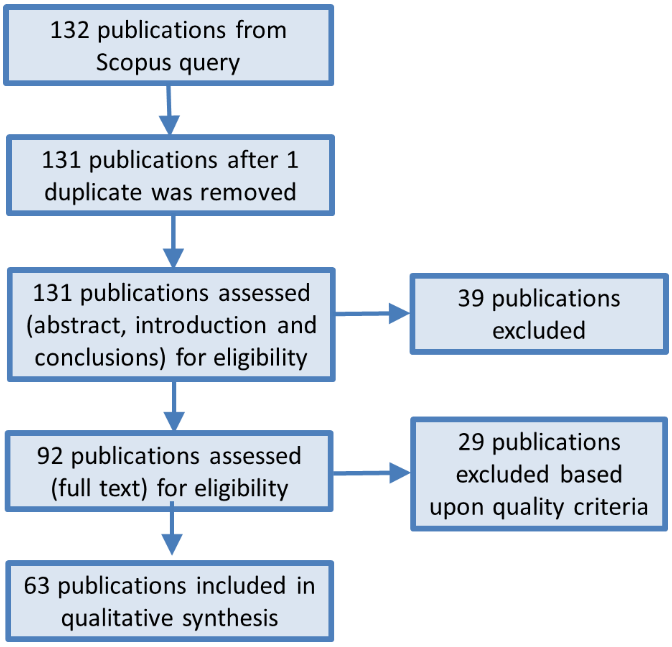

Figure A1.1: Flow chart of the literature selection process.

Appendix 2: Detailed results from literature review.

Appendix 2 of this article corresponds to Appendix 1 of the dissertation

Article 2

Halbe, J., Pahl-Wostl, C., Lange, M. A., and Velonis, C., 2015. Governance of transitions towards sustainable development – the water–energy–food nexus in Cyprus. *Water International* 40(5-6), 877-894.

Governance of transitions towards sustainable development – the water–energy–food nexus in Cyprus

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Abstract

This paper presents a methodological framework to analyse sustainability innovations in the water–energy–food nexus and strategies for governing transition processes towards their widespread implementation. An application to a case study in Cyprus shows the interrelations of several sustainability innovations in the water, energy and food sectors, and specific learning requirements that need to be addressed to achieve a transition towards sustainable development. The framework helps to explore systematically responsibilities of different stakeholders for the implementation of innovations and thereby provides critical information for reflexive governance processes.

Keywords: reflexive governance; water–energy–food nexus; systems thinking; viability loops; Cyprus

Introduction

The water–energy–food (WEF) nexus perspective supports the assessment of the interactions of multiple innovations across sectors. Reflexive governance, developed to highlight the increasing relevance of actor networks that comprise policy-makers, civil society and entrepreneurs, amongst others, is a promising approach to such an assessment. The concept provides five strategies to deal with complex problems: integrated knowledge production, experiments and ability of strategies and institutions to adapt, anticipation of long-term systemic effects, iterative and participatory goal formulation, and interactive strategy development (Voss & Kemp, 2006). Transition management is a specific reflexive governance approach that aims "at long-term transformation processes that offer sustainability benefits" (Kemp & Loorbach, 2006, p. 103). It considers the importance of network governance, long-term collective goals, innovation and learning for transition processes.

Learning processes are fundamental to several key dynamics of sustainability transitions (cf. van den Bergh, 2011), including innovation processes (Bergek, Jacobsson, Carlsson, Lindmark, & Rickne, 2008), niche formation and development (Kemp, Schot, & Hoogma, 1998), as well as breakthrough and diffusion of innovations (Geels, 2005). A differentiated understanding of learning is particularly needed in reflexive governance approaches that aim at the proactive facilitation of sustainability transitions through social learning processes (Voss & Kemp, 2006). Limitations of transition management, relying on reflexive governance, have been noted in the literature. First is the issue of who acts in sustainability issues and who decides on what is the problem and how it should be solved (Genus & Coles, 2008; Shove & Walker, 2007; Voss, Smith, & Grin, 2009). Thus, reflexive governance could even impede innovation, as actors from the regime participate, such as business leaders and government employees, who might not have an interest in radical transitions (Avelino, 2009; Voss et al., 2009). Second, the terminology of transition management is often too unspecific and abstract to enable stakeholders to agree about the meaning of key terms (Avelino & Bressers, 2008). Third is the problem of how the sustainability of solutions can be assessed and monitored in practice so as to avoid undesired dynamics (Shove & Walker, 2007).

This paper proposes a methodological framework that addresses these three challenges by providing critical information at the initiation of reflexive governance processes. The proposed framework allows for a case-specific assessment of potential sustainability innovations, understood as innovative approaches for the provision of societal functions (e.g., for water, energy and food supply) that reside at a niche level today, but which might be an important element of a sustainable supply system in future. The methodological framework furthermore supports the governance of transitions by systematically exploring the learning requirements of different stakeholders (e.g., public agencies, civil society, entrepreneurs) toward the up-scaling of innovations. In contrast to Rogers (2003), who emphasized the role of ideas, implemented practices and objects in defining innovations, we focus only on implemented practices and objects that are perceived to be new.

This paper is structured as follows. First is a presentation of the methodological framework, followed by its application to a case study of the WEF nexus in Cyprus.

Methodological framework: governance of transitions in the water–energy–food nexus

A nexus approach has to consider inter-sectoral linkages to avoid shifting problems from one sector to another. Integrated assessment methods can help to anticipate such shifts and detect measures to avoid detrimental side-effects (Ness, Urbel-Piirsalu, Anderberg, & Olsson, 2007). Figure 1 shows a methodological framework that includes an integrated assessment of innovations as well as analysis of learning requirements to disclosure the responsibilities of multiple stakeholders for a transition towards sustainable development.

First, a problem and stakeholder analysis is conducted. Selected stakeholders are contacted and asked to participate in individual interviews in which causal loop diagrams (CLDs) are built to examine their system perspectives with respect to prevalent problems in the WEF nexus, potential innovations to solve these problems and potential barriers towards the implementation of innovations. These outcomes from the stakeholder interviews are assessed in an integrated fashion to evaluate proposed solutions and investigate potential side-effects from a nexus perspective. Case-specific learning requirements in different societal contexts (individual, group, organizational and policy contexts) are identified that show the roles of stakeholders to actively govern a transition process towards sustainable development. Specific solutions are examined that can be fostered through individual action (i.e., individual context), group processes (i.e., group context), services or products provided by organizations such as companies or specific public agencies (i.e., organizational context), or appropriate regulations (i.e., policy context).

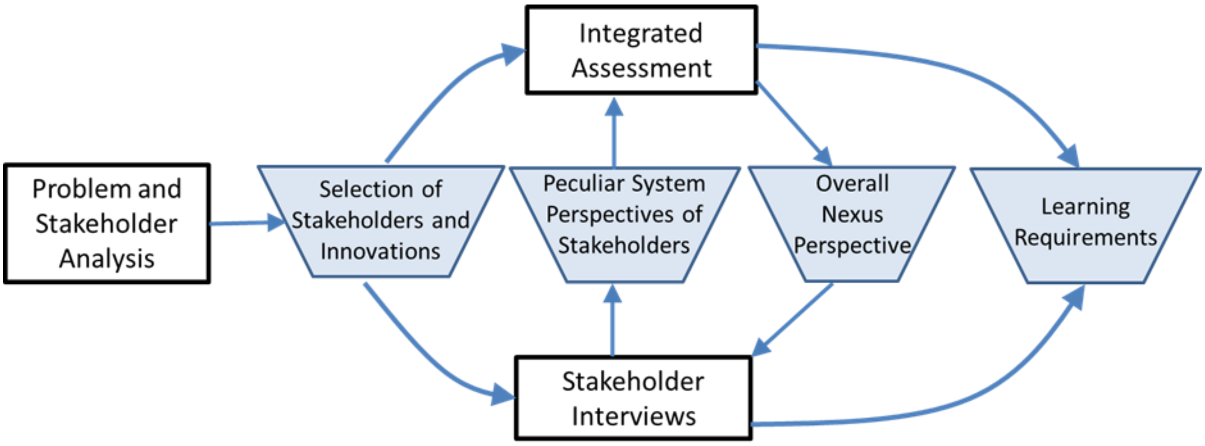

Figure 1. Methodological framework for the governance of transitions towards sustainable development in the water–energy–food (WEF) nexus. Methodological steps are provided in rectangular boxes; related outcomes are depicted in trapezes.

The following explains in detail each step of the framework.

Problem and stakeholder analysis

Several sustainability issues (e.g., water scarcity, fossil fuel dependence, food security) as well as innovations can be defined from a WEF nexus perspective. Given the complexity of most problem situations, several plausible and legitimate problem framings are possible that might lead to quite different conclusions on what is the problem and how it should be addressed (cf. Dewulf, Craps, Bouwen, Taillieu, & Pahl-Wostl, 2005; Pahl-Wostl, 2002, 2007). The initiators of a reflexive governance process (e.g., scientists, policy-makers or concerned citizens) need to come up with a preliminary problem definition as a basis for the selection of stakeholders. Stakeholders can change or refine the initial problem definition during the individual modelling process in the next step. The initial problem definition should be broad enough to comprise various interpretations of stakeholders rather than being constrained to the specific interests like those of the initiators of the participatory process (cf. Carr, Blöschl, & Loucks, 2012).

This is of particular importance since the starting position can significantly affect the evolution of the process.

The main sources of information for the initial WEF analysis are the scientific literature dealing with the WEF nexus, as well as other documents that reflect the opinions and interests involved (e.g., newspapers articles, communication from interest groups). These different kinds of information are consolidated through the construction of a CLD. The CLD is a powerful tool of the systems thinking approach that allows for the depiction and qualitative analysis of systems (cf. Halbe, Pahl-Wostl, Sendzimir, & Adamowski, 2013; Inam, Adamowski, Halbe, & Prasher, 2015). In these diagrams, elements of the system are connected by arrows that together form causal chains (for an example, see Figure 2). A positive link indicates the parallel behaviour of variables: in the case of an increase in the independent variable, the dependent variable increases above what it would have been, while a decrease in the independent variable implies a decrease in the dependent variable beyond what it would have been (Sterman, 2000). A negative link indicates an inverse linkage between variables. A further central concept in system dynamics is the elaboration of feedback loops. Two different sorts of feedback loops exist that can be detected in CLDs: the self-correcting ‘balancing loop’ and the selfamplifying ‘reinforcing loop’ (Sterman, 2000).

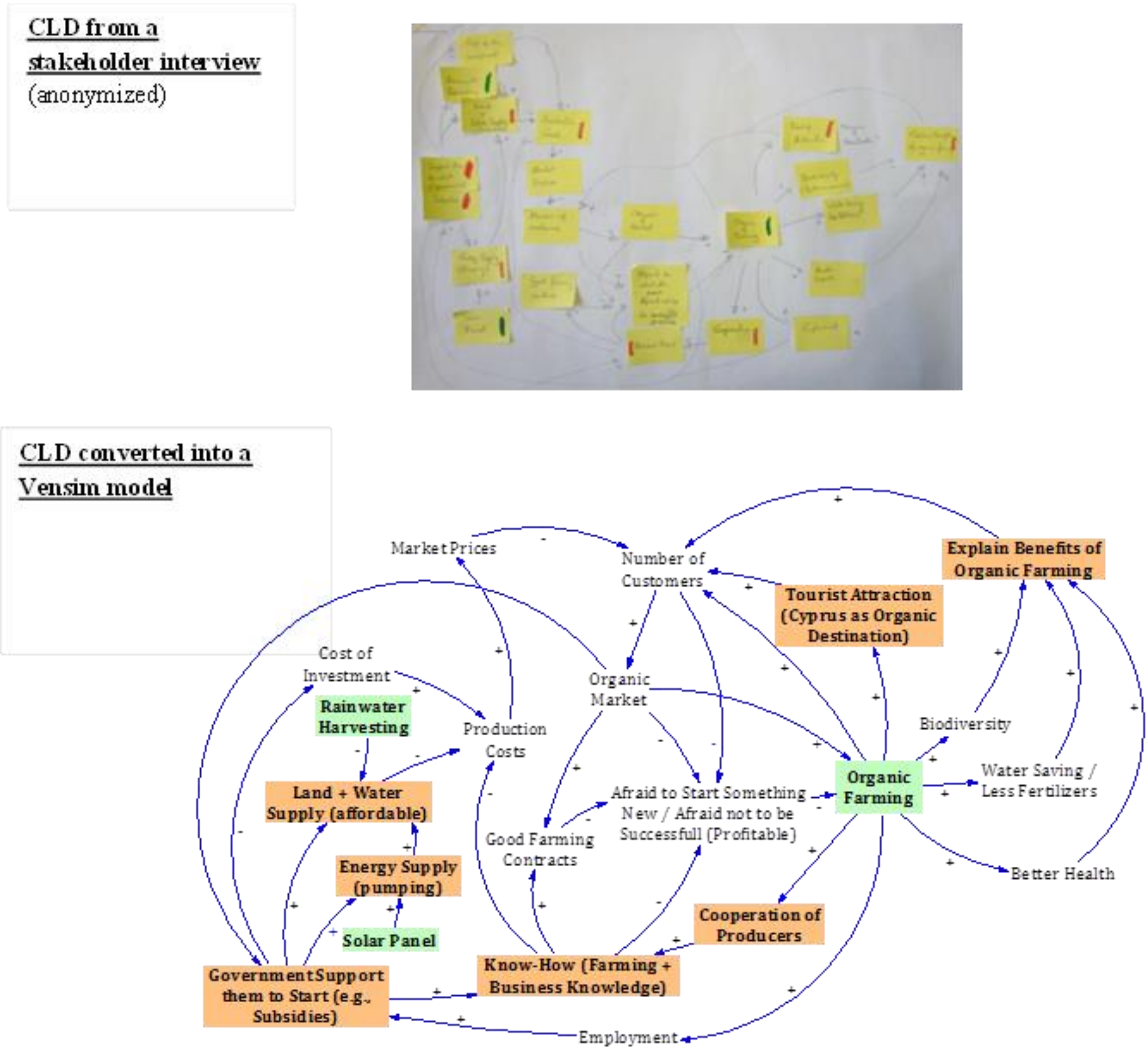

Figure 2. Example of a causal loop diagram (CLD) from an innovator of the organic farming sector (original model above; digitized and analysed model below). The green variables represent the innovations, which comprise the actual innovation implemented by the interviewee and two further innovations. Variables marked in orange are learning requirements that need to be addressed to support the organic farming sector.

In the next step, relevant stakeholders have to be identified to complement the process of developing a CLD based upon the existing literature through a participatory process (see next section) that reveals more subjective and unknown perspectives (e.g., with regard to innovations). By including a broad range of stakeholders in the process, the influence of the starting position (i.e., initiating team and initial problem definition) decreases as new viewpoints and ideas enter the process. Two types of stakeholders can be distinguished that are experts (who can provide an overview on nexus problems and innovations) and innovators (who play a role in the implementation of innovations). Different methods, purposes and application areas for stakeholder analysis exist (cf. Stanghellini, 2010). A promising first step of stakeholder analysis is the construction of a ‘stakeholder map’ by the initiating teamvia a brainstorming session with the aim of developing a list of all potential stakeholders (experts and innovators). The identified stakeholders are sorted into further categories according to their role in the water, energy or food sectors: decision makers (e.g., policy-makers), users (e.g., consumers), implementers (e.g., public servants) and suppliers (e.g., funding agencies) (cf. European Commission, 2003). Stakeholders are assigned to the respective groups, while gaps in the composition are examined to explore the omission of relevant parties.

Individual modelling

Stakeholders (i.e., experts and innovators) who have been identified in the first research step are asked for an interview. During this interview (which lasts for about 1–1.5 hours), experts are requested to build a CLD that represents their system perspective on the problems involved in the WEF nexus. Innovators are asked to develop a model of the barriers and drivers of a specific innovation. The interviewee builds the CLD independently by choosing variables (which are written on sticky notes and placed on a large sheet of paper) and drawing linkages (using a pencil). The interviewer provides only methodological support without influencing the content of the model (for more details on building CLDs in individual interviews, see Inam et al., 2015). The interview process is similar for innovators and experts and is described in detail in the following.

Experts start with the definition of problems in the WEF nexus (which could me more than one). The second step involves the identification of the causes of the defined problems as well as the polarity of causal links. In the third step, the consequences of the problem are studied. In the fourth step, the interviewee is encouraged to find feedback loops (Vennix, 1996). In the fifth step, potential solution strategies and innovations are included to address the problems. Finally, in the sixth step, the barriers of potential solutions and innovations are added. In summary, the presented approach encourages the structured construction of a holistic system structure that includes a representation of the participants’ mental models of the status quo as well as their preferred strategies and challenges related to the problem being explored.

Innovators start with the definition of causes that influence their particular sustainability innovation (i.e., efficient irrigation technologies, energy-efficient buildings or organic farming practices). These causes can be constraining or supporting factors, or aspects that motivated them to implement the innovation. In the second step, the consequences of the innovation are added (e.g., desirable effects on the environment), and in the third step potential feedback processes are included. In the fourth step, the interviewee is asked to think about further barriers to the innovation, as well as solution strategies (fifth step). In the sixth step, stakeholders are identified by the interviewee who could be responsible to implement the solution strategies included.

The individual interview process results in two different kinds of CLDs: experts build CLDs that show the issues in the WEF nexus and point to innovations that might address them; and innovators build CLDs that provide insight into the opportunities and issues of particular innovations, and promising approaches to foster the diffusion of innovations

(Figure 2 shows a CLD built by an innovator). The CLDs are later analyzed and digitized by the process facilitators using the software Vensim.

Integrated assessment

While the construction of CLDs by stakeholders is a bottom-up approach to analyse perceptions of the WEF nexus and potential innovations, integrated assessment puts these individual perceptions into a broader picture. Conceptual modelling using CLDs is a repeatedly used tool for integrated assessment (Ness et al., 2007). The advantages of CLDs are the flexible application to physical, environmental as well as social processes, and the opportunity to include participants in the model building process (Vennix, 1996). CLDs can also form the basis for quantitative systems analysis using a system dynamics approach (cf. Sterman, 2000).

In this paper, CLDs are used for the qualitative analysis and assessment of innovations in the WEF nexus. First, a CLD is built for an initial problem analysis based upon a thorough literature review. Stakeholder-built CLDs are merged into a comprehensive CLD that depicts the interrelation between key elements of the water, energy and food sectors, including problems and innovations. The diagrams from different stakeholders can consist of redundant, complementary or controversial elements. Controversial system representations should be highlighted (e.g., by an exclamation mark) since these aspects might create potential conflicts between stakeholders. Redundant and complementary system elements are included in as much detail as possible to allow for a precise replication of causal chains. Certainly, merging individual CLDs is a challenging task as interviewees can use different words for the same concept, can refer to different concepts with the same words or use concepts that overlap but do not fit entirely. Interpretations should be made transparent and discussed with stakeholders.

Due to the high number of variables and linkages, a comprehensive CLD quickly becomes unwieldy. To make the CLD manageable and to assess the sustainability of the system, the concept of viability loops is used. Viability loops are the most critical balancing processes in a system that adjust detrimental reinforcing processes. According to Hjorth and Bagheri (2006, p. 86), "sustainable development is a process in which the viability loops can remain intact. Planning for sustainable development is therefore to identify the viability loops and to keep them functional". Different steps are required to develop a simplified model using the concept of viability loops. First, reinforcing processes are identified that cause the unsustainable system behavior within and between sectors. Second, balancing processes and viability loops are included in the model. Third, sustainability innovations are included within these viability loops to analyse their behaviour in the WEF nexus. Viability loops can also support monitoring of sustainable development; sustainability indicators can be detected within each viability loop that show whether the system develops in the direction of sustainability (Bagheri & Hjorth, 2005).

Learning requirements

In the last step of the framework, learning requirements are defined based on results from the integrated assessment model and stakeholder-built CLDs. Learning requirements comprise operational aspects (e.g., funds, tools), process-related aspects (e.g., a forum allowing interaction with other actors), institutions (e.g., new policies) or knowledge (e.g., skills or experience in particular practices) that support the implementation and diffusion of innovations. Stakeholder-built CLDs are analysed with respect to innovations that have been found promising in the integrated assessment (i.e., innovations that have sustainability benefits and avoid detrimental effects within or across sectors). The following steps are proposed to analyse CLDs:

- Identification of innovations in the WEF nexus.
- Identification of drivers and barriers towards the implementation and diffusion of innovations.
- Definition of learning requirements to overcome barriers of innovations.

To define the barriers and drivers of innovations, as well as learning requirements, the CLDs from innovators are analysed. Each innovator was asked to include such barriers, drivers and learning requirements that are assigned to particular stakeholder(s). These learning requirements are sorted into their societal contexts (i.e., individual, group, organizational and policy contexts) to define specific responsibilities of stakeholder groups to induce a sustainability transition. The results demonstrate the multiple responsibilities of stakeholders, and can form the basis for a concerted governance strategy. Rather than passing the responsibility to specific stakeholders (such as politicians or certain businesses), this methodology reveals the need for concerted action.

Cyprus case study

From 2009 to 2014, the framework was applied and tested in a case study on the WEF nexus in the Republic of Cyprus. Cyprus is the third largest island in the Mediterranean Sea after Italy's Sicily and Sardinia. The need for a nexus perspective is particularly obvious in Cyprus due to high water consumption in the agriculture sector and application of energy-intensive seawater desalination for potable water supply. Decreasing and unstable precipitation quantities are the central source of concern for water users and authorities (Katsikides et al., 2005). The national mean annual precipitation data show a high inter-annual variability of rainfall and an overall decreasing trend by 14% from 560 to 480 mm in the last century (Geological Survey Department, 1998). The agricultural sector's share in the overall water demand constitutes 69%, followed by the domestic sector (20%), tourism (5%), the environmental sector (5%), and industry (1%) (Savvides, Dörflinger, & Alexandrou, 2001).

The increase in water demand by a simultaneous deterioration of natural water resources induced a shift in the water policy to the development of non-conventional water sources. The capacity of the desalination plants (more than 200,000 m3/day) is sufficient to satisfy the potable water demand in Cyprus (Water Development Department, 2011a, 2014). The desalination process requires 5.3 kWh/m3 in the Dhekelia plant, and 4.4 kWh/m3 in the Larnaca plant (Koutsakos, Savvides, & Savva, 2005; Sallangos, 2005). The difference in energy consumption illustrates the rapid technical development of the desalination methods. The power for operation of the reverse-osmosis plants is obtained from oil-fuelled power stations (cf. Koroneos, Fokaidis, & Moussiopoulos, 2005) so that a future increase in the oil price would significantly influence water prices as well.

The following presents the results of the case study.

Results: the water–energy–food nexus in Cyprus

Initial problem analysis and stakeholder selection

The framing of the WEF problem in Cyprus was based on a review of the relevant literature and insights from experts in Cyprus (Velonis, 2015). The initial problem analysis revealed several issues in the WEF nexus in Cyprus, including water scarcity, seawater intrusion in groundwater bodies, impacts of climate change, and the widespread perception that water, energy and food are abundant (which causes a wasteful consumption behaviour). The stakeholder analysis revealed an important role of government agencies (e.g., Water Development Department, Department of Agriculture, Department of Environment, Cyprus Energy Agency), water boards, farmer unions and research institutes (e.g., Agriculture Research Institute, Cyprus Institute, University of Cyprus). Initial expert interviews showed that several sustainability innovations already exist, but are held back by socio-economic aspects, such as consumer habits or lack of financial support. Innovators related to the following sustainability innovations were contacted in the course of this case study:

- *Organic agriculture* was selected as a sustainability innovation due to several benefits, such as improved biodiversity (Topping, 2011), pollination (Gabriel & Tscharntke, 2007) and soil fertility (Mäder et al., 2002).
- *Adapted agriculture* through cultivation of plants adapted to the local climate (e.g., xeriscaping), such as herbs that can be used for pharmaceutical and cosmetic products, or teas, was mentioned as a related sustainability innovation (cf. Small & Catling, 2008).
- *Urban gardening* (e.g., community gardens) is a more bottom-up initiative in urban areas to secure the food supply and improve social cohesion (Nasr, MacRae, & Kuhns, 2010).
- *Aquaponics* is a soil-less farming approach that can be implemented for both personal consumption and as a business. Fish and vegetables are produced in a closed-loop system in which water is pumped between different basins.

Accumulating ammonia in the fish tank is converted by bacteria into nitrates, which are consumed by plants (Borg, Little, Telfer, & Price, 2014).

- *Aquifer recharge* was mentioned by several stakeholders as an important approach to increase groundwater levels and avoid seawater intrusion (cf. Koussis et al., 2010).
- *Rainwater harvesting* (Palla et al., 2012) and grey water recycling (Memon et al., 2007) can significantly reduce water consumption in the agriculture, domestic, tourism and industry sectors (UNDP, 2011).
- *Decentralized renewable energy* systems using photovoltaics (cf. Dincer, 2000) were mentioned by several stakeholders as an option to improve energy security and reduce CO2 emissions.
- *Conscious water, energy and food use* can also be considered as sustainability innovations which are currently supported through different kinds of measures, such as education in schools or awareness campaigns (e.g., UNDP, 2011; Water Development Department, 2011a).

Individual modelling process

CLDs were constructed by 27 stakeholders (16 experts and 11 innovators) and about 10 further informal interviews were conducted. Different types of innovators were contacted and interviewed, including innovative individuals (e.g., people who constructed an aquaponics system in a household context), community groups (e.g., who started a community garden), organizations, such as businesses and special-interest groups (e.g., that lobby for organic agriculture), and policy-makers (e.g., who implemented innovative policies or initiatives). Each innovator represented at least one of the innovations mentioned in the previous section. After the introduction of the method by the interviewer, participants were asked to build their individual models. The outcomes of these individual model-building sessions consisted of a number of multifaceted CLDs. The participants were generally satisfied with their models and believed they reflected their point of view comprehensively.

Figure 2 presents an original CLD model (upper part) and the digitized version (lower part). The CLD shows the various factors that influence organic farming, such as a low number of customers and the fears of potential farmers to start a new business (e.g., convert a conventional farm into an organic farm), and to invest sufficient finances to become professional and profitable. The low number of customers is caused by high market prices that reflect high production costs that could be decreased by improved know-how and investments (e.g., solar panels or a rainwater harvesting system). The interviewee points to several (beneficial) consequences of organic farming, including the use of less water and fertilizers, health benefits, and increased biodiversity. In the next step, the interviewee added learning requirements, which are those variables that could improve the implementation of this particular innovation (in this case, organic farming). Thus, farmers and their organizations need to communicate the benefits of organic farming in a clearer way to increase their number of customers. In addition, organic farming could attract a high number of tourists if organic farming and healthy living could become a more dominant part of the Cypriot tourism strategy. Another learning requirement relates to the development of business and farming know-how by farmers. This could be achieved by more intensive cooperation of farmers (a community solution) or through the support of governmental organizations. The minimization of production costs is another issue that can be addressed by farmers themselves with the support of government (e.g., through subsidies or credits). This and other models built by innovators show the various learning requirements needed to support implementation of sustainability innovations. All learning requirements will be systematically analysed in a subsequent section.

Integrated assessment model for the WEF nexus in Cyprus

As a result, the CLD in Figure 3 shows important relationships between water, energy and food supply systems, and potential sustainability innovations. The following sections introduce general interactions in the WEF nexus as well as embedded viability loops. Each section provides a general description of feedback loops followed by an analysis of current empirical data to assess the relative strength of feedback processes.

General interactions in the WEF nexus

As depicted in Figure 3, the water and energy sectors are mainly connected through the energy consumption of desalination plants, water and wastewater treatment facilities, and water conveyance systems. Water scarcity can initiate the further development of desalination and wastewater capacities to increase water supply and solve the initial water scarcity problem (balancing loop, B1). From a nexus perspective, this balancing loop is not included as a viability loop due to the energy consumption related to seawater desalination and wastewater treatment. The water and food sectors are also tightly linked through the use of water for irrigation. The provision of water, energy and food positively influences the standard of living, which in turn encourages migration to Cyprus. A rising population (including tourists) as well as an increased standard of living causes a higher demand for water, energy and food, and creates a reinforcing process (reinforcing loops, R1–R3) (cf. Bagheri & Hjorth, 2005).

Empirical numbers confirm this system behaviour. Total water demand is expected to increase by about 18% until 2020 (using 2000 as the base year) (Savvides et al., 2001). The value of food imports nearly tripled between 1996 and 2011 (Food and Agriculture Organization of the United Nations (FAO), 2013), and gross inland energy consumption increased by about 57% between 1990 and 2012 (EUROSTAT, 2014a).

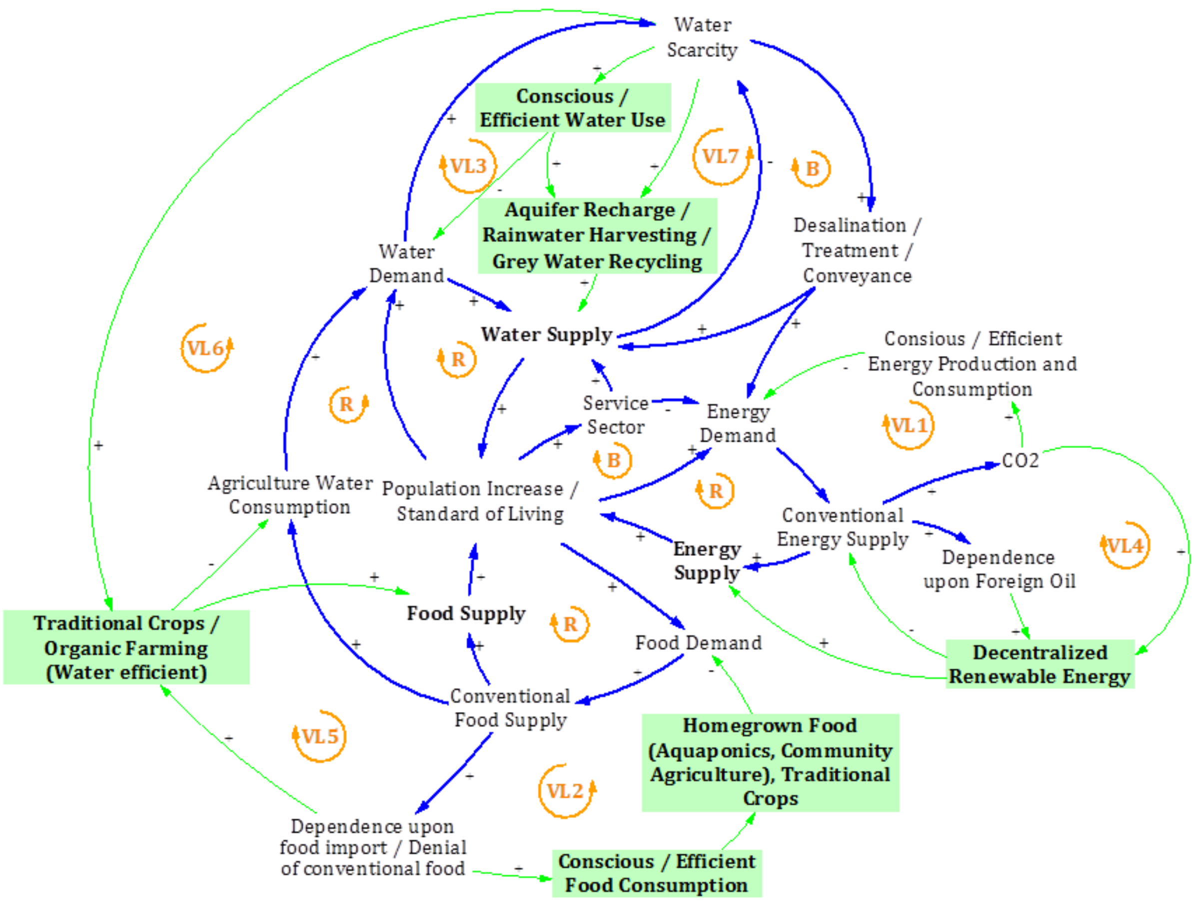

Figure 3. Simplified model showing important relationships in the water–energy–food (WEF) nexus in Cyprus. Reinforcing processes, which are marked with an 'R' and blue causal links, are disadvantageous from a sustainability perspective as they cause increasing resource use. Balancing loops are marked with a 'B'. Viability loops (marked 'VL') counteract reinforcing processes and include sustainability innovations proposed by stakeholders.

However, there are also balancing loops in the energy sector that can induce a stable or even decreasing energy consumption. First, the development of the service sector and decline of the agriculture sector as well as continuing movement of resource-intensive industry (e.g., mining) to newly industrializing countries supports decreasing water and energy consumption and other resource requirements (B2) (cf. Bringezu, Schütz, Steger,&Baudisch, 2004). As this process cannot be assessed as sustainable from a global perspective, this loop is not rated as a viability loop.

Viability loops in the WEF nexus

Efficiency gains and use of higher-quality energy sources lead to a lower energy demand and consumption (Richmond & Kaufmann, 2006). This process can be seen as a viability loop, which balances the increase of energy demand (VL1). In general, more conscious and efficient use of resources is a key approach in all sectors (VL1–VL3). The measure of conscious resource use was also identified by Bagheri and Hjorth (2005) as a key approach for sustainable development. Citizens can be animated to choose a resource-saving behaviour through awareness campaigns (e.g., about the actual scarcity of water resources) or price signals (e.g., through an increase of water prices). More conscious resource use decreases the water demand and counteracts the reinforcing effects of migration and a higher standard of living. The support of urban agriculture through community gardens or aquaponics systems can be part of a strategy to induce more conscious consumption of food, as citizens learn about the process of growing food (VL2). Decentralized renewable energy was proposed by stakeholders as a cleaner approach for energy production (VL4). CO2 emissions and dependence on foreign oil imports were mentioned as the main reasons to lower the share of conventional energy sources and increase the share of renewable energy. In the food sector, the dependence upon food imports was also criticized by several stakeholders. To solve this issue, urban farming was proposed (VL3) as well as organic agriculture and the planting of tradition crops that are adapted to the Cypriot climate (VL5). This will lead to a higher food security and less agricultural water consumption. Planting of less water-intensive crops is also stimulated by the water scarcity problem (VL6), which already urged farmers to optimize irrigation efficiency (Tsiourtis, 2004). The water scarcity issue is also expected to animate the instalment of rainwater harvesting, grey water recycling and aquifer recharge infrastructure (VL7).

The availability of data to assess the strengths of the viability loops is generally low and often requires some interpretation to be used as a proxy. The energy productivity, which increased by 22% between 1995 and 2012, can be used as a rough proxy to assess the improvement of energy use efficiency (VL1) (EUROSTAT, 2014b). Data on home-grown food (VL2) is totally absent, while the consciousness and efficiency of water use (VL3) can be measured by the fresh water abstraction per capita, which decreased by 7% between 2000 and 2012 (EUROSTAT, 2014c). The share of renewable energy (VL4) in gross final energy consumption increased from 3.1% (2004) to 6.4% (2012), which is however far below the European Union average (14.1%) (EUROSTAT, 2014d). The share of the organic food sector (VL5 + VL6) is increasing at a high pace (it increased 32 times between 2004 and 2012), but still accounts only for 3% of the total utilized agricultural area (EUROSTAT, 2014e). Data on traditional crops in Cyprus are currently not available. Grey water recycling (VL7) has been supported by government subsidies (UNDP, 2011), but actual numbers about the installed capacity were not available. Infrastructure (as well as data) for rainwater drainage and harvesting is currently limited in Cyprus (WDD, 2011b). Artificial recharge through recycled wastewater and water from the reservoirs is conducted at a small scale today, but is recommended to be increased in future (WDD, 2010).

Learning requirements to transform the nexus

The integrated assessment model shows the importance of sustainability innovations, which include social innovations (e.g., conscious consumption) and technical innovations (e.g., renewable energy). The analysis of sustainability indicators within each viability loop showed that a sustainability transition is at an early stage in Cyprus. To govern a transition towards sustainability, a governance strategy is required that defines the specific responsibilities of different stakeholders.

CLDs were analysed to reveal learning requirements that need to be addressed to foster the different sustainability innovations. These different learning requirements were sorted to their societal contexts in which action needs to be performed. For instance, conscious resource use was seen as a responsibility that encompasses all learning contexts and several stakeholders, such as individuals, communities, schools and government. Table 1 overviews all learning requirements, associated stakeholders and related innovations (which are positively affected if the learning requirement is addressed).

Table 1. Learning requirements to support a transition towards sustainable development sorted to their respective contexts.

Learning Context	Learning Requirement	Stakeholders	Related Innovation(s)
Individual Context	Implementation of conscious resource-use practices for energy, water, food	Citizens	Conscious water, energy and food use; urban gardening
	Support of organic, small-scale farmers	Citizens	Organic agriculture; adapted agriculture
	Sustainable building (natural materials, solar, insulation, etc.)	Homeowners	Decentralized renewable Energy; grey water recycling
	Learn about sustainability issues and solutions	Citizens	All innovations
	Learn basic farming and craftsman skills	Citizens	Aquaponics; urban gardening; conscious water, energy and food use
	Participate in community activities	Citizens	Organic agriculture; adapted agriculture; aquaponics; urban gardening; conscious water, energy and food use
Group Context	Exchange of seeds, practices and products	Urban farmers community	Urban gardening; organic agriculture; adapted agriculture; aquaponics
	Development of stable networks (e.g., for learning or exchange)	Citizen groups	Conscious water, energy and food use; organic agriculture; adapted agriculture; aquaponics; urban gardening
	Involve Children in Community Projects	Citizen groups	Conscious water, energy and food use
	Cooperation of Producers to improve know-how (e.g., apprenticeships, workshops, etc.)	Farmers community	Organic agriculture; adapted agriculture; aquaponics
	Explain the benefits of organic and traditional Farming	Farmers community	Organic agriculture; adapted agriculture
	Farmer-led distribution	Farmers community	Organic agriculture; adapted agriculture
Organizational Context	Conduct market studies to learn about customer demands plus develop viable business plan	Farming businesses	Organic agriculture; adapted agriculture

	Funds for community projects	Non-governmental organizations (NGOs)	Urban gardening; conscious water, energy and food use
	Optimize land, water, energy requirements	Farming businesses	Organic agriculture; adapted agriculture
	Research on decentralized renewable energy systems and electric mobility	Research organization	Decentralized renewable energy
	New tourism strategy: Organic Destination	Cyprus Tourism Organization	Organic agriculture
	Study of agricultural water use and options for groundwater recharge	Research organizations	Organic agriculture; adapted agriculture; aquifer recharge
	School projects on sustainability topics	Schools	Conscious water, energy and food use
	Implementation of conscious resource use practices for energy, water, food	Farming businesses, processors, industry	Conscious water, energy and food use
Policy Context	Structures and funds for community projects	Government agencies	Urban gardening; conscious water, energy and food use
	Support of decentralized structures; development of a long-term plan	Government agencies	Decentralized renewable energy
	Improve water policies (increase water prices)	Government agencies	Conscious water, energy and food use
	Startup support (e.g., loans, subsidies, land)	Government agencies	Organic agriculture; adapted agriculture; aquaponics
	Policies to promote water-efficient crops	Government agencies	Organic agriculture; adapted agriculture; aquaponics
	Policies to promote grey water recycling systems	Government agencies	Grey water recycling
	Provide sufficient funding for investments in infrastructure (e.g., maintenance of water pipes)	Government agencies	Conscious water, energy and food use; aquifer recharge

Note: The list cannot be considered to be comprehensive as further sustainability innovations might exist in Cyprus.

The analysis of CLDs reveals that all societal contexts have to be addressed in a concerted governance strategy to foster sustainable development. The interview process specifies the need for actions by citizens, farmers, non-governmental organizations (NGOs), schools, as well as government agencies and organizations. This information can lay the foundation for a reflexive governance process that finally brings these stakeholders together.

Discussion

The results showed that there are several opportunities to support the implementation and up-scaling of innovations. Breaking down complex system interactions into a simple set of actions is likely to facilitate the engagement of stakeholders. Such a process can be started by government agencies, as well as NGOs or citizen groups. The framework presented above supports a reflexive governance process by providing a systematic overview of seeds of change (i.e., sustainability innovations) that already exist in Cyprus, along with their supporting and inhibiting factors. Instead of proposing a sustainability transition implemented top down or from the bottom up, the results show a more balanced and interrelated picture. Community actions as well as enabling institutions are required to induce a broad sustainability transition.

The results demonstrate the potential of the methodological framework to address the challenges of reflective governance processes that were mentioned above in the introduction. The framework provides an overview of practical innovations as well as their positive and negative side-effects, which can help reflexive governance processes to become more tangible (cf. the theory–practice gap). Furthermore, the framework helps to explore systematically the responsibilities of different stakeholders (e.g., public agencies, civil society, entrepreneurs) toward the up-scaling of these innovations. Instead of providing specific actor groups with exclusive power and responsibility to manage the process, the results show multiple practical starting points for a transition and the responsibilities of various stakeholders in the process (cf. participation issue). The viability loop concept is a useful approach to assess the current state of sustainable development in Cyprus, which also allows the monitoring of strategies (cf. assessment and monitoring challenge). The assessment of the strengths of viability loops identified in Figure 3 shows a mixed picture with some encouraging developments in Cyprus. Several viability loops are already working, but not at a scale sufficient enough to induce a broader sustainability transition.

CLDs turned out to be a helpful tool to gather, depict and compare stakeholder perspectives. They were also an integral part to analyse qualitatively the WEF nexus and the effects of sustainability innovations. However, the CLD method only allows for qualitative analysis of interactions, and required substantial simplifications to remain clear and understandable. The merging of CLDs towards a whole-nexus perspective turned out to be problematic, as CLDs quickly become unwieldy due to a high number of variables and causal linkages. Future research should progress towards quantitative approaches for integrated assessment (e.g., system dynamics modelling) to deal with this complexity.

This study provides government agencies and other stakeholders with an overview of potential interventions to foster learning in the individual, group, organizational and policy contexts. Implementation of this kind of enabling policies not only offers new options towards further policy instruments but also requires a deeper change from a control-and-predict paradigm to an adaptive and integrated management paradigm (cf. Halbe, Pahl-Wostl, Sendzimir, & Adamowski, 2013). While a control-and-predict paradigm builds upon an expert culture and controllability of actions, an adaptive and integrated paradigm requires stakeholder engagement and policy experimentation. In contrast to this general challenge, the diversity of existing sustainability innovations may become supportive factors for a sustainability transition in Cyprus.

Conclusions

This paper presented a methodological framework for governing transitions towards sustainable development, which is understood as the support of learning processes in different societal contexts. The proposed framework helps to detect and assess case-specific sustainability innovations, and analyse their interactions in the WEF nexus. Learning requirements are finally defined that specify responsibilities of a range of stakeholders to induce a transition towards sustainability. This information can support the development of a comprehensive governance strategy that includes cooperation across a range of stakeholders.

Participatory model-building using CLDs turned out to be a suitable method to analyse systematically stakeholder perceptions on issues in the WEF nexus and related sustainability innovations. The information from stakeholder interviews was consolidated in an overall CLD of the nexus that specified important system dynamics. The concept of viability loops helped to produce a simplified model that contains major reinforcing and balancing processes.

The framework helps to address current challenges of transition management and governance processes. First, the participatory analysis of the WEF nexus and related innovations supports a transparent choice for a specific problem perspective and stakeholder composition (cf. 'participation issue'). The framework requires openness towards ongoing sustainability initiatives which can reduce the influence of the initiating team and support a balance between purposeful process management and self-organization. Second, the focus on specific innovations can close the theory–practice gap. Participatory modelling turned out to be an accessible approach for stakeholders to analyse current barriers and drivers of innovations in their particular local context. Third, the use of the viability loops concept allows for the definition of specific sustainability indicators for the assessment and monitoring of sustainable development.

The results point to the need for a reflexive governance approach to induce a sustainability transition in Cyprus. Learning processes have to take place simultaneously in the individual, group, organizational and policy contexts to implement sustainability innovations through coordinated action. Several sustainability innovations currently exist at a small scale and they require cooperation of actors across various societal sectors and contexts to become relevant at a larger scale. The framework was able to determine specific factors for the governance of such a broad sustainability transition.

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Article 3

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Towards Adaptive and Integrated Management Paradigms to Meet the Challenges of Water Governance

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Abstract

Integrated Water Resource Management aims at finding practical and sustainable solutions to water resource issues. Research and practice have shown that innovative methods and tools are not sufficient to implement IWRM – the concept needs to also be integrated in prevailing management paradigms and institutions. Water governance science addresses this human dimension by focusing on the analysis of regulatory processes that influence the behaviour of actors in water management systems. This paper proposes a new methodology for the integrated analysis of water resources management and governance systems in order to elicit and analyse case-specific management paradigms. It builds on the Management and Transition Framework (MTF) that allows for the examination of structures and processes underlying water management and governance. The new methodology presented in this paper combines participatory modelling and analysis of the governance system by using the MTF to investigate case-specific management paradigms. The linking of participatory modelling and research on complex management and governance systems allows for the transfer of knowledge between scientific, policy, engineering and local communities. In this way, the proposed methodology facilitates assessment and implementation of transformation processes towards IWRM that also require the adoption of adaptive management principles. A case study on flood management in the Tisza River Basin in Hungary is provided to illustrate the application of the proposed methodology.

Keywords

IWRM, water governance, water management, management paradigms, participatory modelling, Management and Transition Framework (MTF)

INTRODUCTION

The persistence of water issues in many parts of the world has given rise to innovative concepts that advocate an integrated approach to address complexity and uncertainty. Integrated Water Resources Management (IWRM) is the most prominent of such concepts that stresses the importance of integrated and participatory management processes and reform of water governance systems (Medema et al., 2008). The term “management” refers to operational activities including the operation, monitoring, strategic planning and implementation of measures, whereas the term ”governance” comprises the rules under which a management system operates and different actors and networks that help develop and implement water policies (cf., Pahl-Wostl 2009). However, theories and methods for sustainable water resources management and governance are still in the developmental phase and continuous experiments in application are required to determine effective approaches for research and practice (cf., Galaz, 2007; Medema et al., 2008). Methodologies are needed that deal with real world complexity in order to find effective solution strategies, and facilitate knowledge transfer between science, policy, engineering and local communities. Even though IWRM is a widely aspired concept, it is often still rooted in a traditional “predict and control paradigm” despite its linkage to the idea of adaptive management (cf., Jeffrey and Gearey, 2006). The need for the integration of adaptive approaches like policy experimentation and learning into IWRM is increasingly acknowledged in order to effectively realize the concept of IWRM (Galaz, 2007).

Management paradigms are appropriate concepts to systematically and comprehensively analyse the interlinkages between a resource system (e.g. groundwater resources), water management system (e.g. infrastructure) and water governance system (i.e. regulatory structures and processes). A specific analysis of the multiplicity of elements of water resource management paradigms has been discussed by Pahl-Wostl et al. (2011). They define a management paradigm as “a set of basic assumptions about the nature of the system to be managed, the goals of managing the system and the ways in which these goals can be achieved” (Pahl-Wostl et al., 2011). By being explicit about underlying paradigms, inconsistencies in water management and governance systems become apparent (as discussed by Jeffrey and Gearey (2006)). For instance, public participation can be applied in a “predict and control water management paradigm” (i.e. stakeholders are only informed and consulted), as well as in a “community involvement paradigm” (i.e. co-management of stakeholders). The ignorance of underlying paradigms can lead to miscommunication and subsequent management problems (e.g., stakeholders expect active involvement but can become frustrated due to missing opportunities for engagement).

This paper presents a methodology for the participatory analysis of management and governance systems that supports the design and implementation of transformation processes towards sustainable water management. In this methodology, participatory model building is applied to elicit case specific water management paradigms held by stakeholders. This information is then used to comprehensively analyse the management and governance system through the application of the Management and Transition Framework (MTF) developed by Pahl-Wostl et al. (2007; 2010). Based on such an analysis of the status-quo, the methodology allows for the participatory envisioning and design of pathways towards sustainable water management and governance. In this way, the proposed methodology facilitates the development, assessment and implementation of strategies towards sustainable water resources governance and management.

The methodology builds upon the management paradigm concept developed by Pahl-Wostl et al. (2011) and the use of group model building for the analysis of paradigms (cf., Sendzimir et al., 2007). Innovative elements of the methodology proposed in this paper are the conceptualization of sub-system and overall-system paradigms, and the delineation of a structured action research process including elicitation, analysis and assessment of paradigms. Another innovative element of the proposed methodology is the application of the MTF for the design of pathways towards implementation of integrated and adaptive water management. The approach presented in this paper goes beyond theoretical explanations of institutional and policy change (cf., Cashman, 2009) by allowing for participatory analysis and active governance of transformation processes.

This paper is structured in two parts. First, the underlying concepts and methods upon which the proposed methodology is built are presented. Following this, a case study on flood management in the Tisza River Basin in Hungary is provided to illustrate the application of the proposed methodology.

METHODS

The proposed methodology combines an analysis of the overall water management and governance system (using the MTF) with an investigation of embedded management paradigms using the systems thinking method in a participatory modelling process. Participatory modelling supports the analysis of case-specific elements of resource management and governance systems, while the MTF analysis allows for a broader perspective by integrating the detected elements found via participatory modelling into an overall system perspective.

Participatory Model Building

Different participatory modelling approaches exist that follow different objectives and apply a range of methods (cf., Jonsson et al., 2007; Renger et al., 2008; Voinov and Bousquet, 2010). In this paper, the method of participatory model building using systems thinking and system dynamics methods is proposed for analyzing the perceptions of stakeholders regarding the management and governance system. Systems thinking is a method for the qualitative analysis of systems and their dynamic behaviour through time. System dynamics modelling is based on this qualitative analysis and comprises the quantitative simulation of systems to discover their inherent dynamics as well as allowing for the testing of strategies.

Causal Loop Diagrams (CLDs) are powerful tools of the systems thinking method for the qualitative analysis of systems. They help to depict the system's structure, and mark time delays and feedback processes that are often responsible for difficulties in controlling the inherent dynamics of the management system. In these diagrams, elements of the system are connected by arrows having positive and negative polarities. A positive link indicates the parallel behaviour of variables: in the case of an increase in the 'cause' variable, the variable that is affected also increases, while a decrease in the 'cause' variable implies a decrease in the affected one. A negative link indicates an inverse linkage between variables (see Figure 1 as an example of a CLD).

Despite the fact that expert models often offer comprehensive and scientifically validated results, missing ownership and understanding of the model by decision-makers and other stakeholders often impedes the implementation of model based recommendations. This has led to the development of system dynamics applications which involve stakeholders in quantitative model building. Group model building processes (also called mediated modelling) for collaborative management of complex human-environment problem situations have begun to be applied more frequently over the course of the last decade (e.g., Costanza and Ruth, 1998; van den Belt, 2004; Tidwel et al., 2004; Metcalf et al. 2010; Halbe et al., accepted).

Management and Transition Framework (MTF)

Understanding processes of change towards sustainable resource management and governance requires an analytical approach that allows for the analysis of the interdependence between structural context and process characteristics. The Management and Transition Framework (MTF) developed by Pahl-Wostl et al. (2010) supports such analyses of water governance regimes and transition processes towards more adaptive and sustainable systems. The MTF builds upon the three conceptual pillars of adaptive management (cf., Holling 1978), social learning and transformation processes (cf., Pahl-Wostl et al., 2007), as well as the Institutional Analysis and Development Framework (which is aimed at the analysis of the role of institutions in collective choice processes, c.f., Ostrom, 2005) Specific emphasis is given to the analysis of adaptive capacity and multi-level learning processes. However, the MTF is not constrained to one specific theory; instead it provides a flexible language that can be tailored to specific research questions (for examples of applications of the MTF, see Schlüter et al., 2010; Sendzimir et al., 2010).

The MTF helps to formalise structural elements of a water system (which are denoted as "classes") as well as policy and learning processes (cf., Pahl-Wostl et al., 2010). Central classes in the MTF are as follows: An **'Action Situation'** refers to formal or informal social processes that lead to relevant outcomes for water management. Results can be '**Institutions**' (e.g., a new water legislation), '**Knowledge**' (e.g., increased understanding of stakeholder problem perspectives)or '**Operational Outcomes**' (i.e., direct physical interventions in the system such as the implementation of infrastructure or distribution of water to different uses). The **'Action Arena'** class sets the context for the management of a specific water related problem such as flood management, and is characterised by '**Strategic Management Goals**', '**Actors**' and a number of '**Action Situations**'. In this way, the MTF provides a common language to analyse and discuss complex management and governance systems in research and practice. Relational databases are used to support formalization and standardization of data collection and analysis protocols (cf., Knieper et al., 2010). A graphical interface allows for the straightforward presentation and discussion of analyses.[13]

A management process can be depicted as a temporal sequence of action situations which are linked by institutions, knowledge or operational outcomes (see example in Figure 3) and represent different phases in an overall policy cycle (e.g. policy formulation or implementation). Another approach to analyse a management and governance system is the interpretation of action situations as governance and management functions (e.g. water purification or allocation or conflict resolution). While temporal analysis is more suitable to examine the evolution of management issues over time, functional analysis allows for the comprehensive analysis of the status quo of management and governance systems at specific points in time.

RESULTS AND DISCUSSION

In this section, the proposed methodology is described in more detail and its application is illustrated with an example of flood management in the Tisza Basin, Hungary. The Tisza is a transboundary River and extends from the Ukrainian Carpathian mountains along the Romanian border, flows across the great Hungarian plain and enters the Danube in the Serbian Republic. It is the largest tributary of the Danube with a total catchment area of 157,200 km^2. In the Hungarian reach of the Tisza Basin, a centralized water management regime has existed since the 19^{th} century, with a focus on engineered flood protection through the large-scale construction of dikes in order to allow for intensive agriculture and to protect residential and industrial areas. Rising flood intensities and frequencies have resulted in significant challenges for the existing water management paradigm over the past decade. A bottom-up learning process was formed by activists and academics that brought innovative ideas into the flood policy debate. However, a transition towards alternative paradigms has stalled due to weak linkages between the informal learning process and the formal institutions (Sendzimir et al., 2010). To address issues such as this, the methodology proposed in this paper supports a structured action research process of water management and governance systems, comprising three steps: (1) Elicitation of management paradigms at the sub-system level; (2) Analysis of the status-quo in management and governance regimes; and (3) Design of pathways to overcome detected barriers towards sustainable water management.

Methodology

[13] URL: http://www.yworks.com/en/products_yed_about.html.

A management paradigm is defined by a specific “system perspective” regarding the management problem, chosen “solution strategies”, as well as “risk and uncertainty management strategies” (cf. Pahl-Wostl et al., 2011). The proposed methodology differentiates between paradigms linked to the sub-system level (e.g. the social, environmental, or technical system) and the overall system level (i.e. comprising the complete management and governance system). The former are called “sub-system paradigms” and the latter “overall-system paradigms”.

Management paradigms can co-exist at the sub-system level, either by being complementary (i.e. reinforcing each other) or competing (i.e. balancing each other). The proposed methodology builds on the notion that a concerted set of paradigms is usually needed, each tailored to the specific sub-system, to find effective and sustainable solutions. For instance, technical sub-systems (e.g. infrastructure) can be managed by a “control paradigm” that aims at controlling the behaviour of the sub-system (different paradigms are presented in detail below, cf. Table 1). Selected social issues (e.g. an allocation system) can be governed by a “community paradigm” that builds upon the self-organization capacity of stakeholders (e.g. installing irrigation associations). Several paradigms can also belong to the same sub-system by complementing each other. For instance, water pricing can be implemented by applying a “market paradigm” (i.e. prices are set by demand and supply) as well as a “control paradigm” (i.e. the range of prices is pre-determined). Alternative sub-system paradigms can also co-exist by being linked to different locations. For example, an “adapt to floods paradigm” can be applied in rural areas where retention areas are available, while a “control floods paradigm” might be more likely to be implemented in urban areas due to fewer adaptation options.

An encompassing “overall-system paradigm” is linked to the overall resource system and can emerge from the sub-system level (e.g. through the supersession of other sub-system paradigms), or can be purposefully implemented by a higher-level institution (e.g. a ministry for water). In the case of a “control paradigm” at the overall system level, heterogeneity of sub-system paradigms is constrained as only a limited number of paradigms are compatible with this overall-system paradigm. However, an “integrated and adaptive overall-system paradigm” (cf., Pahl-Wostl et al., 2011) allows for the coordination of various sub-system paradigms and increases the adaptive capacity of the overall management system.

The proposed methodology that allows for the elicitation of management paradigms at the sub-system level (Step 1) and overall system level (Step 2), as well as the visioning of pathways towards sustainable water management (Step 3) is presented in the following sections.

Step 1:”Elicitation of sub-system specific management paradigms”. Participatory model building using systems thinking can support the elicitation of sub-system specific management paradigms from individual participants or groups. The interviewee/group is asked to include the causes and consequences of the particular problem (i.e. the “system perspective”), as well as preferred “solution strategies” (e.g. technical approaches like building dams or socio-economic aspects like stakeholder involvement). The resulting CLDs will comprise elements of the resource system (e.g. variables like “precipitation” or “vegetation type”), the management system (e.g. “dams” or “retention areas”), and the governance system (e.g. “public participation” or “water legislation”). Further information about the “risk or uncertainty management” strategies is needed to derive management paradigms from CLDs. Uncertainties are commonly typified in ontological and epistemological uncertainties. While the former denotes complex phenomena whose behaviour cannot be predicted, the latter refers to incomplete knowledge or information about a system that can be attained through scientific research (Walker et al., 2003). Relational uncertainties are a third type of uncertainty and acknowledge subjective perceptions of actors. People perceive objects differently depending on personal values, roles, and interests (Brugnach et al., 2008). Based on this categorization, possible strategies for the handling of uncertainties and risks comprise (cf., Brugnach et al., 2008):

- Acceptance of uncertainty since *ontological uncertainties* imply that predictions cannot be made.
- Reduction of uncertainty since *epistemological uncertainties* can be minimised through purposeful research.
- Uncertainty dialogue since relational uncertainties requires a dialogue between stakeholders. For instance, the method of participatory model building facilitates the learning of groups and the revision of mental models and frames of participants. The goal of this reframing process is not to determine a “true” frame – rather, the process aims at widening individual frames to one that considers multiple values and interests of stakeholders.

Figure 1 shows a CLD that was developed via a group model building process in the Tisza River Basin (see Sendzimir et al., 2007). The CLD contains case-specific elements of the resource (e.g. soil quality), management (e.g. dikes), and governance system (e.g. lobbying capacity of community actors).

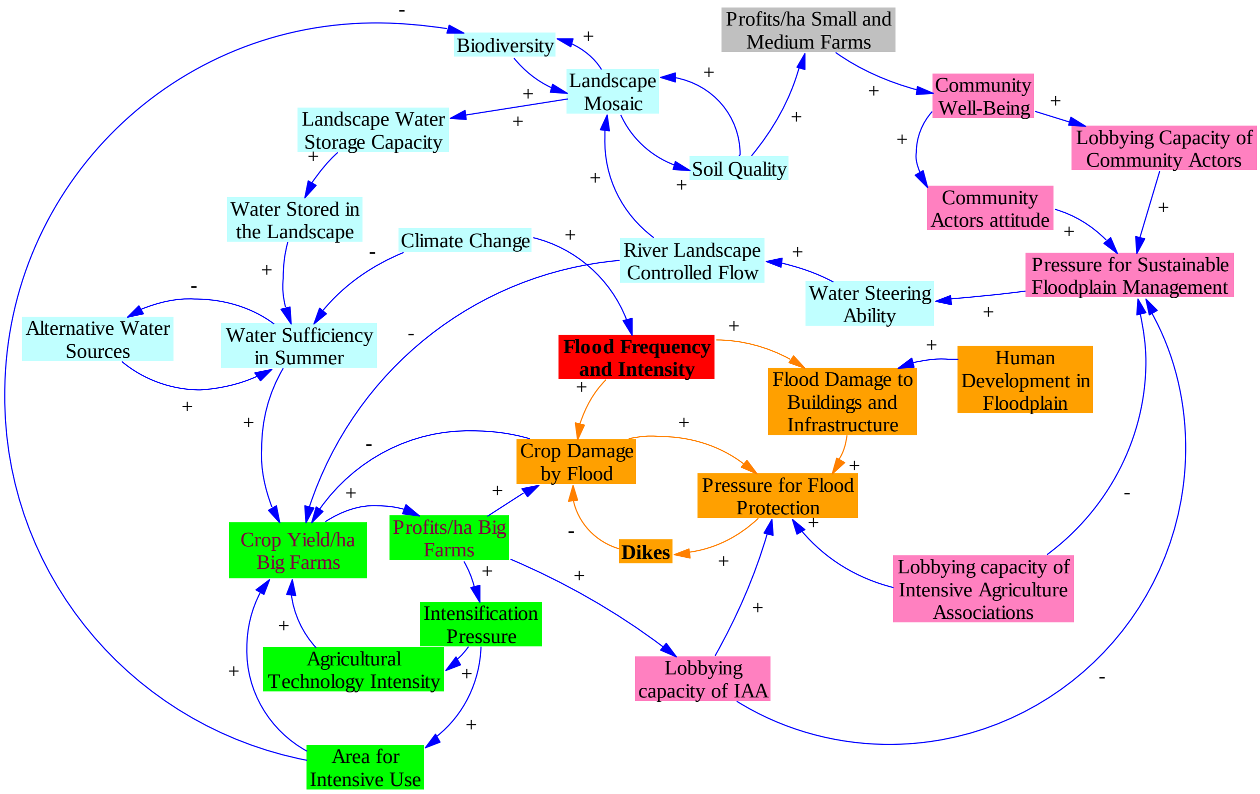

Figure 1: Causal Loop Diagram regarding the flooding problem in the Tisza River Basin (extended from Sendzimir et al. 2007). The colours reflect the sub-system paradigms: “Adapt to Floods” paradigm (blue); “Control Floods” paradigm (orange); “Economies of Scale” paradigm (green); “Tradition” paradigm (grey); “Community Involvement” paradigm (pink). The problem variable is highlighted in red.

The group model in Figure 1 integrates different aspects of the flooding problem in the Tisza Basin that were mentioned by stakeholders including government representatives, local activists, and scientists. The CLD shows two different paradigms that are directly related to the flooding problem (represented by the problem variable “Flood Frequency and Intensity”), namely the “Adapt to Floods” paradigm (related elements are marked in blue in Figure 1) and the “Control Floods” paradigm (marked in orange). For the specific attributes of paradigms, see Table 1. Further paradigms are indirectly related to flooding, including the “Economies of Scale” paradigm (marked in green) of the intensive agriculture sector, and the “Tradition” paradigm (marked in grey) that is more applicable to small farms. In addition, there are societal processes that demand more of a “Community Involvement” paradigm (marked in pink) that relies on dialogue between actors.

The group model presents the interplay of different paradigms held by stakeholders related to the flooding problem in the Hungarian reaches of the Tisza Basin. The model clarifies the specific system elements that are related to paradigms. Thus, the CLD can support a purposeful discussion and handling of management paradigms.

Table 1: Management paradigms elicited in Figure 1.

Name / Dimension	"Economies of Scale" Paradigm	"Control Floods" Paradigm	"Adapt to Floods" Paradigm	"Community Involvement" Paradigm	"Tradition" Paradigm
System Perspective	Big farms	River and protected values	Floodplain landscape	Flood prone communities	Small farms
Solution Strategies	Economics of scale; rationalization	Build dikes	River-Landscape controlled flows	Community involvement	Traditional farming methods
Risk and Uncertainty Management	Reduce flooding risk and uncertainties	Reduction of uncertainty	Accept flood risk; Adaptive Management (through experimentation)	Uncertainty dialogue	Build on the experience from the past

Step 2: "Analysis of management paradigms embedded in the overall management and governance system". Management paradigms can not only belong to the sub-system level but also to the overall system. Management paradigms of the overall system can be considered as a general 'mindset' that dominates in the management and governance system. Such overall-system paradigms are not only represented in the way of governing water resources, but are also manifested in infrastructure, information management, and finance, amongst others (cf., Pahl-Wostl et al., 2011).

Overall-system paradigms can influence paradigms at the sub-system level. For instance, a "Control" overall-system paradigm might only be compatible to the "Economies of Scale" sub-system paradigm due to a similar uncertainty and risk strategy (cf., Figure 1 and Table 1), but usually hampers the functioning of other paradigms at the sub-system level. However, an overall "Adaptive and Integrated" paradigm, as conceived by Pahl-Wostl et al. (2011), allows for the functioning of all paradigms at the sub-system level due to its integrative nature. This permits diversity in management approaches which increase the resilience of the social-ecological system (cf., Folke 2006).

Management paradigms pertain to both structural as well as process characteristics of management and governance systems. In the MTF, sub-system paradigms are considered as a type of cultural-cognitive institution and can therefore be an input or output of action situations (i.e., sub-system paradigms are social rules that can influence water management processes). Each action situation is characterized by at least one paradigm. The designation of paradigms to an action situation depends, first, on participating stakeholders who include their perspectives, and, second, on input factors (e.g. knowledge, institutions, operational outcomes).

Overall-system management paradigms have a more general influence on the water system and are therefore linked to the Action Arena. As mentioned above, an "Integrated and Adaptive" paradigm can function as such an overall-system paradigm. However, a "Predict and Control" paradigm might be the most prevalent current overall-system paradigm which hampers the application of most of the paradigms at the sub-system level (and thereby limits diversity).Figure 2 shows a graphical representation of the management and governance system in the Tisza Basin comprising action situations as management functions (boxes), institutions (circles), knowledge (trapezes), and operational outcomes (octagons).

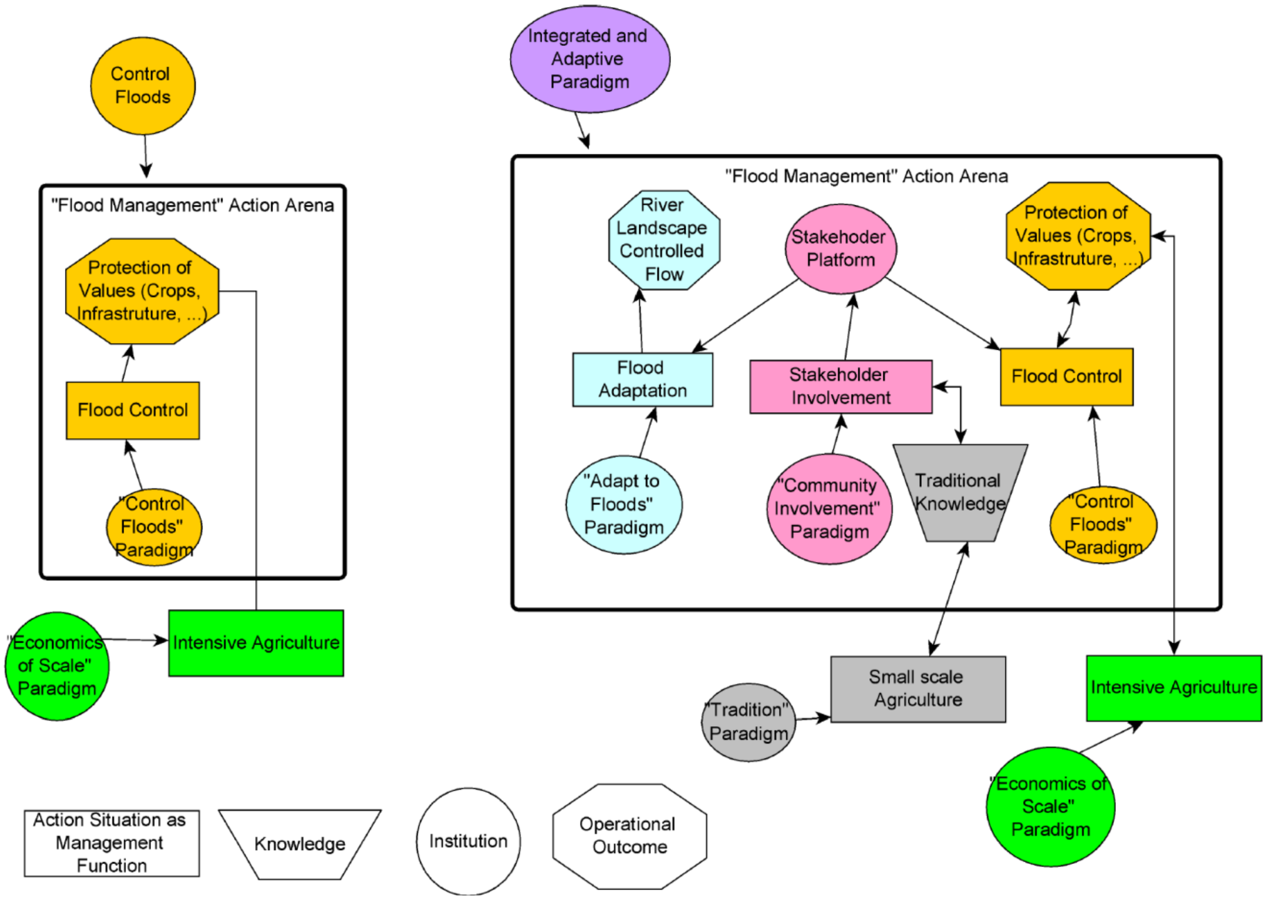

Figure 2: Functional analysis of the management and governance system (purple colored variables reflect the new "integrated and adaptive paradigm"; other colors refer to sub-system paradigms, cf. Figure 1).

On the left hand side of Figure 2, the "status quo" of the management and governance regime in the Hungarian Tisza Basin is depicted. It is characterized by the dominance of a "predict and control" paradigm at the overall-system and sub-system level that hampers solution strategies other than "flood protection". Intensive agriculture is tightly linked to this kind of management and governance system (Sendzimir et al., 2007). On the right hand side, a future vision of an alternative system is presented which is based on the combination of paradigms included in the group model (see Figure 1). In this future system, an "integrated and adaptive" flood management paradigm has emerged at the overall-system level, which allows for a diversity of paradigms at the sub-system level (cf., Grabs et al., 2006). A "stakeholder platform" coordinates the "Flood Control" and "Flood Adaptation" management functions. Small-scale and intensive agriculture are exogenous elements that are linked to this Action Arena.

Step 3: "Visioning of pathways towards sustainable water management". Based on the functional diagnosis of the status quo and the desired future of the management and governance system (cf., Step 2), necessary measures through time are defined in Step 3 to achieve the desired changes. The transformation towards sustainable water management and governance usually requires substantial investments of resources and reform of institutions. The MTF can be applied to explore these required changes in a holistic manner, and specify a temporal succession of action situations in order to achieve the desired future. The outcome from this task is the design of a concrete pathway towards a sustainable water management and governance system. The resulting pathways include requirements for institutional change, dissemination or production of knowledge, physical interventions (i.e. "operational outcomes"), as well as participation of actors.

Figure 3 shows an example pathway towards an integrated and adaptive flood management system for the Hungarian reaches of the Tisza River Basin that was developed based on literature review and expert opinion. The pathway starts from a present action situation comprising the reinterpretation of a flood management policy called VTT2[14] (cf., Sendzimir et al., 2010), which reflects the mindset of the dominating "Control Floods" paradigm. The transformation process ends with an "Integrated and Adaptive Flood Management" action situation that delivers the outcome of "integrated and adaptive flood-land-agriculture management" (see Figure 3). In the example pathway depicted in Figure 3, two action situations are envisioned to lead to the desired outcome. First, a round table is advised under participation of the Ministry of Environment and Water, responsible engineers and water managers, and representatives of the "Living Tisza Alliance" which is formed of local activists, national NGOs and the Village Municipalities Association (cf., Sendzimir et al., 2007). This round table sets the rules for a working group for a long-term flood strategy (institution) that includes all participating actors, and facilitates the institutionalization of a community of practice at the ministry level. The community of practice is supposed to link different departments and facilitate a continuous deliberative process on innovative solutions for the flood management problems in the Tisza Basin. In the past, this was temporarily achieved by the leadership of an individual at the ministry level, before his departure from the parliamentary committee stopped this process. A community of practice could lead to a more sustainable network that is less vulnerable to change of personnel. These activities together with experience from other EU-countries with innovative flood management could set the basis for the development of a new flood management policy (named VTT3) that could lead to the institutionalization of a stakeholder platform at the local and regional scales as well as more experimentation with alternative approaches (e.g. through pilot studies). The established institutions and the experimental approach would result in the "Integrated and Adaptive Flood Management" action situation that brings together the ministerial "community of practice" and the stakeholder platform. This leads to river-landscape controlled flows (operational outcome), which reflects a transformation of the

[14] In Hungarian: „Vásárhelyi TervTovábbfejlesztése“

overall management and governance system towards a more “integrated and adaptive” overall-system paradigm.

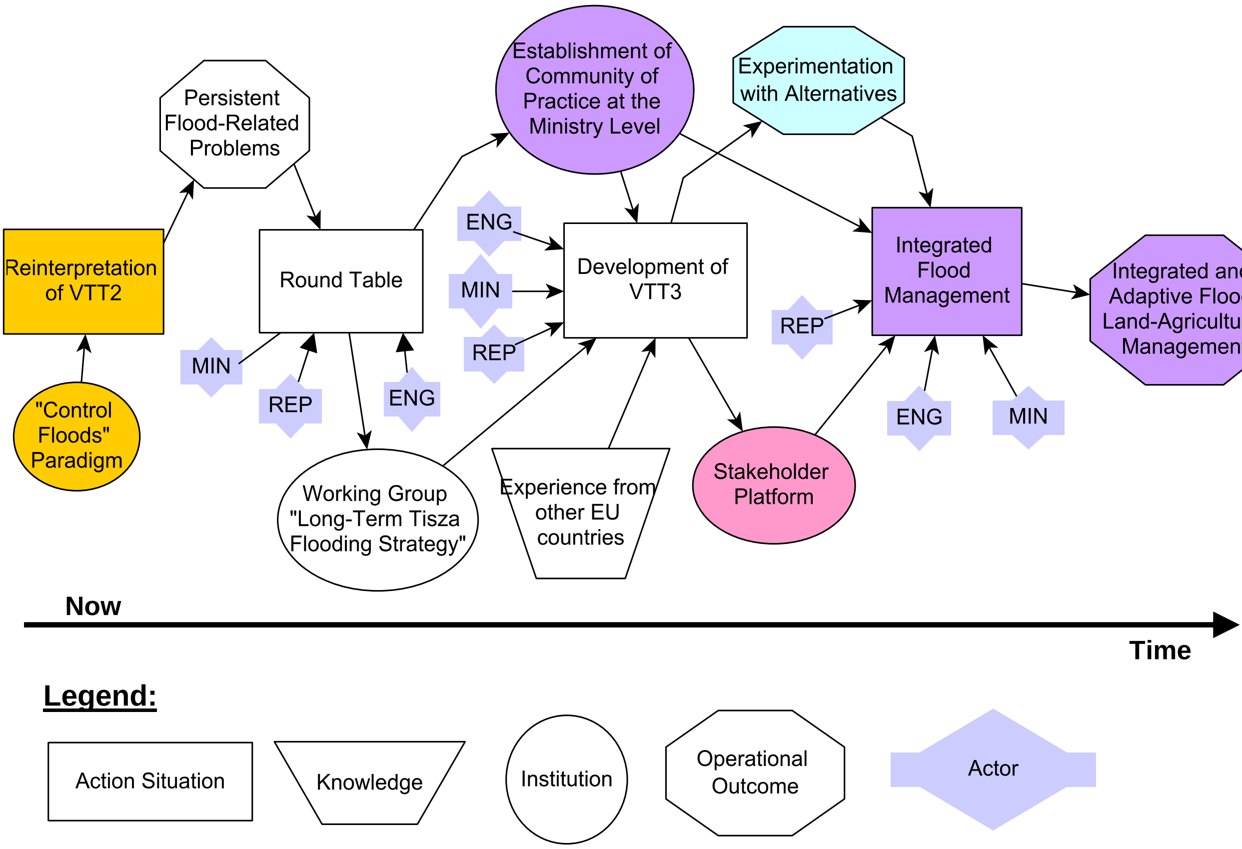

Figure 3: Example of a possible pathway towards a sustainable water management and governance system in the Tisza River Basin (purple colored variables reflect the new “integrated and adaptive paradigm”; other colors refer to the respective management paradigm, cf. Figure 1). Abbreviations of actors mean the following: REP:= representatives of “Living Tisza Alliance”; ENG:= Responsible Engineers and Water Managers; MIN:= Ministry of Environment and Water.

The example application of the proposed methodology demonstrates a structured approach to analyse water management and governance systems in an integrated way, and envision transformation processes towards IWRM. Through the use of the proposed methodology, hidden assumptions about the management and governance system, as well as requirements for integrated and adaptive solution strategies, are elicited. This approach can be particularly useful in transboundary river basins as paradigms might vary considerably between international water authorities due to different historical and cultural developments. While the Tisza case was confined to the Hungarian reach of the Tisza, a basin-wide study would be very useful to reveal differences in management paradigms in order to explore opportunities to deal with them constructively. The proposed methodology builds on straightforward methods and is therefore particularly suitable to be applied in collaborative management processes. At the same time, the proposed methodology composed of participatory modelling and the MTF allows for in-depth analysis of the water system. In this way, the linkage of the MTF and participatory modelling allows for the inclusion of scientific insights on water governance into management practice, and vice versa.

In future studies stemming from this research, empirical research will aim at determining concrete sets of management paradigms that facilitate IWRM. In particular, the relationships of overall-system and sub-system management paradigms require additional empirical research to identify which sets of sub-system paradigms are supported or inhibited by overall-system paradigms. In addition, the applicability of the proposed methodology to design concrete pathways towards IWRM will also be evaluated through further case-study research in other basins with different socio-economic and hydrological characteristics (especially transboundary basins).

CONCLUSIONS

The analysis of management and governance systems is a complex task. Methods and tools have to deal with this complexity in order to avoid resorting to simplistic solutions or panaceas. In addition, effective science-policy-engineering dialogues need to be initiated to transfer findings between research and policy-making, and facilitate implementation on the ground.

The methodology presented in this paper complies with these requirements by building on participatory model building and the Management and Transition Framework (MTF). Participatory model building is a suitable and widely tested method to structure complex problems and elicit different perspectives held by stakeholders. Participatory model building supports the analysis of objective and subjective dimensions of resource issues. The MTF allows for the integration of elicited knowledge into an overall system perspective, and supports subsequent discussions of pathways towards sustainable management and governance systems. The MTF provides a formalization of complex management and governance systems and a “common language” that can be used in participatory processes.

Management paradigms are proposed in this paper as suitable concepts to analyse the inter-linkages between resource, management and governance systems in a comprehensive way. The consideration of sub-system specific management paradigms acknowledges that the effectiveness of paradigms depends on the respective application area or sub-system. However, an overall-system paradigm usually emerges that reflects the common mindset for the overall system. Such an overall-system paradigm can support a variety of management paradigms at the sub-system level (e.g., an adaptive and integrated management paradigm), or hamper variety by being incompatible with other paradigms (e.g., a predict and control paradigm).

A case study in the Tisza River Basin, Hungary, demonstrated the application of the proposed methodology. Further empirical research will be conducted in the future to evaluate the applicability and effectiveness of the proposed methodology in different water management contexts. In addition, concrete sets of management paradigms will be examined that support integrated and adaptive water resources management.

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Article 4

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Multi-level analysis and design of case-specific transition governance processes

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ABTRACT: Sustainability transitions require broad societal engagement ranging from individual behavioral change, to community projects, businesses that offer sustainable products as well as policy-makers that set suitable incentive structures. Concepts, methods and tools are currently lacking that help to explore such diverse interactions of actors, as well as help to find strategies to actively facilitate sustainability transitions. This article presents a methodology for the analysis and design of transition governance processes that specify case-specific actions for the pro-active facilitation of sustainability transitions. The methodology focuses on the implementation of sustainability innovations which requires learning processes at multiple societal levels (i.e., ranging from the individual, to the group, organization and state levels). Case-specific learning factors for implementing sustainability innovations are identified in a participatory process. These stakeholder-based learning factors are compared to factors derived from a general literature review. A case study on sustainable food systems in Ontario is provided to exemplify the methodology. The results demonstrate the merit of combining stakeholder-based and literature-based factors to analyze and design a transition governance process that builds upon local and scientific knowledge.

INTRODUCTION

Broad societal transformation processes towards sustainable development require actions at different societal levels ranging from the individual, to the group, organizational and policy levels (cf. Adomßent, 2013). The pro-active steering of societal transformations is challenged by high complexity, ambiguity and distributed control (Voss and Kemp, 2006). Governance approaches have to deal with a fading distinction between subject and object of steering (Mayntz 2004). These challenges impede a pro-active initiation and design of transition governance processes. Loorbach (2007) propose the application of integrated systems and stakeholder analysis in an 'expert preparation phase'with the intention of providing a factual basis of the issue and selection of 10-15 stakeholders. Supplemental to such analytical approaches for initiating a transition management process, we propose the prior application of participatory methods that provide an overview of current challenges, as well as existing initiatives and innovations. Methodologies are currently lacking that examine the plurality of intervention points, implementation barriers as well as roles of multiple actors for facilitating a sustainability transitions.

The methodology presented in this article aims at the analysis and design of transition governance processes by specifying the various opportunities to contribute to sustainable development at multiple societal levels through purposeful action of multiple actors. The methodology focuses on practical sustainability innovations, which are understood as innovative approaches for the provision of societal functions (e.g., for water, energy and food supply). Sustainability innovations are often residing at a niche level today, but might be a promising element of a sustainable supply system in the future (Halbe et al., 2015). The term 'innovation' draws on Rogers's (1995, p.11) definition as an "idea, practice, or object that is perceived as new by an individual or other unit of adoption". Thus, sustainability innovations must not necessarily be novel, but can also include traditional practices that are re-discovered to contribute to the solution of sustainability issues. The methodology considers processes of societal change as learning processes that take place at different societal levels, each forming a distinct learning context. Supportive factors of learning are understood as practical leverage points for the implementation of sustainability innovations, which can take the form of knowledge (e.g., skills), institutions (e.g., a piece of legislation) or operational aspects (e.g., infrastructure). The methodology combines a structured, expert approach to examine general learning factors based upon a systematic literature review, and participatory modelling to examine case-specific learning factors.

The article is structured as follows. First, the proposed methodology is presented comprising a systematic review of general learning factors, a participatory approach for stakeholder-based factor identification, and a method to translate these findings into a case-specific design of a transition governance process. A case study on sustainable food systems in Ontario, Canada, is provided to exemplify the application of the methodology.

METHODOLOGY FOR THE ANALYSIS AND DESIGN OF TRANSITION GOVERNANCE PROCESSES

In the following, a methodology is presented that combines different streams of previous research: 1) a framework-based synthesis approach that combined the development of a conceptual framework about individual, group, organizational and policy learning in sustainability transitions with a systematic literature review of supportive and impeding factors of learning (Halbe et al., submitted); 2) A participatory modeling approach to identify case-specific sustainability innovations as well as related implementation barriers, drivers, and actor roles (cf., Halbe et al., 2015); and 3) a governance system analysis approach to operationalize these findings in the design of case-specific transition governance processes (cf. Halbe et al., 2013).

Systematic literature review to derive general learning factors

Participatory research processes can reveal case-specific problem and solution perspectives that base upon local knowledge. However, stakeholder processes might disregard important aspects of sustainability due to a selective perception. Thus, expert-led approaches are still necessary to provide scientific rigor and a factual base to stakeholder processes (cf. Reed et al., 2006). A systematic literature review has been conducted in prior research to provide a systematic analysis of learning processes in sustainability transitions based upon available conceptual and empirical studies (Halbe et al., submitted).

The conceptual framework presented in Halbe et al. (submitted) comprises the various dimensions and aspects of learning processes in sustainability transitions. The framework differentiates between learning intensities, learning objects (what changes?), processes (how?), subjects (who learns?), and contexts. The learning intensity addresses the depth of learning ranging from routine learning to reframing and paradigm change. Learning intensities are related to specific learning objects. For instance, an iterative improvement of *conventional strategies* pertains to routine learning, while changing *fundamental values* and *beliefs* are related to a paradigm change. Concepts on the process of learning describe different mechanisms, by which learning objects are altered. Thus, learning processes can involve direct interactions with a particular issue or object (e.g., experience of an environmental problem, or experimentation with innovative solutions) as well as social interactions (e.g., a collaborative process). Different social units can be the subjects of learning, ranging from individuals to groups, organizations and policy actors. Social units are related to particular learning contexts, comprising the individual, group, organizational and policy learning contexts. Learning contexts are defined by an agency perspective, i.e., whether an individual, a group, an organization or a policy actors are becoming active to address a sustainability issue (cf. Halbe et al., submitted).

The systematic review resulted in a list of supportive and impeding factors of learning that were sorted according to individual, group, organizational and policy learning contexts (see the factor list from Halbe et al. (submitted) in Appendix 2). All factors were assessed regarding their susceptibility to change in a specific learning context ranging from endogenous (i.e., factors can be addressed in a learning context) to exogenous (i.e., factors cannot addressed but depend upon exogenous forces). In particular, endogenous factors are key leverage points to actively facilitate learning in a self-reliant way. Exogenous factors however point to exogenous events (e.g., an environmental disaster or an economic crisis) or interdependencies between learning contexts. As an example of the latter, a community garden project (related to a group learning context) can be supported by policy actors who provide public land (related to a policy learning context). The identification of learning factors and their susceptibility to change allows for the design of transition governance processes that consider opportunities for self-reliant action as well as inter-dependencies between stakeholders at multiple societal levels (cf. Section 2.3).

Participatory model building to identify case-specific learning factors

The participatory development of conceptual models supports a structured and in-depth analysis of stakeholder perceptions on complex sustainability issues (e.g., Inam et al., 2015). In the following, a participatory modelling approach is presented basing upon previous research (cf., Halbe et al., 2013; Halbe et al., 2015). The participatory modelling approach includes three steps: 1) General problem and stakeholder analysis; 2) Participatory modeling with experts and innovators; and 3) Case-specific analysis and assessment of learning factors. Further participation methods, such as stakeholder interviews and surveys, can complement the participatory modelling approach to interrogate stakeholders' visions as well as perceived implementation barriers, drivers and roles.

The first step includes the gathering of data and information about the transition topic at hand. Societal transitions are complex phenomena, due to multi-domain and multi-level interactions as well as path-dependent and self-reinforcing processes (Holtz 2011). Thus, analytical frameworks are needed to guide the analysis of transition processes. The multi-level perspective (MLP) (Geels 2002, 2011) is such an analytical framework that can guide data collection and gathering of relevant information (cf. Auvinen et al., 2015). Various transition scholars have applied the MLP to analyze elements of past transition processes including case-specific niches (e.g., sustainability innovations), regime elements, and landscape signals (e.g., Geels, 2005; Broto et al., 2014). After the analysis of landscape, regime and niche elements, a preliminary list of relevant stakeholders is needed to prepare the participatory modeling process. Two types of stakeholders can be distinguished which are experts (who can provide an overview on perceived problems and solution perspectives) and innovators (who can offer more in-depth information of innovations and their barriers and drivers) (Halbe et al., 2015). In the end the problem and stakeholder analysis should be considered as a preliminary analysis, which needs to be adapted throughout the process based upon new experiences and input from stakeholders (cf., Nevens et al., 2013).

In the second step, stakeholders (i.e., experts and innovators) who have been identified in the first research step are asked for an interview. The methodology of building causal loop diagrams (CLDs) with innovators and experts is described in detail by Halbe et al. (2015). Experts interviews start with the definition of problems with regard to the transition topic (e.g., landscape pressures or regime internal issues). Second, causes of the problems are identified. Third, the consequences of the problem(s) are studied, and the interviewee is encouraged to find feedback loops (Vennix, 1996). Fourth, potential solution strategies and innovations are included to address the problems. Finally, the barriers of potential solutions and innovations are added (cf. Inam et al., 2015). In summary, the presented approach encourages the structured construction of a holistic system structure that includes a representation of the participants' mental models of the status quo as well as their preferred strategies and challenges related to the problem being explored. In addition, the naming of potential innovations can guide the selection of innovators for subsequent interviews. Innovator interviews start with the definition of their vision of a sustainable food, energy or water system (depending on the topic of the study), which usually includes practical sustainability innovations (such as organic farming, or renewable energy). Second, innovators examine aspects that influence their particular innovations or general vision. These can be constraining or supportive factors (e.g., aspects that motivated them to implement the innovation). Third, the consequences of the innovation are added (e.g., desirable effects on the environment), and potential feedback processes are included. Fourth, the interviewee is asked to think about further barriers to the implementation of the innovation, as well as solution strategies. Finally, the interviewee is asked to name stakeholders who have a role in the implementation of solution strategies (cf. Halbe et al., 2015).

In the third step, interview results (i.e. CLDs) are analyzed to identify learning objects, learning contexts and supportive/impeding factors. First, sustainability issues (i.e., problem variables) are identified in each diagram, which represent the learning objects. Second, the learning context is determined by examining the social unit related to learning objects (i.e., individuals, groups, organizations or policy actors). For instance, lack of consumer knowledge is related to an individual learning context, as the learning object (i.e., consumer knowledge) pertains to the individual. Third, supportive factors of learning are identified, which are specific interventions that aim at overcoming learning objects. These case-specific learning factors have been added to the CLDs by asking interviewees for solution strategies to address the identified problems. Fourth, impeding factors are identified, which are the barriers of proposed solution strategies.

Governance system analysis for the design of case-specific transition governance processes

Lower tier analytical frameworks are needed (in comparison to the MLP) that help to depict key elements of transition governance processes, including specific actions, actor roles and expected outcomes (Halbe and Ruutu, 2015; Halbe et al., submitted). A useful tool is the Management and Transition Framework (MTF), which is a conceptual and methodological framework that allows for the analysis of properties and dynamics of complex resource governance systems (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 (see Ostrom, 2005). The framework consists of a static and process-related representation of governance systems. The static representation provides an ontology of the governance system by defining important elements, including the societal system, ecological system, and technical infrastructure. The process-related representation allows for the analysis of governance processes by reconstructing the sequence of interaction processes (called 'action situations') that are linked by institutions, knowledge and operational 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 governance processes through ex-post analysis (e.g., Sendzimir et al., 2010; Schlüter et al., 2010; Knueppe and Pahl-Wostl, 2011). However, the same framework can also 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 in prior research (Halbe et al., 2013).

In the proposed methodology, the MTF is used for the representation of multi-level learning processes as interlinked action situations. These action situations address detected issues (i.e., learning objects) and are embedded in a particular learning context. Learning factors are represented as linkages between action situations, and are marked as institutions, knowledge and operational outcomes. Thus, sustainability transitions are visualized as interlinked learning processes within and across learning contexts. For instance, a learning process within a group context (e.g., a community project) can result in an operational outcome (e.g., a community garden), which can function as a supportive factor of learning in an individual learning context (e.g., an individual who gains knowledge about food processes by participating in the community garden).

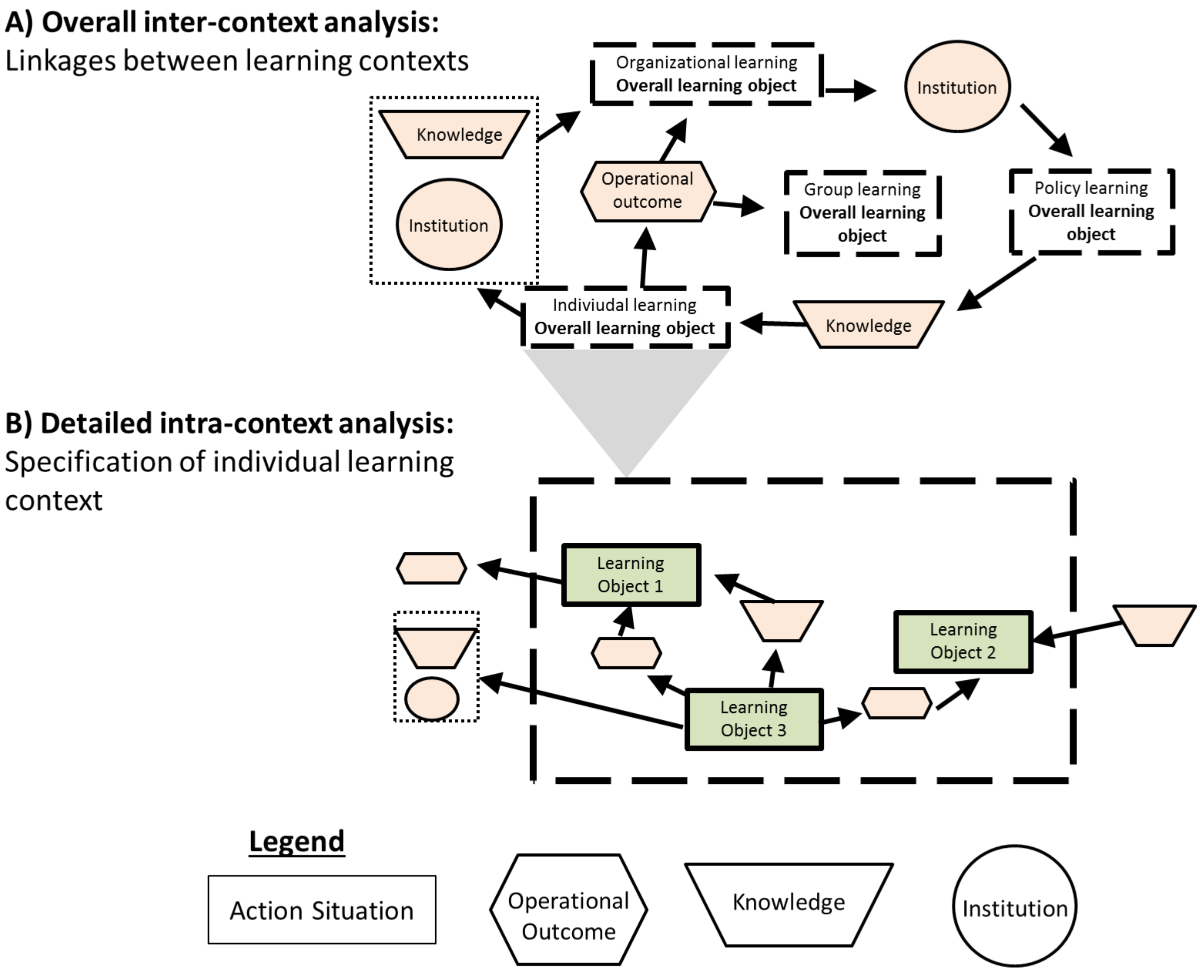

Fig. 1. Graphical representation of the methodology for analyzing governance systems from an overall system perspective (Figure 1a) and a context-internal perspective (Figure 1b).

The governance system analysis is conducted at two different abstraction levels (see Figure 1): an (1) overall inter-context analysis addresses interactions between learning contexts, and (2) a detailed intra-context analysis focused on interaction processes within learning contexts. In the overall inter-context analysis, a small number of high-level action situations are defined that subsume similar context-internal learning objects. For instance, a high-level action situation might be the development of consumer awareness for sustainable consumption, which subsume a number of learning objects, such as values, knowledge or behavior. In Figure 1a, a high-level action situation is defined for each of the individual, group, organizational and policy learning contexts. In the detailed intra-context analysis, a context-internal analysis is conducted for each high-level action situations, comprising the design of more detailed action situations (i.e., interaction processes) (see Figure 1b). Following the above example, the intra-context analysis of the individual learning context would include detailed and interlinked action situations that address consumer values, knowledge and behavior.

In the following section, we present a case-study on sustainable food systems in Southwestern Ontario in which the presented methodology is applied.

RESULTS OF A CASE STUDY ON SUSTAINABLE FOOD SYSTEMS IN ONTARIO

The proposed methodology was applied in a case study on sustainable food systems in Southwestern Ontario, Canada, comprising Bruce, Grey, Huron, Wellington and Middlesex counties, along with the area around the city of Guelph. A transition governance approach is particularly suitable for sustainable food systems, as multiple actors have to cooperate along the value chain.

Problem and stakeholder analysis

Canada is in the top ten of food exporting countries (rank 9 with a $ 21.7 billion total agriculture exports in 2012, cf. FAO, 2015) and thus a key player in the global food system. Agriculture in Ontario is an important sector which is reflected in the province’s lead in the number of farms in Canada (Statistics Canada, 2011). Visions of a sustainable food system were collected through a literature review, as well as a survey and the organization of a visioning exercise at an organic food conference in Guelph. Participants at the conference were asked to explain their personal vision of a sustainable food system. In addition, 27 stakeholder interviews were organized. The interviews and surveys (55 surveys were completed) revealed the existence of multiple alternative visions regarding a sustainable food system: some participants envisioned a large-scale organic food production system while others stressed the importance of a localized food system including small-scale organic agriculture and urban farming (see Halbe et al., 2014). Thus, farming for self-supply, e.g. in the form of community gardens (cf., Wakefield et al., 2007), could become a significant approach to develop farming skills as well as consciousness of food production. The visions were grouped in three alternative system designs for food production, namely “large-scale, organic agriculture”, “small scale, diversified, organic agriculture”, and “organic subsistence agriculture in urban and rural areas” (Halbe et al., 2014).

The agriculture regime in Ontario is mainly related to the large-scale, conventional type of farming. Small farms (less than 10 acres / ~4 hectares) account for only 5% of the total number of farms in Ontario. Certified and non-certified organic farming remains at a niche level, representing roughly 1% and 5% of farms, respectively (Statistics Canada, 2006). Data on the relevance of farming for self-supply (e.g., community gardening) is currently unavailable, as official statistics focus on commercial forms of agriculture. There are several current challenges (e.g., a changing climate), as well as likely challenges in the future (e.g., depleting resources for fossil fuel and phosphate) that could pose significant landscape challenges to the food system.

The initial stakeholder analysis was based on a desk study and a survey at the organic food conference in Guelph. Survey results pointed to several innovators in the field of sustainable food systems, including community gardening initiatives, actors that foster the development of more regional food systems (e.g., owners of local food stores, and small scale, diversified farmers), or governmental initiatives that support newcomers to farming (e.g., FarmStart).

Our desk research complemented the list of stakeholders by adding interest groups at the provincial and national level (e.g., National Farmers Union; Canadian Organic Growers; Canadian Organic Food Association) and governmental agencies (e.g., Ministry of Agriculture, Food and Rural Affairs; Agriculture and Agri-Food Canada).

Participatory modelling on sustainable food systems

In September 2012, a participatory modelling process was initiated by the first author of this article that included individual interviews with farmers, distributors, and other stakeholders. Over the course of 1.5 years (until March 2014), 27 stakeholder interviews have been conducted. These interviews aimed at the analysis of alternative approaches for a sustainable food system (i.e., sustainability innovations), and their implementation barriers and drivers (cf., section 2.2). CLDs have been built in 21 interviews, while six interviews proceeded in a more informal way without the construction of a CLD. Each CLD was analyzed with respect to learning objects and supportive factors of learning. Figure 1 shows an example of a CLD that was constructed by an innovator in the Ontario case.

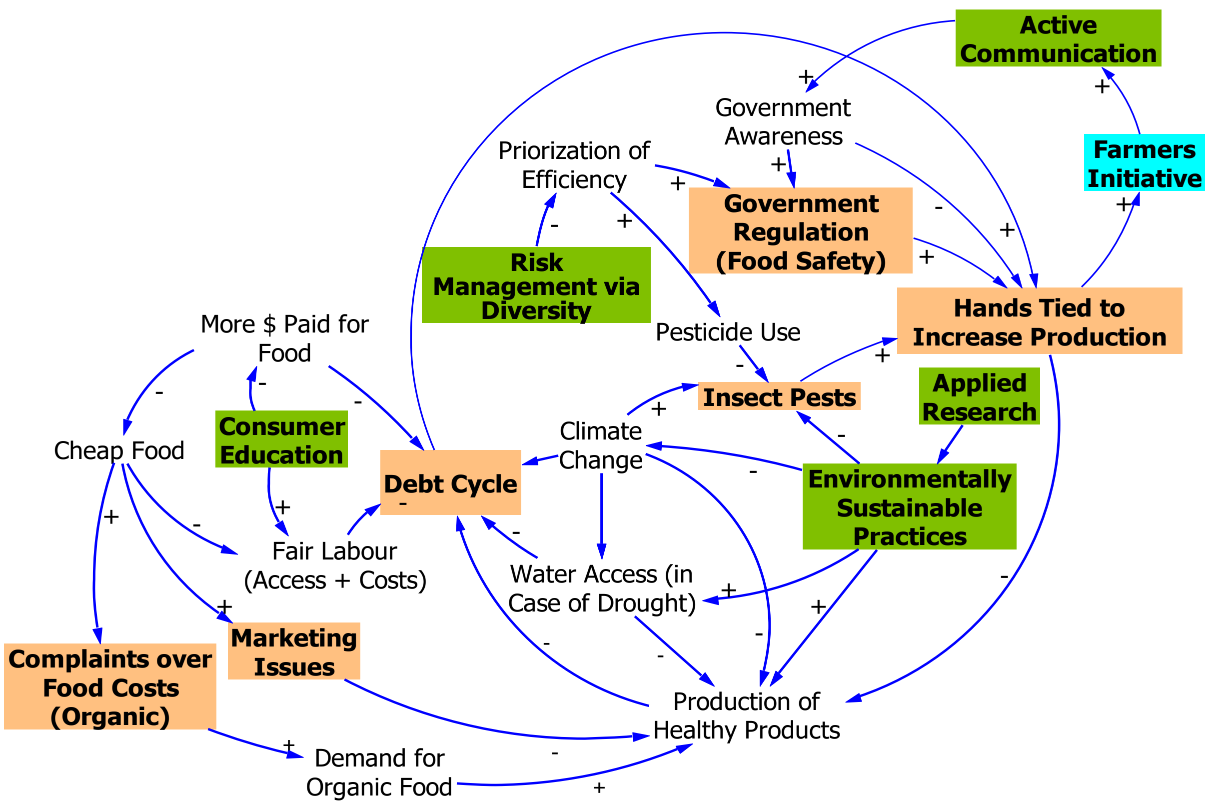

Fig. 2. Causal loop diagram prepared in an individual interview with a small-scale, diversified organic farmer. Problem variables (i.e., learning objects) are marked in orange; drivers of innovations (i.e., supportive factors of learning) are marked in green; potential barriers to innovations are marked in blue.

Figure 2 shows the system perspective of the interviewee, including perceived problems (orange), drivers (green) and barriers (blue) of small-scale, diversified organic farming. The interviewee distributed his produces in a self-reliant way, i.e., customers were either able to pick-up their ordered products on the farm site, or buy it at local farmers markets. The farmer identified several issues with regard to his farming approach, which need to be addressed in the future. First, the demand for organic produce is relatively low, as many potential customers are used to cheap food (i.e., they *complain over higher costs of organic products)*. In addition, there are *marketing issues* as the farmer has to justify a higher price by convincing customers about a superior quality of his products and the sustainability of the production process (i.e., the consumer has to trust the farmer, due to the absence of official certificates). *Insect pests* and tight *governmental regulations* are further factors that *tie the hands of farmers to increase production*. Due to a limited production, the danger increases of getting caught in a *debt cycle*. Several solutions were identified to address these issues. First, the farmer proposed the *education of consumers* (in particular in their early ages) to increase the consciousness of customers about the quality of food and the production process. In addition, *applied research* needs to be accomplished to find innovative *environmentally sustainable practices* to deal with insect pests and droughts. The concept of "*risk management via diversity*" needs to be propagated to suppress the economies of scale paradigm that runs the current regime. This can be achieved through *active communication* with the government to induce supportive regulations for the small-scale, diversified organic food sector. Lacking *farmer initiative* is however found to be a potential impeding factor of active communication.

The CLD in Figure 2 shows the interconnections between prevalent sustainability issues (learning objects), solutions (supportive learning factors) and barriers (impeding learning factors). Learning objects in the CLD of Figure 2 mainly relate to a higher learning intensity, such as paradigms (economies of scale), values (customers' prioritization of cheap food) and missing experiences and knowledge (customers' consciousness about food quality). But also learning objects related to routine learning and reframing are included in the CLD, such as the improvement of agricultural practices. Supportive factors for learning, as perceived by the interviewee, are partly related to education and research institutions (i.e., schools, or universities). Further learning factors require action by the farmer community and farmer associations (e.g., communication with the government).

Case-specific analysis of learning factors

All learning objects, supportive factors and roles that have been derived from the analysis of CLDs and surveys in the Ontario case study are listed in Appendix 1. A crisis of conventional food systems is considered to be a supportive learning factor with regard to most learning objects, as a crisis let people rethink the current regime and actively look for alternatives. However, other learning factors can be related to specific learning objects, as presented below.[15]

The *individual learning context* particular deals with improving the consumer awareness for local and organic food. Contemporary consumer preferences and values (learning object #1) focusing on the price of products (i.e., food has to be cheap) and its outer appearance (products have to look perfect) have been determined to constrain the development of a sustainable food system. Interviewees found that consumers need to acknowledge the benefits of a regional and organic food system in order to develop the willingness for paying higher prices. Various factors have been proposed to address this issue, such as rising public attention through the media, clear labelling of food (e.g., local food labels), as well as actions that support people to regain connectedness to nature and place. Interviewees complained about a general lack of knowledge with respect to food and agriculture (learning object #2) that can be addressed through consumer education, active communication of alternative farming approaches and healthy nutrition, as well as translation of research findings into a generally understandable wording. Another related issue is the resistance of people to take action (e.g., getting informed; develop new habits) (learning object #3). Stakeholders proposed to develop a clear vision of a desirable future as well as leadership of public organizations (e.g., by offering local food in cafeterias).

The *group learning context* contains the issue of lacking cooperation within the farmers' community, due to a more individualistic lifestyle of farmers (learning object #4). Cooperation can gain momentum through actions that offer visible results and tangible benefits for farming. A farmer community research center or an alliance to educate the public have been mentioned as a potential starting points to initiate and coordinate joint actions within the farmer community. In addition, programs that connect young farmers are seen as critical intervention points. A number of specific options for cooperation have been proposed, such as exchange networks for seeds (cf. learning object #5), knowledge, equipment (cf. learning object #6) and fertilizers (cf. learning object #7) Lack of skilled labor (learning object #8) can be tackled through a marketing and information platform (e.g., online) to help people to find ways to contribute to a local food system, which can be implemented in a group effort. The aforementioned activities are sorted to the group learning context, as a local food system bases upon a more personal exchange between farmers (organizational actors) and other stakeholders (e.g., consumers).

Most of the objects of learning take place in the context of a farm, and thus, were sorted to the *organizational learning context*. First, starting a new farming business in the organic/local food sector is challenging due high costs and initially low revenues (learning object #9). Stakeholders suggest special programs or subsidies for diversified, organic farmers to bear the costs of buying a farm or transitioning to organic. Another issue addresses the need to increase the customer base despite higher prices compared to conventional products (learning object #10). This can be achieved by producing high-quality premium products for customers

[15] We only present some examples of learning factors; a comprehensive description of learning factors is provided in Appendix 1.

who accept higher prices. Active consumer education (e.g., by information campaigns) is another complementary solution to inform customers about the production process and particular quality of products. Planting of perennial crops was suggested to lower work and equipment requirements on farm (learning object #11). On-farm fertility management (learning object #12) can be addressed by integrating livestock or increase crop rotation. The lacking food distribution infrastructure (learning object #13) is a major problem of local food systems. Stakeholders propose the application and improvement of practical marketing models that provide access to local food, such as community supported agriculture (CSA), super fresh markets, farmers markets, or wholesalers that offer local food. There is also a lack of regional storage and processing facilities (e.g., abattoirs) (learning object #14), which require the strengthening of local food production as well as specific regulations that are adapted to smaller facilities. Interviewees pointed to limited financing opportunities (learning object #15), which require more opportunities for grants and microloans tailored to small-scale farming.

In the *policy learning context*, current land planning policies are mentioned as an issue, as they reduce the availability of affordable land (learning object #16), due to proliferation of residential areas and land speculation. Some stakeholders demanded the rezoning of urban/suburban lands for small-scale production (e.g., designating a "small farm enterprise zone"). Another important issue was mentioned to be the contemporary power of the conventional agriculture regime which is reflected in legislation, standards, infrastructure and funding opportunities (learning object #17). Lobbying organizations can contribute toward the broadening of this focus by pointing to the importance and (synergetic) benefits of local/organic food systems. This can result in the development of specific regulations for small scale farmers (e.g., with respect to safety management or quotas), as well as subsidies for local/organic agriculture and products. As a consequence of the contemporary regime power, stakeholders demand more research on local food systems (research funding is currently more focussing on conventional agriculture) (learning object #18). A further key issue was mentioned to be the integration of knowledge and management levels to find best practices for specific locations (learning object #19). University research on local/organic food systems (e.g., on soil fertility, distribution systems or water use) can play a key role in solving this issue. In addition, integrated assessments of sustainable agriculture and food systems, which also consider the possible synergies between local and international food systems, is proposed by stakeholders. This is impeded by a lack of dialogue between regime (conventional agriculture) and niche actors (e.g., organic, local agriculture) (learning object #20), which could be addressed through integrated research as well as identification of best practices between countries (i.e. best practices that demonstrate the benefits of integrated food systems).

The following section describes the analysis and design of a transition governance process in the Ontario case study.

Analysis and design of a transition governance process

The comparison of case-specific learning factors (cf. Appendix 1) and general factors from the literature review (cf. Appendix 2 and Halbe et al, submitted) reveals several compliances as well as potential gaps in the list of stakeholder-based factors. In the following section, factor identifiers are provided, which can be related to literature-based learning factors in Appendix 2.

Comparative analysis of general and case-specific learning factors

Most of the case-specific factors can also be found in the literature-based factors (cf. Appendix 2). For instance, case-specific and literature-based factors comply that a drastic crisis in society (I-1, G-1, O-1, P-1) is a key factor to weaken the current regime and support the development of alternatives. Given the tendency of destabilizing landscape pressures to rise (e.g., climate change, depletion of fossil fuels and phosphate), pressure on the political system might increase in the future as well as the willingness of regime actors to consider alternative approaches. Physical resources (I-9; G-9; O-15; P-15), information and knowledge (I-10; G-10; O-16; P-16) are also found to be relevant in all learning contexts. From the 50 case–specific factors, only 9 factors are not contained in the general, literature-based factor list. These factors are specific for the study topic, such as community supported agriculture as a specific financing and distribution approach. This underlines the value of participatory research, as general, top-down analyses might have overlooked these case- and topic-specific factors.

With respect to the *individual learning context*, environmental values (I-2) are considered as important in the development of a local food system according to case study and review results, as people has to regain connectedness to nature and place. Further compliant factors are a clear vision of the future (I-4) and inspirations by others (I-6), for instance through role models that lead by example or TV shows about local food. Interactive concepts are another supportive factor (I-8.1), which can be achieved by using the internet. Public organizations can furthermore support individual learning (I-9.3), for instance by actively promoting local food in their cafeterias. Finally, knowledge exchange is another compliant factor in case study and review results (I-10.2), which might be achieved by citizens who actively communicating about healthy nutrition in everyday lives (i.e. ‘spread the word’) or parents and teachers who educate children. However, the list of factors from the literature review point to gaps further important aspects that can influence individual learning objects. First, educational efforts (e.g., from schools or citizen groups) should use simple and honest messages without a bargaining mentality attached (I-8.1), and require a continuous observation, evaluation, and reflection of the process and its outcomes (I-7.2). Second, campaigns should highlight relative advantages as well as compatibility to current consumer practices in order to reach a broader customer base (I-3).

In the *group learning context*, consistent stakeholder and literature-based factors underline the relevance of tangible community actions (G-3.1) (e.g., exchange of seeds) that address and urgent problem (G-3.4) (e.g., lack of locally-adapted plants). Some activities also require active networking with group-external actors (G-6.4), such as a seed saving network or marketing activities to attract skilled workers. A positive reputation requires the development of a clear and inspiring future vision (G-7.8). Further case study results point to the relevance of measures for exchanging physical resources (e.g., farming equipment) (G-9) and knowledge (e.g., education programs for young farmers) (G-10.1). Knowledge integration is another compliant factor (e.g., connect scientific findings with experiential knowledge through a famer-led research center) (G-10.2). Several learning factors from the literature review were not mentioned in the case study results. In the following, we present only some examples of promising learning factors that should be considered in the design of effective group learning processes. The complexity of joint actions and experiments should remain manageable in order to have time and resources to reflect on the social aspects of the process as well (G-5.2). A continuous process monitoring and evaluation should furthermore be conducted (G-7.1) to select viable from less viable solutions (G-5.1). A purposeful stakeholder selection (G-6.1) and design of an involvement strategy (G-6.2) are further important supportive factors.

In the *organizational learning context*, compliant factors include a societal appreciation of sustainable products (O-2), a supportive institutional context (e.g., regulations tailored to local food systems) (O-3) and networking skills to cooperate with actors along the value chain) (O-11.4). In addition, low regret experiments (O-10.4) that only imply a low financial risk are mentioned as a supportive factor. Further compliant factors are related to programs that provide resources (O-15; O-15.1) to local/organic food systems (e.g., subsidies or funding of education programs) and support knowledge exchange (O-16.1) between farms as well as other actors in the food system. However, the literature review revealed a number of further factors that were not mentioned in the interviews and questionnaires. Thus, a supportive factor suggests the consideration of capability and expertise in choosing potential innovations (O-6.2) and the ability of being open towards different solutions (O-10.1). A number of additional factors are related to a purposeful design of participatory processes, such as aligning the process and solution strategies towards opportunities in the landscape (O-12.3) rather than sticking to ideal solutions. This can also involve the active exploration of experiences in other countries through networking organizations (O-12.6). An overarching vision of a local food system (O-13.5) can be helpful to guide activities within and across organizations.

In the *policy learning context*, case-specific and literature-based learning factors consider a change of government as a supportive factors for policy learning (P-2). In addition, results comply with respect to a visionary leadership by policy-makers (P-7) that considers the benefits of local/organic food. An important role is furthermore seen for networks that connect local with (inter-) national lobbying efforts to share experiences (P-9.6). The implementation of supportive contextual factors (P-11.1) is furthermore important to foster the development of local food systems (e.g., through tailored legislation, subsidies or land planning). This requires the acknowledgement of diversity in food systems (e.g., a mix of local and international food systems) (10.7). In addition, an important role is seen for lobbying organizations for local/organic food (P-12.6). Knowledge exchange and integration (P-16.1; P -16.2) is also seen as pivotal, for instance to allow for integrated land planning and integrated assessment of measures. Governments can furthermore provide resources to research and initiatives in the local food system (P -15.1). Case study results also confirm some impeding factors, such as the dominance of a command-and-control approach (e.g., with respect to food safety) (P -10.4) and lock-in effect due to encrusted power structures (P -10.5). The literature review adds further potentially important factors to this list. The existence and active communication of forerunners in the case study region can support policy learning (P -8). Policy entrepreneurs could also play a key role in fostering local/organic food (P -10.1), for instance by supporting transdisciplinary research processes (P -11.4) that aim at the integration of knowledge and achievement of tangible outcomes. Public involvement programs require a neutral party for process design and facilitation (P -12.1), which actively addresses power asymmetries (P-13.4). Participatory policy processes also require a long-term continuation and institutionalization (P-13.12), for instance by actively fostering capacity building within the network (P-10.6).

Design of transition governance process

Transition governance design has to address the various linkages between learning contexts, as revealed in the previous analysis. The results of the governance system analysis are presented below, distinguishing between two different levels of analysis (cf. section 2.3): (1) at an overall systems level to specify the interactions across learning contexts (Figure 3a); and (2) at a more detailed context-specific level to define action situations within learning contexts (Figure 3b).

The structural inter-context analysis results in an overview of learning contexts and their linkages, as depicted in Figure 3a. The action situation in the **individual learning context** is named ‘c*onsumer awareness and engagement’* and comprises learning objects #1-#3. Consumer awareness and engagement can be actively facilitated by individuals, such as citizens (e.g., lead by example) and parents (e.g., teach the importance of healthy food to their children). However, also the other learning contexts play an important role. Thus, policy actors can foster a clear labelling of local/organic food, offer local/organic food in public cafeterias, and demand a translation of research findings from projects that are funded by public funds. In addition, actors from the local food system can contribute by engaging consumers (e.g., through a CSA model) and bringing agriculture to people (e.g., through urban farms). In this respect, community gardens run by citizen groups can also be an important element. The **group learning context** addresses the overall learning object of ‘*cooperation within the local food system’*, which comprises learning objects #4-#8. Learning in the group context is supported by consumer awareness and engagement (individual learning context), local food infrastructure (organizational learning context), as well as general physical infrastructure (including cyber infrastructure), regulations, payment schemes and research/training programs (policy learning). The **organizational learning context** addresses ‘*supply of local/organic food’* and includes learning objects #9-15. The organizational learning context is influenced by a supportive legislation, subsidies and applied research projects from the policy learning context. Learning in this context is furthermore supported by a cooperative mind-set of actors in the local food system as well as infrastructure (which depends upon the cooperation of food system actors as well as the availability of sufficient supply). Finally, the **policy learning context** addresses the overall learning object of "*setting an enabling context for local/organic food systems*", which comprises more specific learning objects (i.e., learning objects #16-20). Policy learning is fostered by outcomes from the individual learning context, including consumer knowledge and preferences that could lead to pressure on the political system to take action (e.g., by an increasing number of voters that are interested in food topics). Lobbying organizations from the group learning context can also support policy learning.

Figure 3b shows a **structural intra-context analysis for the policy learning context**. Specific action situations are identified for each learning object. Thus, a participatory policy-making process is required to tailor subsidies, payment schemes, land planning and infrastructure investments to local food systems. Supportive legislation and regulations as well as vertical/horizontal integration can reduce power asymmetries and thereby foster a dialogue between regime and niche actors. The democratic process is another action situation within the policy context that allows citizens to influence the policy process (e.g., voting for policy-makers that favour local food systems). Some action situations are located at the border of the policy learning context to express that these action situations also include external actors. For instance, the interaction process of integrated and transdisciplinary research has an integral function by bringing actors from different learning contexts together. These "inter-context action situations" can support participatory policy making, e.g. through integrated and transdisciplinary research (e.g., to provide facilitation skills) or more informal dialogues between regime and niche actors.

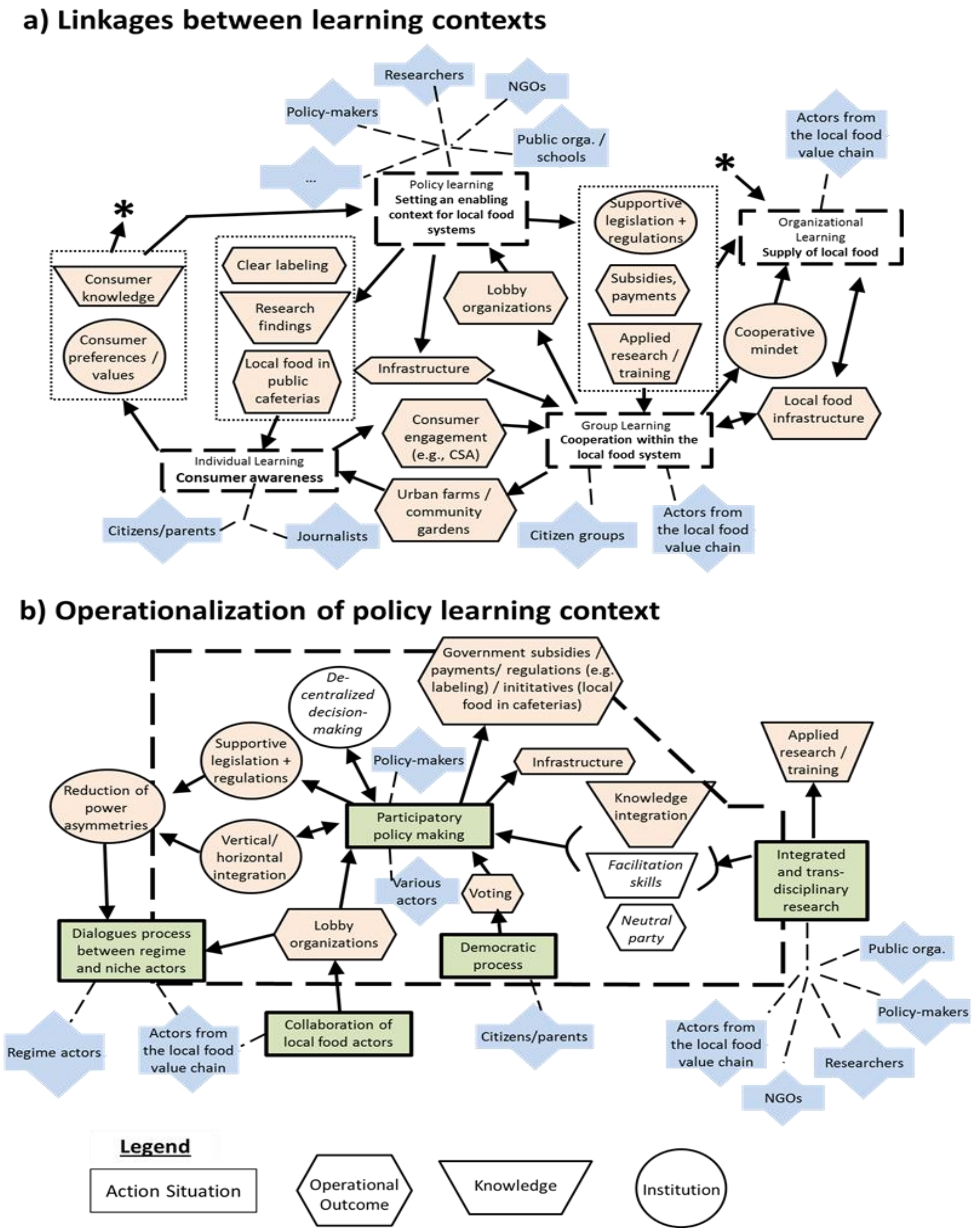

Fig. 3. Visualization of transition governance process design from an overall systems point of view (i.e. overall inter-context analysis, cf. Figure 2a), and a context-internal perceive (i.e., detailed intra-context analysis, cf. Figure 2b). Orange coloured elements are derived from case study research, while white coloured elements stem from the general literature review.

DISCUSSION

The presented methodology allowed an analysis of multiple intervention points to support the implementation of case-specific sustainability innovations. The learning perspective allowed for the specification of objects, processes and supportive factors of learning, as well as actor roles in the implementation of learning factors. Such a perspective highlights opportunities for pro-active engagement and the necessity of collaboration across different types of actors (ranging from consumers to producers and policy-makers). Several success factors from the literature review were congruent to case-specific factors identified in the case study on sustainable food systems in Southwestern Ontario. Various literature-based factors were also identified that complement case-specific factors. Thus, stakeholder knowledge was substantiated through scientific knowledge on the one hand, and complemented by findings from the scientific literature on the other.

The methodology does not result in simple solution strategies to initiate sustainability transitions. Instead, the methodology aims at finding a balance between analyzing the complexity of sustainability transitions from an integrated system perspective, and breaking down the complex topic into specific process steps. Instead of providing a small number of actors with power and responsibility to design and manage the process, the methodology shows multiple practical starting points and actor roles. Thus, this methodology is a promising approach to broaden the perspective from singular engagement processes towards transition governance processes that build upon a broad societal engagement. The relatively low share of endogenous learning factors (individual context: 20%; group context: 33%; organizational context: 31%; policy context: 38%, cf. Appendix 1) in the case study results underlines the interdependencies between individual, group, organizational and policy actions, and highlights the importance of addressing these inter-context linkages in the design of transition governance processes.

The broad perspective on sustainability transitions ranging from individual to policy-actors should also be reflected in the application of the methodology. Besides “conventional researchers” from universities or other research facilities, the analysis of multiple intervention points and responsibilities can be accomplished in a collaborative research process of citizens, communities, university scholars and other societal actors. The farmer research center proposed by stakeholders in the Ontario case underlines a trend towards a rising engagement of non-scientists in research (cf. Hand, 2010). This trend is reflected in the recent development of participatory research concepts including citizen science, crowdsourcing and transdisciplinary research, which enables the participation of non-scientists in all research phases (Wechsler, 2014).

The collection of learning factors needs to be tested and verified through further research in the future. Up to now, studies are lacking that are explicit about the contexts, processes, objects and supportive factors of learning (cf., van den Bergh et al., 2007). Methodologies are needed to systematically analyze the context of reflexive governance processes, monitor the process and evaluate the outcomes (cf., Forrest and Wiek, 2014). Methodological and conceptual frameworks are available that support an analysis of learning processes and their outcomes, and allow for the identification of general success factors through the comparison of multiple case studies.

As a next step of this research, the results will be presented to stakeholders in order to facilitate reflections of the findings, and verify their relevance in the specific case. While the analysis of the governance system was focusing on the linkages between action situations (cf. Figure 3), the transition governance process can also be analyzed through time (cf. Halbe et al. 2013 for a temporal analysis of a transition process). This might results in the definition of even more specific action situations. In addition, more research is required on assessing stakeholder visions, in order to test the plausibility and sustainability benefits of visions. While the research presented in this paper focused on governing the process of transformation, a thorough assessment of visions is required to analyze the interactions of different system designs (e.g., between local and international food systems). Research on assessing sustainability visions of stakeholders through integrated modelling is at an initial stage (e.g. Trutnevyte et al., 2011; Iwaniec et al., 2014), and requires innovative approaches to handle complexity, data limitations and ambiguity.

CONCLUSIONS

Reflexive governance approaches are expected to play an important role in dealing with the complexity of global environmental change and achieving a societal transition towards sustainable development. This paper presented a methodology to analyze and design case-specific transition governance processes, which was tested in a practical case study on sustainable food systems. A participatory modelling approach was applied to identify barriers and drivers of sustainability innovations, and derive case-specific learning objects and supportive factors, as perceived by stakeholders. The comparison of general factors from literature research and case-specific factors showed, on the one hand, conformity of several factors, and, on the other hand, revealed the ability of literature-based factors to complement factors derived from stakeholder interviews.

The results from the case study demonstrate the ability of the methodology to analyze case-specific transition governance processes by identifying multiple entry points for interventions and roles of several actors. This approach highlights the responsibility of society as a whole to take action towards sustainable development. Besides addressing sustainability issues within a particular learning context (e.g., an individual who considers sustainability aspects in his/her consumption behavior), linkages across learning contexts allow for influence of other social units (e.g., organizations might be animated for cleaner production due to changing consumer values). Thus, the methodology points to (1) specific opportunities for different social units to take action (including individuals, groups, organizations and state actors), as well as (2) the importance of observing and actively influencing the actors at other societal levels.

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Appendix 1: Stakeholder-based learning objects, supportive factors and roles for a transition towards a sustainable food system in Southwestern Ontario.

Appendix 1 of this article corresponds to Appendix 2 of the dissertation.

Appendix 2: Detailed results from literature review (Halbe et al., submitted).

Appendix 2 of this article corresponds to Appendix 1 of the dissertation.

Article 5

Halbe, J., J. Adamowski and C. Pahl-Wostl, C., 2015. The role of paradigms in engineering practice and education for sustainable development. Journal of Cleaner Production 106, 272-282.

The Role of Paradigms in Engineering Practice and Education for Sustainable Development

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Abstract

Engineers have always had to deal with complex challenges. However, a profound change has occurred over the last two decades with a realization of the need to transition from a focus on technical issues to sustainability problems that require an integrated, adaptive and participatory approach. Such an engineering approach does not only necessitate new methods and tools, but also the consideration of epistemology to deal with different kinds of knowledge and high uncertainties. The concept of paradigms can support the case-specific analysis of concrete solution strategies based upon an understanding of the epistemological dimension of sustainability issues. A systematic and integrated discussion of paradigms and their interactions in engineering practice is currently lacking in the scientific literature. This paper examines the role of paradigms in engineering practice and presents a system science approach for the analysis of paradigms. A case study on sustainable flood management and a literature analysis are provided to show the relevance of multiple paradigms in sustainable development issues. Engineers should be aware of paradigms and their respective application context, as well as the particular role of the "community involvement" paradigm for sustainable development. We propose an iterative learning approach to continuously deepen students' understanding of participatory processes and develop their ability to facilitate stakeholder processes. An overview and some reflections on the experiences of the authors in the teaching of these new paradigms at McGill University, Canada, and the University of Osnabrueck, Germany, are provided. In particular, group model building exercises were found to provide students with important experiences regarding stakeholder interaction in the safe space of the classroom.

Keywords: Higher education; sustainable development; systems thinking; paradigms

1 Introduction

Engineering practice and education need to be revised continuously to address technical and methodological innovations, and to react to the challenges and demands of changing environments and societies. Engineering is not built upon a specific set of theories, but its concepts, methods and tools are evaluated in terms of their usefulness to solve contemporary engineering problems. In this way, the classical engineering fields of civil and mechanical engineering have been expanded by the fields of electrical, chemical, biological and ecological engineering, amongst others. This practical orientation has made engineering a very effective and flexible problem solving approach. Koen (2003) defines the engineering method as "the use of heuristics to cause the best change in a poorly understood situation within available resources". This definition highlights that engineers often cannot build upon a complete knowledge of a particular system, and have thus developed heuristics to find the best possible solutions. Heuristics can be understood to be anything that provides a plausible and tested aid or direction in the solution of a problem, such as the application of an empirical equation or the use of safety factors.

This nature of the engineering method is also reflected in the evolution of engineering curricula. In recent years, traditional engineering education in such areas as material science and construction has been complemented with education in ecology, economics, stakeholder participation or ethics in order to react to new challenges in the engineering profession (cf., Bordogna *et al.,* 1993; Woodruff , 2006). One of the more recent challenges in engineering practice and education is the consideration of sustainable development issues. Sustainable engineering comprises a life-cycle perspective and consideration of ecological, economic, and socio-cultural aspects (Maydl, 2004). The implementation of engineering for sustainable development requires a multi- and interdisciplinary approach, knowledge integration, higher levels of thinking, and the ability to organize dialogues with a range of stakeholders (Kumar *et al.*, 2005; Woodruff, 2006; Bergeå *et al.*, 2006; Bagheri & Hjorth, 2007). Sustainability related tasks often have the character of 'messy' problems which are indicative of the diverging opinions regarding the definition of the problem and potential solution strategies (cf., Ackoff, 1974; Vennix, 1996). Dealing with such complex problems requires higher levels of reasoning that builds upon an acceptance of incomplete knowledge and context-dependent evaluation of available data (King & Kitchener, 2002). Systems thinking, epistemological reflection, and real world experiences are seen as critical ingredients for higher levels of reflection (Bergeå *et al.*, 2006).

This article suggests paradigms as a helpful concept for engineering students and practitioners to reflect on the linkage between epistemological aspects and case-specific solution strategies. Paradigms comprise our basic assumptions about how the world works, including perceived risks, our goals, and the solution strategies we consider. An ignorance of underlying paradigms can lead to miscommunication and subsequent management problems. For example, the prevalent "predict and control" paradigm in engineering can constrain participation of stakeholders to merely information provision or consultation events, which can frustrate stakeholders who expect to be more meaningfully involved (Tippet *et al.*, 2005). The relevance of paradigms in engineering education and practice have been explored by some scholars (e.g., Mulder 2006), but a systematic approach for the comprehensive analysis of their relevance and interactions in real-world issues is currently lacking.

This article presents a method for the case-specific elicitation and analysis of paradigms, and an approach to teach the relevance of paradigms at the university level. Problem-based learning is a suitable approach to develop expertise in dealing with complex problems (cf., Savery, 2006), and is thus chosen to support students in the development of a deeper understanding of the context-dependence of knowledge and context-dependent application of paradigms. Following Sheppard *et al.* (2009) who described an ideal learning trajectory to be “spiral, with all components revisited at increasing levels of sophistication and interconnection”, we propose an iterative approach that starts with lectures to introduce concepts and methods, and continues towards group exercises that combine role-playing games and participatory model building (using systems thinking) to sensitize students to different worldviews and their handling in participatory processes. Finally, students explore the applicability of concepts and methods in real world problem situations. Here, students learn how to facilitate multi-stakeholder processes by systematically collecting and analysing their problem frames and moderating group discussions.

The article is structured as follows: First, a definition of paradigms and a methodology for their case-specific elicitation and analysis are presented. A case study on flood management provides an example of the application of the methodology and reveals the interrelatedness of paradigms that often occur in sustainability issues. Further, a literature review examines the prevalence of each of these paradigms in engineering practice and education. Based on the experiences of the authors, a combination of lectures, exercises and projects are finally proposed to teach these innovative concepts and methods at the university level.

2 Paradigms in Engineering for Sustainable Development

Several new paradigms have been proposed for sustainable engineering. For example, Brandt et al. (2000) highlight the paradigm of clean technology that is aimed at the minimization of resource consumption and wastage during production processes and the product life-cycle. However, relying on only technical solutions is not sufficient to solve sustainability problems since human aspects of engineering systems (e.g., organization of a company, awareness of stakeholders on environmental issues) also need to be addressed. In addition to the human dimension, the inter-linkages between technical systems and ecosystems are another component of sustainable engineering which has resulted in the development of new methods and tools (cf., Mitsch, 1998; Matlock & Morgan, 2011).

The evolution of engineering approaches from a strong technical focus towards a more integrated perspective also requires new approaches in engineering education. This implies changes in the curriculum such as the inclusion of topics like listening and communicating to communities (Lucena et al., 2010), or material and energy flow analysis (Briefs and Brandt, 2002). Mulder (2006) proposes a sustainable technological development paradigm that advocates that engineers should join public debates and closely interact with stakeholders (e.g., customers and politicians, amongst others). Thus, participatory approaches and project-based learning need to be included in engineering curricula (see also Lenschow, 1998). Several pedagogical approaches have been developed in the field of education for sustainable development, such as interdisciplinary learning, or problem-based learning (Dale & Newman, 2005). Problem-based learning is a widely applied learning approach in education for sustainable development that "empowers learners to conduct research, integrate theory and practice, and apply knowledge and skills to develop a viable solution to a defined problem" (Savery, 2006, p. 12). Problem-based learning aims at motivating students and fostering deep learning and professional development, which can also be a first step towards a new culture within university departments that profoundly affects research and community activities (Hadgraft, 1998). Litzinger *et al.* (2011) also highlight that effective learning experiences need to be integrated across the entire curriculum. Wals (2014) concludes that such systemic changes in higher education institutions (HEI) are beginning at a broader scale by integrating sustainability elements in existing curricula or even designing new curricula. A paradigm change from prescriptive education to empowerment-oriented education (Læssøe 2010) does not necessarily require an immediate removal of existing structures which would face substantial barriers (cf., Lozano 2006; UN-DESD, 2006). Sterling and Thomas (2006) underline the importance of even small and stepwise change through "curriculum ideas that any HEI can begin to implement, ideally as a precursor to deeper change".

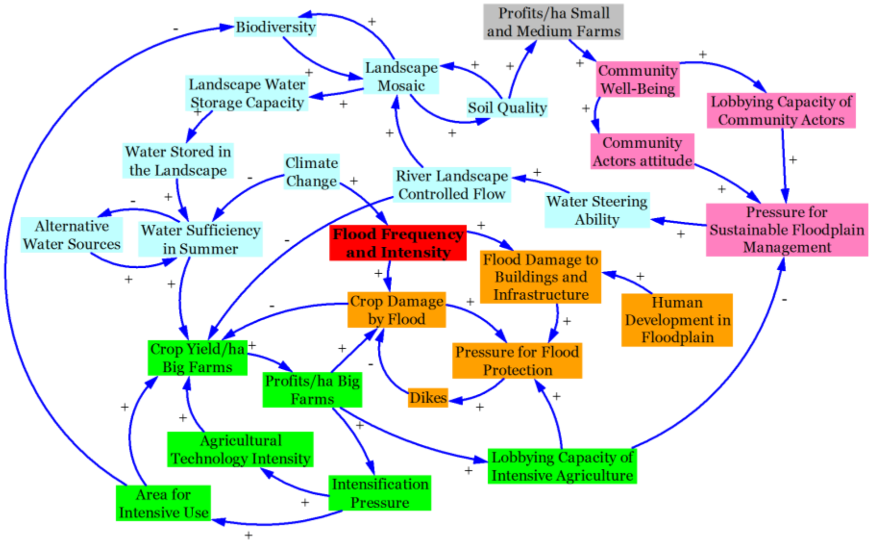
Paradigms describe the often unconscious assumptions of people about the nature of the world ("worldview") and potential ways to take action. New paradigms emerge due to the inability of conventional approaches to address contemporary challenges. As shown by the examples above, sustainable engineering requires profound changes in engineering practice and education. However, the meaning of the term 'paradigm' is unclear in the literature, and denotes different aspects such as the need for a broader perspective on engineering problems, new skills or methods. In addition, most articles highlight the shortcomings of conventional engineering and advantages of a paradigm change rather than offering a more differentiated picture of the application areas. Therefore, a more systematic analysis of paradigms is helpful to (a) establish a thorough definition of the term and, based upon this, (b) develop a methodology to analyze paradigms that are relevant for case-specific engineering tasks.

According to Kuhn's work on paradigm changes in science, paradigms are shared by an epistemic community that has a consensus on what is to be observed and analyzed, the kind of questions that are supposed to be asked, how these questions are to be structured, and how the results of investigations should be interpreted (Kuhn, 1962). Pahl-Wostl *et al.* (2011) provide a more practical definition of paradigms for the management of natural resources. A management paradigm is understood as "a set of basic assumptions about the nature of the system to be managed, the goals of managing the system and the ways in which these goals can be achieved" (Pahl-Wostl *et al.*, 2011). Based upon this definition, Halbe *et al.* (2013) present a methodology for the elicitation and analysis of paradigms in resource management using the participatory model building method and institutional analysis. Here, a management paradigm is defined by a specific "system perspective" regarding the management problem, chosen "solution strategies", as well as "risk and uncertainty management strategies".

Halbe *et al.* (2013) present a participatory model building approach to analyze paradigms held by stakeholders, as well as an example application on the issue of flood management in Hungary. In a participatory model building process, a stakeholder group built a causal loop model that described their perspective on flood management in the Tisza Basin in Hungary (Sendzimir et al., 2007). The causal loop model comprises *system perspectives* of stakeholders (i.e., those system elements that are considered to be relevant to the issue), and their *proposed solutions* as well as *risk and uncertainty management strategies*. Causal Loop Diagrams (CLDs), which were used in this case study, are powerful tools for the qualitative analysis of systems (cf., Senge, 1990). In these diagrams, elements of the system are connected by arrows that together form causal chains (see Figure 1a). A positive link indicates the parallel behavior of variables: in the case of an increase in the causing variable, the variable that is affected also increases, while a decrease in the causing variable implies a decrease in the affected one. A negative link indicates an inverse linkage between variables.

Figure 1a shows the results of a group model building exercise that addressed the issue of flood management in the Hungarian reach of the Tisza River Basin. Since the 19th century, a centralized water management regime has been implemented with a focus on engineered flood protection. The large-scale construction of dikes allowed for intensive agriculture and protection of residential and industrial areas. However, rising flood intensities and frequencies have challenged the existing water management paradigm in the past decade. A bottom-up learning process initiated by activists and academics brought innovative ideas into the flood policy debate (cf., Sendzimir *et al.*, 2007). The causal loop diagram (CLD) in the Tisza study was built around the system's problem variable: "Flood Frequency and Intensity" (red variable). This problem variable is connected to further system elements including technical (e.g., "Dikes"), environmental (e.g., "Soil Quality"), economic (e.g., "Profit/ha"), and social (e.g. "Community Well-Being") variables.

a)



b)

	"Economics" Paradigm	**"Predict and Control" Paradigm**	**"Adaptive Management" Paradigm**	**"Community Involvement" Paradigm**	**"Tradition" Paradigm**
System Perspective	Large farms (intensive agriculture)	River and protected values	Floodplain landscape	Flood prone communities	Small farms
Solution Strategies	Economies of scale; rationalization	Dike construction	River-Landscape controlled flows	Community involvement	Traditional farming methods
Risk and Uncertainty Management	Reduce flooding risk and uncertainties	Reduction of uncertainty	Accept flood risk; Adaptive Management (through experimentation)	Uncertainty dialogue	Build upon experience from the past

Figure 13: a) Causal Loop Diagram of the flooding problem in the Tisza River Basin (extended from Sendzimir et al. (2007)). The colors reflect underlying management paradigms, as specified in b) (Halbe et al., 2013).

By analyzing the CLD and the risk and uncertainty management strategies of stakeholders, the variables can be related to specific paradigms (see Figure 1b). The "economics" paradigm has a focus on the economies of scale principle that is applied in large farms in the area by using an industrial farming approach. This paradigm is tightly linked to the "predict and control" paradigm that focuses on the control of river flows and protection of economic goods (e.g., crops) through the construction of dikes. An alternative paradigm is the "adaptive management" paradigm that allows for river-landscape controlled flows through retention areas. Another paradigm is related to "community involvement" that is based upon the discussion of flooding risks and uncertainties in affected communities. Finally, small farms have a separate paradigm called the "tradition" paradigm that comprises the application of traditional farming methods (e.g., planting of native fruit trees that can deal with temporary flooding).

These paradigms reflect diverging system perspectives on the same problem (i.e., flooding in the Tisza Basin), various solution strategies (e.g., construction of dikes, allowing flows between river and landscape), as well as different risks and uncertainty management strategies (ranging from the reduction of uncertainties and control of risks, towards the acceptance of uncertainties through an adaptive management approach, the discussion of perceptions of uncertainties with communities, and confidence in traditional approaches).

The problem of flood management requires careful handling of all these different paradigms. Instead of allowing one specific paradigm to dominate (e.g., the “predict and control” paradigm or the “community involvement” paradigm), sustainable solutions should acknowledge the value of each paradigm. Sustainable engineering should therefore also include the elicitation and analysis of paradigms, and reflect upon their purposeful application.

Engineering is often related to a control paradigm that involves the structured analysis of the problem situation, and the prediction of the effectiveness of policies. However, Koen’s (2003) definition of the engineering method as the use of heuristics attests that engineering is more than prediction and control, as engineers continuously adapt their practices to contemporary challenges and available knowledge. The following section presents a literature review on the consideration of paradigms in engineering practice and education based upon the following main paradigms discussed in the Tisza Basin flooding case study: “predict and control paradigm”, “adaptive management paradigm”, “economic paradigm”, “tradition paradigm”, and “community involvement paradigm”. This list of paradigms reflects prevalent paradigms related to sustainable development. However, other topics in engineering for sustainable development (e.g., sustainable construction and energy systems) will have other types and characteristics of paradigms. The next section presents a general overview on the paradigms detected in the flooding case study and the ways in which they are considered in engineering education and practice rather than focusing on the specific implementation of these paradigms in the Tisza example.

3 Consideration of Paradigms in Engineering Practice and Education

This section contains an overview of paradigms that have been defined in the preceding section. Based upon this, potential gaps and challenges in the application of paradigms in engineering practice and education are identified. As this article provides an overview of several paradigms, a more detailed discussion and analysis of each paradigm is beyond the scope of this paper. Where available, references to more detailed examination of specific paradigms are provided.

3.1 Predict and Control Paradigm

The engineering method is usually associated with a “predict and control” paradigm (cf., Pahl-Wostl, 2011), which can have different characteristics depending on the particular engineering branch. The paradigm is clearly recognizable in engineering branches that directly have to deal with uncertain external conditions, such as hydraulic or transport engineering. Other branches, such as mechanical or chemical engineering, apply the paradigm for the design of the technical system, but to a lesser extent with regard to external conditions that define performance characteristics (e.g., customer or societal demands). Engineers are expected to find and implement solutions that work with certainty rather than based upon trial and error. Thus, engineers utilize mathematics, verified physical laws and models, as well as empirical knowledge in order to minimize uncertainty. Stochastic methods and safety factors are prevalent approaches to deal with remaining uncertainties. The most appropriate tools and methods for the achievement of best possible results are specified in the state-of-the-art, which can be defined as the set of heuristics that represent best engineering practice at a specific time (cf., Koen, 2003). These heuristics are first and foremost specified through engineering codes, but also in engineering curricula and contemporary engineering design and practice itself.

An example of the "predict and control" paradigm was already introduced in the flooding example in section 2. By using this paradigm, flood management relies upon the accurate forecasting of flood incidence and amplitude. Today, a variety of physical and data-based modeling approaches are available to predict flooding events (e.g., Razi *et al.*, 2010; Adamowski 2008). Through time, the validity of assumptions like the principle of annuality (i.e., that variables like river water levels can be described by a time-invariant probability density function) are continuously revised in order to improve the evidence of methods and adapt them to contemporary challenges (cf., Milly *et al.*, 2008). Based upon this information, advanced technical measures or warning systems can be designed and applied.

In the Tisza example, the "predict and control" paradigm resulted in the construction of over 4500 km of primary and secondary dikes to protect around 97% of the basin at risk from flooding (Sendzimir *et al.*, 2010). However, an unexpected rise of flooding parameters (i.e., peak elevation, volume, frequency) has resulted in the failure of the defense infrastructure (Sendzimir *et al.*, 2004 and 2010). Another example of the application of the "predict and control" paradigm are the flood management practices implemented in the Netherlands. The Deltaworks is a sophisticated system of dams, sluices, locks, dikes, levees, and storm surge barriers that aim at protecting the Netherlands from storm surges and river floods. Even though the Deltaworks is certainly a remarkable and unique engineering construction, the appropriateness of the underlying assumption can be questioned, like future storm wave properties and maximum river discharges (see Bouwer & Vellinga 2007). Thus, there are also signs in Dutch water management that reflect a paradigm shift towards a more adaptive flood management paradigm (cf., Pahl-Wostl, 2011). Another example of a predict and control paradigm is the South-North Water Transfer Scheme in China that aims at solving water scarcity issues in the Yellow River basin (north) by diverting water from the Yangtze (south). The enormous scale of the project that includes large investments and an extensive construction phase (Barnett *et al.,* 2006) builds upon the premise that climatic, environmental and socio-economic factors will remain stable to ensure benefits from this project. The Tisza example shows that such assumptions are questionable in a time of climate and global change. However, China's water policy also shows signs of a paradigm shift towards a more adaptive paradigm since they have now begun to consider water-saving measures in their water policy (Boxer, 2001). In the 10th National Five-

Year Plan (2000–2005), the central Chinese government promoted even the strategy of a 'Construction of a Water Saving Society' (Xia and Pahl-Wostl, 2012).

3.2 Adaptive Management Paradigm

An "adaptive management" paradigm is based upon experimentation and an iterative refinement of policies and strategies. In this paradigm, "policies are really questions masquerading as answers" (Gundersson, 1999). Instead of defining the optimal policy (through prediction), an adaptive management approach can deal with high uncertainties through the continuous monitoring and revision of measures. An adaptive approach is already acknowledged through engineering concepts like "resilience engineering" (Hollnagel *et al.*, 2006), "adaptive engineering" (VanderSteen, 2011) or "ecological engineering" (Diemont *et al.*, 2010). In addition, concepts for sustainable engineering usually include an adaptive management approach as a core requisite to find sustainable solutions in messy problem situations (cf. Dodds & Venables, 2005; Fenner *et al.*, 2006).

Some stakeholders in the Tisza example (see section 2) prefer such an adaptive management approach which would include the reconfiguration or removing of dikes in order to allow more natural river-landscape flow of water. Such a paradigm has been termed "living with floods and giving room to water", which is also emerging in the flood management practices in the Netherlands (Pahl-Wostl, 2006). An adaptive management paradigm is also seen as a central approach to deal with the regional and global scientific, economic, and political uncertainties of climate change and global change (Peterson et al., 1997; Pahl-Wostl 2007). Hallegatte (2009) discusses several strategies to adapt to a changing climate comprising no-regret strategies, preference of reversible and flexible options, including safety margins, promoting soft, non-technical adaptation strategies, and reducing time horizons of decisions. While a "predict and control" paradigm still dominates in engineering practice and education around the globe, there have been various attempts to foster the implementation of an adaptive management paradigm (e.g., Krysanova *et al.*, 2010). Besides the focus on experimentation and flexible solutions, social learning of groups and communities is also a central component of developing adaptive capacity (Folke *et al.*, 2002). Thus, the community involvement paradigm is also closely related to an adaptive management approach, and supports sustainable resource management by addressing diverging stakeholder interests and perceptions (cf., Pahl-Wostl *et al.*, 2010).

3.3 Economic Paradigm

Economic methods and tools like project management or accounting are important in engineering practice. The choice of technological options usually involves the calculation of economic viability, requiring proficiency in both engineering and economics. Engineering curricula generally includes more business economics (comprising, inter alia, statistics, econometrics, as well as decision and risk analysis) than economic theory (cf., Ashford, 2004 and Chinowsky, 2002).

The flooding case study in section 2 highlights the importance of the "economies of scale" principle which is a theoretical concept of microeconomics. Even though not included in the group model, the strengthening of the local economy to deal with the challenges of globalization, such as migration of qualified workers and loss of skills at the local level, is also highly relevant to the topic of sustainable development (cf., Bellows & Hamm, 2001). However, micro- and macroeconomics are often not included in engineering curricula (compared to courses in business economics). There are nevertheless examples where micro- and macroeconomics are taught as part of a humanities and social sciences module (see Meyer & Jacobs, 2000). The Tisza example also shows the close relationship of massive infrastructure for the protection of valued land and property (i.e., the predict and control paradigm) and an economies of scale approach. Water markets are another example that demonstrate the role of the economic paradigm in water issues. Water pricing is expected to be an instrument that can improve the sustainable use of water resources, but it requires consideration of case-specific conditions, such as the defined and enforced water rights (e.g., Roger *et al.*, 2002). Other engineering issues also involve interactions between technical solutions and economic processes. For instance, more decentralized systems for energy production can be more amenable to regional value creation (e.g., local wind parks, cf., Walker, 2008). Knowledge of the fundamental principles of economics allows engineers to understand and evaluate these connections between technology and economics in sustainable development issues.

3.4 Tradition Paradigm

Traditional knowledge is usually not taught as a separate course in engineering studies. Traditional approaches are sometimes mentioned as historical examples in design courses. For instance, the design of ancient composting toilets in Vietnam can be presented as part of a course about wastewater systems (cf., Mara *et al.*, 2007). Traditional and local knowledge can, however, be a vital part of sustainable solutions as they are adapted to a specific context (cf., Berkes *et al.*, 2000). There are numerous studies that show that local stakeholders can have a deep understanding of environmental or social processes that goes beyond scientific knowledge. For instance, local fishermen on Lake Como, Italy, were able to accurately describe hydrodynamic processes that scientists had been unable to model (Laborde *et al.*, 2011).

The tradition paradigm in the Tisza example (see section 2) also shows the relevance of traditional knowledge and cultural aspects for sustainable engineering. There is currently a gap in engineering education regarding the teaching of traditional design and solution strategies. Courses on traditional knowledge could present different cultural approaches for decision making and applications of technology, and offer methods to deal with cross-cultural education and projects (cf., Aikenhead, 1997; McCullough & Farahbaksh, 2012). In this respect, community involvement can be an important approach to include local knowledge in engineering projects.

3.5 Community involvement paradigm

Participation of stakeholder groups is considered a key approach for sustainable engineering (see for instance: Ashford, 2004; Dodds & Venables, 2005; Fenner *et al.*, 2006). A community involvement paradigm is tightly linked to an "adaptive management paradigm" (i.e., adaptation can be understood as a social learning process in which stakeholders develop the capacity to solve prevalent problems through collaboration, cf., Pahl-Wostl, 2006) as well as a "tradition paradigm" (i.e., as an approach to communicate between cultures as well as experts and lay people). Thus, community involvement can also be regarded as a central approach to coordinate the application of paradigms.

Approaches like consensus building exercises (Fenner *et al.*, 2005) and the application of participatory methods like backcasting (Quist *et al.*, 2006) or participatory model building are increasingly being embedded into engineering curricula. However, in actual engineering practice, participation often consists of merely information provision or consultation events, which can frustrate stakeholders who expect to be more meaningfully involved (Tippet *et al.*, 2005). Real participation in the design of policies and strategies through a collaborative learning process is rare, as engineers and planning authorities often still operate in a "predict and control" paradigm (cf., Halbe *et al.*, 2013).

The Tisza study serves as an example in which a gap exists between the engineering community and a local bottom-up movement. It seems that both sides cannot acknowledge the value of each other's paradigm. The teaching of paradigms in engineering education could sensitize engineers to the value of community involvement and diversity in paradigms. This could lead to an "integrated management" paradigm that is based upon the purposeful application and combination of paradigms for certain aspects of the system (social aspects could be coordinated through a "community involvement" paradigm) or different localities (e.g., a "prediction and control" paradigm could be applied for urban areas, while an "adaptive management" paradigm could be applied for rural areas) (see Halbe *et al.*, 2013).

In this context, a problem-based learning approach is a central approach to develop the ability of students to deal with such unstructured problems and multi-stakeholder processes. Students have to learn to critically reflect on knowledge from different sources and integrate them into a meaningful whole (more details on problem-based learning are provided in section 4). In addition, students should learn about challenges in the design of participatory processes, such as selection of stakeholders and consideration of the socio-economic context of the process. The initial selection of stakeholders and framing of the problem can significantly affect the evolution of the participatory process (Carr et al., 2012).

3.6 Discussion

The literature review about the relevance of paradigms in engineering education suggests that the "predict and control" paradigm is still dominant with respect to the other paradigms identified in the flooding case study. These preliminary findings are substantiated by a database analysis of Scopus (the academic literature database) that was conducted to assess the evolution and prevalence of these paradigms in engineering practice and education. Search terms were selected as a proxy for each paradigm (see detailed explanations below). Selected key words and the term "engineering" were entered in the search engine of the Scopus database. Figure 2a and 2b show the numbers of publications that have the search terms in their title, abstract or key words from 1975 to 2014 (see Figure 2a) [16], and their normalized development (Figure 2b)[17] (the search procedure is explained in more detail in a footnote below). The graph for each paradigm is colored by using the same colors as in Figure 1: "predict and control" paradigm (orange; search terms: predict and control); "adaptive management" paradigm (light blue; search terms: adaptation or adaptive); "economics" paradigm (green; search term: economics); "tradition" paradigm (grey; search terms: traditional or indigenous); "community involvement" paradigm (pink; search terms: stakeholders or participation).

[16] Search terms in the Scopus database (www.scopus.com): "engineering" AND paradigm key words; Data range: years from 1975 to 2013; Document types: All (article, review, conference paper,…); Search related to all subject areas.

The diagram shows corrected publication numbers (C) for each paradigm (i): $C_i = N_{i,j} / c_j$ where N := number of publications; i := specific paradigm; j := year (j); c := E_j / E_{1975} where c := conversion factor, E := Number of publications for the search term "engineering";

Explanation of the compilation of data: the numbers are corrected as numbers of publications have increased steadily through time (i.e., in the 1970s, total publication numbers were lower than in the 2010s); however, this might distort the results, as an increase in publications related to a paradigm might not necessarily imply an increase in the relative importance of this paradigm, but might be due to a total increase in publication numbers. Thus, results are corrected by computing the numbers of publications for the term "engineering", and relating the results to the number of the year 1975 (i.e., correction term of 1975 is "1"; for the year 2000, the correction term is "3.5" – this means that the number of engineering publications in 2000 are higher by a factor of 3.5 compared to publication numbers in 1975; thus, the numbers of publications for paradigm-rated search terms are divided by the annual correction factors)

[17] Search terms in the Scopus database (www.scopus.com): „engineering" AND paradigm key words; Data range: years from 1975 to 2014; Document types: All (article, review, conference paper,…); Search related to all subject areas.

The diagram shows relative publication numbers (R) for each paradigm (i): $R_i = N_{i,j} / N_{i,1975}$ where N := number of publications; i := specific paradigm; j := year (j)

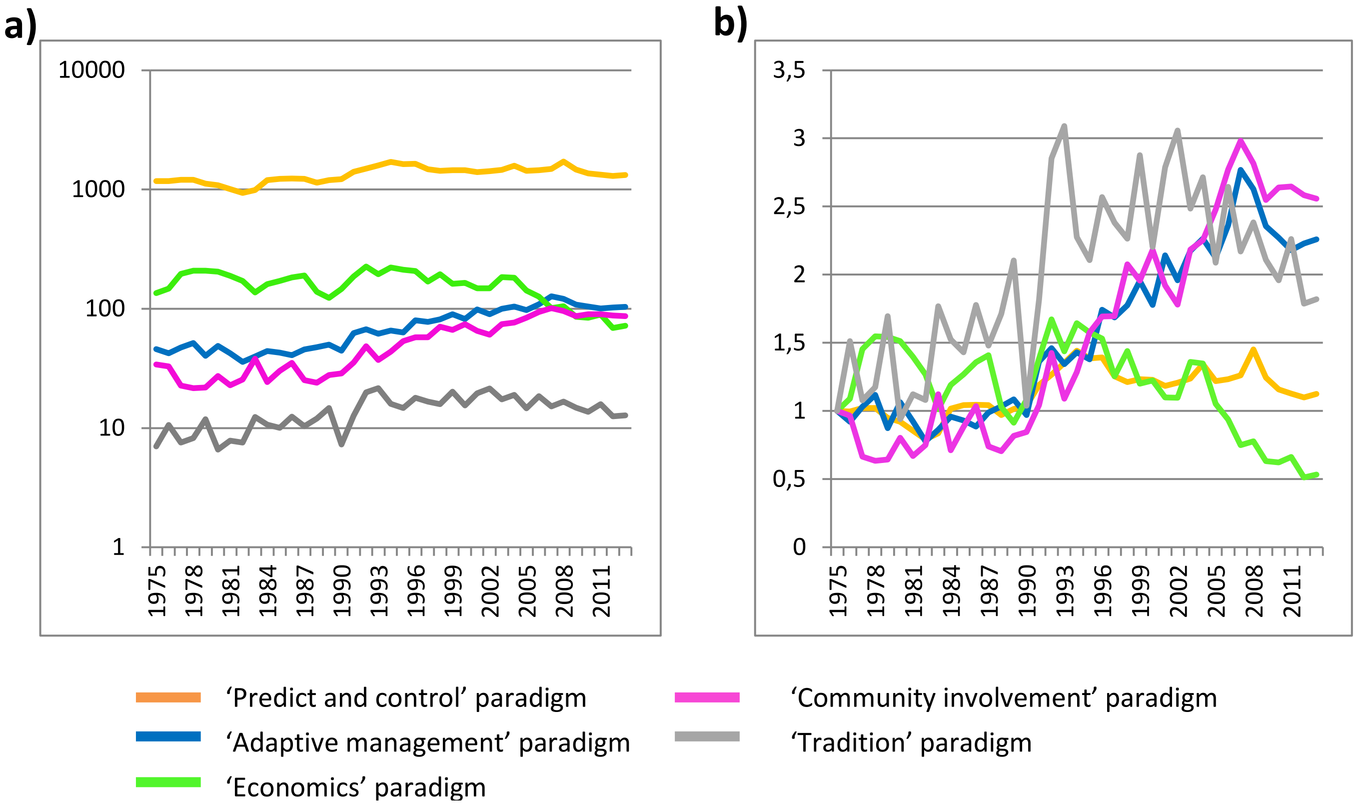


Figure 2: (a) Numbers of publications related to paradigms; (b) Evolution of paradigms in the engineering literature using 1975 as a reference year.

The results of the literature database analysis underlines that the “predict and control” paradigm is the dominating paradigm while the economic, adaptive and community involvement paradigms are represented to a lesser extent. The consideration of traditional or indigenous knowledge in engineering practice and education are at a niche level only (see Figure 2a). Adaptive management, economics and community involvement are, however, increasingly being considered in engineering (Figure 2b). The adaptive management paradigm shows the most significant increase followed by the community involvement and tradition paradigms.

Based on the discussion of the relevance of paradigms in engineering practice, the following section presents experiences in the teaching of paradigms in university courses at McGill University, Canada, and University of Osnabrück, Germany. The focus of the discussion is on the “community involvement” paradigm due to its particular importance for sustainable development issues (i.e., community involvement is a central approach to mediate conflicting perceptions and to help coordinate diverging paradigms) (cf., Lucena *et al.*, 2010).

4 Teaching the Community Involvement Paradigm

The mere enlargement of engineering curricula is not sufficient to apply new methods and tools for sustainable engineering. In particular, the engagement of stakeholders challenges the 'expert' approach of engineers and demands the rethinking of engineering paradigms (cf., Mulder, 2006). Lozano *et al.* (2013) highlight the need to overcome the Newtonian and Cartesian reductionist and mechanistic paradigms in higher education, in order to create new sustainable development paradigms.

We propose the explicit consideration of paradigms in engineering education in order to sensitize students to different epistemologies. In this way, students can learn to understand and appreciate the application areas and limitations of a range of paradigms in order to be able to coordinate diverging solution perspectives and find integrated strategies for sustainable development. Students can benefit tremendously from experiences outside of the classroom (i.e., with real stakeholders) in order to gain confidence in the relevance and applicability of participatory methods. The following sections describe the development process of this teaching approach and its implementation and evaluation in (1) the M.Sc. program in Integrated Water Resources Management (IWRM) in the Department of Bioresource Engineering, McGill University, Canada, and (2) the B.Sc. Program in Applied Systems Science (ASS) at the Institute of Environmental Systems Research, University of Osnabrueck, Germany.

4.1 Development of course elements

The programs in IWRM and ASS introduce technical, social, economic and environmental aspects of sustainability issues and stress the importance of stakeholder engagement, as well as adaptive and integrated management. Teacher-centred education through lectures can only provide a shallow understanding of concepts like integrated and adaptive management. Thus, the authors explored ways to enable students to face the complexities of real-world problems and different paradigms held by stakeholders (such as engineers, citizens, politicians). Systems thinking and participatory model building are suitable methods to induce such an active and integrated learning (Wiek *et al.,* 2011). Even though lectures are often considered not to be useful for deep learning, there are different forms of interactive lectures that are compatible with problem-based learning (Fyrenius *et al.,* 2005). We aimed at the stepwise and iterative development of expertise with respect to analysing and handling paradigms through practices that (1) develop individual skills (e.g., systems thinking), (2) specify the context of their effective applications, and (3) are applicable to real-world problems (cf, Litzinger *et al.,* 2011). In lectures, students obtained information about systems theory, the role of paradigms, the method of participatory modeling and design of participatory processes. This knowledge is deepened by practical group exercises in which students analyze different paradigms in real-world problems (e.g., water scarcity management) through a combination of a role-playing game and participatory modelling using systems thinking. A project further contextualizes this methodological knowledge as students get in touch with stakeholders and actively get involved in a sustainability-related problem. The different course elements are described in more detail in the following section.

Table 4: A combination of lectures, exercises and projects to teach community involvement.

Teaching Units	**Contents**
Lectures	Paradigms in Sustainable Engineering (2h) Systems Science (2h) Participatory Model Building (2h) Design of Participatory Processes (2h) *Supplemental Lectures: Further Methods for Stakeholder Involvement*
Exercises	Individual Modeling (2h) Group Modeling (3h) *Supplemental Exercises: Role Playing Games; Scenario Analysis; Computer Models as Educational Tools*
Project	Individual Interviews (3 weeks) Merging and Analysis of Models (3 weeks) Presentation of Results (2 weeks)

4.2 Description of course elements

Table 1 shows a mix of lectures, exercises and projects that were tested at the University of Osnabrueck, Germany, and McGill University, Canada, to teach the relevance of paradigms and community involvement to undergraduate and graduate students. All three authors have used these different approaches to varying degrees in the two universities. Each of the elements is presented in detail in the following sub-sections.

4.2.1 Lectures

Fyrenious et al. (2005) point to several opportunities for interactive lectures that conform to a problem-based learning approach. Lectures can include individual and group reflections by students, and involvement of students in the planning of the course content (e.g., through writing down questions at the end of a lecture that are addressed in the next lecture). Even though lectures cannot completely replace self-organized forms of learning, we included this element in our course design to introduce new concepts and methods to students. The lecture on paradigms in sustainable engineering introduces paradigms that are frequently found with the various ‘messy’ problems of sustainable development. Students learn about different paradigms and their epistemological foundations. In addition, advantages and limitations of each paradigm are presented and discussed in this lecture by providing examples from practice (e.g., the Tisza example, see section 2). The consideration of a diverse range of worldviews allows students to examine their own paradigms (which might be held at an unconscious level, e.g., based upon previous engineering education, cf. Cech, in press) and to learn about alternative paradigms. This is in line with Ausubel's assimilation theory of learning (Ausubel et al., 1978), which relates deep learning processes to the opportunity to associate new concepts to previous experiences.

Systems science is also a core methodology for sustainable engineering; the lectures on systems science in both the McGill and Osnabrueck courses comprise of the methods of systems thinking and system dynamics (see Sterman, 2000). The application of these methods in a participatory setting is provided subsequently in a lecture on participatory model building in each program (c.f., Vennix, 1996, van den Belt, 2004). Participatory methods cannot be applied in isolation but need to be embedded in a broader design of a participatory process. A related lecture deals with the framing of a sustainability problem, the analysis of stakeholders, the organization of the participatory process, and its embedment in the broader institutional structure.

4.2.2 Exercises

Individual and group modeling exercises are used to provide students with experience dealing with the method of participatory modeling in the "safe environment" of the classroom. In the individual modeling exercise, students learn to build a causal loop model of their individual perceptions regarding a specific environmental issue (e.g. water scarcity). The model is built on a large sheet of paper by the student. Variables are written on sticky notes and connected through causal arrows (see Vennix, 1996 for a detailed description of the methodology). Following the guidelines of Vennix (1996), the problem variable is placed in the middle of the paper. Then, the causes of the problem are placed on the left hand side and causal arrows are drawn. Subsequently, the consequences of the problem are added, and feedback processes are analyzed (i.e., the student assesses whether a consequence of the issue can be connected to a cause variable). This exercise results in a comprehensive causal loop diagram that can be interpreted as the mental model of an individual regarding a particular problem.

In a group modeling exercise with the students, the same method is applied in a group setting, i.e., a group of students (about 4 - 8 students) construct the model jointly. This exercise can be combined with a role playing game. For example, in a group model building exercise on the issue of water scarcity, students assume the roles of farmers, hoteliers, citizens, governmental representatives, and engineers to learn the applicability of the method in stakeholder discussions. In addition, the role of a "facilitator" is represented by a student in each group. This student has the task of moderating the discussion and helping if questions related to the methodology arise. Therefore, facilitators meet once with the lecturers before the actual class exercise for about one hour in order to learn about the application of the method in detail. The group exercise follows the same procedure as the individual modeling exercise (i.e., define the problem variable; add causes, consequences and feedback loops). At the end of the exercise, one or two student groups present their results to the class (see an example of a resulting CLD from one of the classes in Figure 3). Feedback from the students indicates that the students find this exercise very useful in better understanding the concepts of systems thinking and modeling.

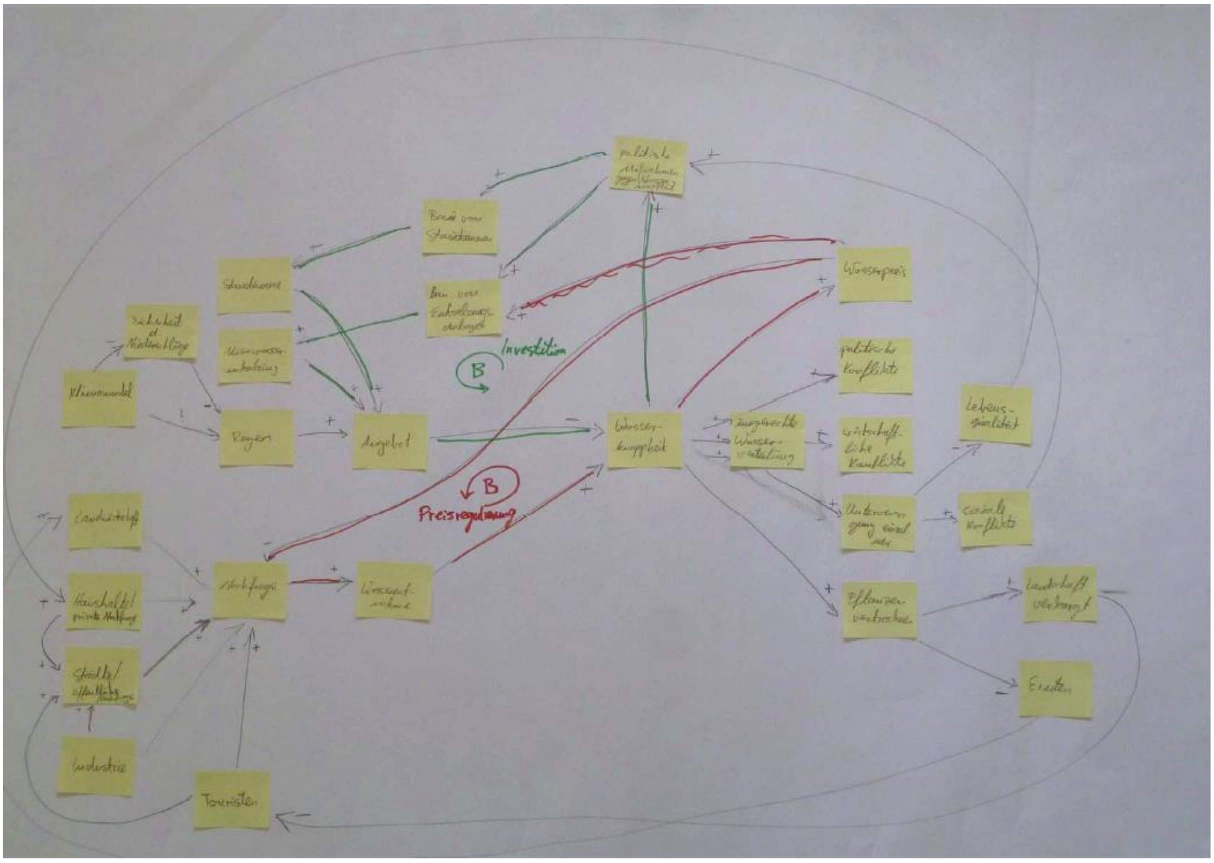


Figure 3: Group model built by students on the issue of water scarcity including causes, consequences, and feedback loops (marked in color).

4.2.3 Project

In group projects, students learn to apply participatory modeling with real stakeholders. Locally-relevant and up-to-date topics are chosen that can ideally be related to an on-going participatory process. The list of stakeholders is discussed with students, and potential participants are contacted by the lecturer (via e-mail or regular mail) in order to ensure an effective and immediate start to the student project. However, students are free to contact further stakeholders during the interview process. During the whole duration of the project, students are assisted by a tutor who helps in case of questions related to the methodology and or organization of stakeholder involvement.

After the initial contact is accomplished through the lecturer, students arrange a meeting time with the stakeholders. Each stakeholder interview is conducted by a sub-group of two students, and takes place at the university or the participant's working place. An interview takes around 1.5 h, and proceeds using the same steps that were learned during the exercises (see section 4.1.2). Each sub-group of students has the task to complete at least two interviews. After the interviews, students compare the individual models and analyze diverging points of view as well as complementary aspects. In addition, students develop a holistic model that contains all the perceptions of the stakeholders and highlights the points where opinions differed. Finally, the project results are presented to the stakeholders in a final meeting. In addition to the discussion and presentation of results, students moderate a discussion between different stakeholder groups.

An example is provided of the above with a project focused on the topic of sustainable mobility in Osnabrueck, Germany. In this project, students supported the work of a "bike traffic" round table that had existed for several years. The round table consisted of various stakeholder groups that promoted cycling in the city (for instance, stakeholders included representatives from the City of Osnabrueck, cycling clubs, and the police). The stakeholder group was trying to determine why cycling was not more popular in Osnabrueck despite positive conditions. The student group was asked to analyze the barriers and drivers of cycling in Osnabrueck, and potential feedback structures that inhibited a higher rate of bike-use.

The results of this project revealed the unexpected finding that the anticipated consensus between members of the stakeholder group was not reflected in the individual models. Only five variables and three causal connections were contained in all individual models of the cycling issue. Thus, the interviewees put their focus on different aspects of the issue of low cycling rates in Osnabrueck. In light of this, the students analyzed certain aspects of the models in detail: "cycling infrastructure", "health", "security", "emissions", and "share of motorized private transport (MPT)". For each of these topics, the students elicited the system structures and feedback processes from the individual models. Following this, the students compiled a holistic model that showed the interrelations and feedbacks of all aspects of the modelled system. Based on this model, potential reasons for the relatively low rates of cycling were analyzed. Three main explanations of the phenomena were found. First, two balancing feedback processes were detected that are expected to slow down the growth of the cycling rate: (1) a rising cycling rate was related to a higher prevalence of bike-related accidents which decreases the feeling of security which ultimately lowers the bike share; (2) if more people used their bike, congestions on MPT would decrease which makes the usage of the car more attractive. Secondly, the reinforcing mechanisms for growth in the cycling rate are subject to constraints. For example, the use of cycling infrastructure is constrained by its publicity (i.e., people need to know about the bike system) and the personal travel range of cyclists (i.e., even with a good bike system, people are only willing to bike for a certain distance). Third, students determined external variables that have an impact on the cycling rate such as standard of living, oil price, or environmental consciousness.

These aspects cannot be influenced at a local level (e.g. oil price), or require a long time to change (e.g., environmental consciousness).

The stakeholder group approved the holistic model as a comprehensive representation of the cycling issue. The model helped to develop a comprehensive overview of the system and potential policy interventions. The group discussion revealed that subjective perceptions of cyclists (e.g., on security or the quality of the bike system) have a critical influence on the system. It was revealed that most measures in the past have focused on the improvement of biking infrastructure rather than considering the influence of bikers' perceptions. The group concluded that a more concerted effort aimed at raising awareness (including positively influencing subjective perceptions) to increase cycling rates in Osnabrueck would be likely to be the most effective policy to pursue.

4.3 Experiences and Evaluation

In the two courses, students acquire various competencies in engineering for sustainable development through a combination of lectures, exercises and projects, as presented above. First, students learn about the value of different paradigms and are encouraged to review their own unconscious paradigm. For instance, the "predict and control" paradigm can be seen as a root cause for the focus on cycling infrastructure development in Osnabrueck. The instalment of new bike lanes is a hands-on and tested approach in which implementation can be controlled and evaluated by standard procedures. Implementation and evaluation of measures for addressing perceptions of cyclists (for instance related to the feeling of security) are, however, less tangible and would require a more adaptive management and stakeholder involvement paradigm. Second, the method of participatory model building that is used in each course is a suitable approach to analyze issues in an integrated manner (as required for sustainability issues) and to involve stakeholders in the analysis and design of sustainable solution strategies. In addition, causal loop diagrams are a helpful method to elicit paradigms and analyze their interrelatedness (see section 2 and Halbe *et al.*, 2013). These group exercises allow students to explore the dynamics of stakeholder discussions about a real-world issue and experiment with the role of a facilitator. Third, the group project provides students with the opportunity to test their methods and insights in real world problem situations. The direct feedback from stakeholders provides opportunities to reflect on the applicability of the method and to get hands-on experience in community involvement. Playing the role of facilitator provides students with an important supplemental experience to the prevalent expert approach in engineering and science. Due to the linkage to an up-to-date and relevant problem, stakeholders are typically willing to devote their time to the interviews. The students generally obtain very positive feedback regarding the value of their work, and the relevance of the results. For example, in another project on the more contested issue of wind energy, stakeholders were impressed that students were able to explain the volatile dynamics of the system due to the dominance of reinforcing loops that can cause a "boom and collapse" dynamic. Students are usually very motivated to produce meaningful results since they feel that their study is relevant for stakeholders. In addition, the moderation of the closing event is a good learning opportunity for students to listen to differing perceptions, and to facilitate a fruitful discussion which is also a critical skill for sustainable engineering.

At the University of Osnabrueck, the proposed course elements are applied in the course "Participatory Modeling" (lectures, exercises and projects). Due to the small group sizes (7 students on average), evaluation in the participatory modeling course has mainly been accomplished in an informal way through continuous discussion with students about their learning progress and potential issues. Students are generally very satisfied with the courses, but point to the high work load of the project and difficulties adapting to a student-centered learning approach. A formal evaluation was conducted after the course to evaluate the perceived long-term learning outcomes after students' graduation. In this evaluation, students assessed the mix of lectures, exercises and the project to be an effective teaching approach (4.6 on a scale ranging from 0 "strongly disagree" to 5 "strongly agree). All students that participated in the evaluation reported that they learnt most during the project. The exercises were seen by 60% of students as the second-best learning approach followed by lectures (40% of students found lectures the second best learning approach). The group model building method was assessed to be particularly helpful for the visualization and analysis of stakeholder perceptions (4.4, same scale as before).

At McGill University, the lectures and exercises are integrated in the courses "Watershed Systems Management" (BREE510) and "Engineering for Sustainability" (BREE420). Table 2 shows the mean values of student evaluations with respect to learning outcomes, active participation and effectiveness of the teaching approach, which are all above the department mean values (mean values for learning outcomes: 3.9; active participation: 4.2; effectiveness of teaching approach: 4.0). Written comments from the evaluation forms demonstrate that the group exercise was particularly helpful for students. For instance, a student wrote that the "group model building project was an effective activity and demonstrated the possibilities of such tools in community development and stakeholder participation".

Table 5: Evaluation results for courses at McGill University (scale ranges from 0 "strongly disagree" to 5 "strongly agree").

McGill					
Course	**BREE510 (37 students on average)**			**BREE410 (21 students on average)**	
Year	**2011**	**2012**	**2013**	**2012**	**2013**
Learning Outcomes[1)]	4.4	4.6	4.3	4.2	4.6
Active participation[2)]	4.5	4.7	4.4	4.5	4.9
Effective teaching[3)]	4.5	4.7	4.6	4.7	4.5

Original questions in the evaluation form:

1) Overall I learned a great deal from this course.
2) The instructor encouraged students to actively participate.
3) The instructor used effective teaching aids.

5 Conclusions

Sustainable development poses particular challenges to engineering. Traditionally, engineering has applied an 'expert' approach based upon a 'predict and control' paradigm. However, sustainability issues require the participation of various stakeholder groups that might have differing perspectives, goals and paradigms. The consideration and management of differing paradigms is thus a critical task in engineering for sustainable development. A systematic analysis of paradigms in engineering practice and education is currently lacking. This paper presents such a systematic analysis of paradigms and their handling in the engineering-related literature. A stepwise and iterative approach is proposed to teach the analysis and handling of paradigms at the university level.

The case study on flood management in Hungary demonstrates that the application of a single paradigm is not sufficient to address the multiple aspects of sustainability problems. The integrated analysis and combination of paradigms is a more promising approach to find sustainable solutions. A literature review examined the prevalence of paradigms related to the flooding example case. The results indicate that the "predict and control" paradigm is still the dominating paradigm in engineering. The "economics", "adaptive management" and "stakeholder involvement" paradigms are additional paradigms that are increasingly considered in engineering education and practice. A "tradition paradigm" that acknowledges the value of traditional knowledge resides at a much lower niche level. Further analysis revealed the central relevance of the "community involvement" paradigm, as this paradigm is linked to the "adaptive management" as well as the "tradition" paradigms.

Based upon this analysis, some of the authors' experiences were presented to sensitize students to different paradigms and to teach practical approaches for community involvement. A combination of lectures, exercises and projects are proposed to introduce the tool of participatory modeling, and to provide students with experiences in its application in stakeholder processes. In particular, the linking of group projects to on-going local stakeholder processes proved to be a valuable approach for students to gain experience in the implementation and facilitation of meaningful stakeholder participation. The stepwise and iterative design of course elements allows for broad applicability in engineering education. Lectures and exercises can be integrated into existing courses easily to present the concept of paradigms to students and induce a questioning of their own paradigms. In particular, group exercises turned out to be an effective way to provide students direct experience of interactions between people who hold different paradigms. Such exercises can certainly not replace the experience of interacting with real-world stakeholders in a group project. High organizational and time requirements might, however, impede their rapid implementation at universities that have not already included these kinds of projects in their engineering curricula.

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Article 6

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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[18] 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.

[18] 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.

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 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.[19] These similar characteristics imply similar challenges and solution strategies, as discussed below in Section 3.

[19] 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.

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: (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.[20] 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[21]

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-evolution and group selection. The absence of theories and formal descriptions

[20] 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.
[21] See Holtz (2011) for a review of models for understanding transitions.

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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Article 7

Halbe, J. and R. Sampsa, R., 2015. Use of participatory modeling in transition governance processes. International Sustainability Transitions Conference 2015, Brighton, UK.

Use of participatory modeling in transition governance processes

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Abstract

There is still a significant potential for the application of participatory modeling methods and tools in transition governance processes. On the one hand, only a few studies have yet used participatory methods in a transition context despite their ability to involve stakeholders and actively facilitate learning and innovation. On the other hand, researchers have proposed transition governance frameworks to guide the effective application of participatory methods and tools. This paper aims at exploring this synergetic potential of transition research and participatory modeling methods. First, distinct process phases are defined from transition governance frameworks that clarify different objectives during transition processes. Second, suitable participatory modeling methods and tools are introduced and sorted according to process phases. The results suggest process phases as a helpful framework to guide the analysis and application of participatory methods. Various relevant methods and tools are identified that have a high applicability in transition governance processes, and thus should be addressed in future research. Participatory social network analysis, use of conceptual transition frameworks as participatory tools, and methods for ex-ante process design are identified as particularly promising approaches.

1. Introduction

Only a few studies have yet used a participatory modeling approach in the context of transition research. Participatory approaches can help to capture knowledge from stakeholders and to make it usable for decision-making processes or scientific research. Non-technical tools and guidelines can also allow for a broader application of transition governance frameworks by practitioners (cf. Raven et al., 2010). While various participatory methods, tools and frameworks exist, Holtz et al. (2015) underline the particular relevance of a modeling approach to deal with the complexity of sustainability transitions. Models are explicit, clear and systematic, allow for inferences about the dynamics of the system, and facilitate systematic experiments that might not be possible otherwise, for instance due to ethical reasons (Holtz et al., 2015). There are several benefits of participatory modeling methods, such as supporting the development of a shared problem perception and inducing communication and learning between stakeholders (cf., Sendzimir et al., 2006; Liu et al., 2008).

Due to the various application areas and benefits, participatory modeling methods are applied in various fields, including resource management (e.g., van den Belt, 2004), foresight (e.g., Bishop et al. 2007) and operational research (e.g., Franco and Montibeller 2010). A framework that guides the application of participatory methods for the support of sustainability transitions is missing though. Cairns et al. (2013) point out that the application of participatory methods alone is insufficient to organize effective participatory processes. A context-sensitive framework is needed that guide the combination and timing of participatory methods and tools. Halbe et al (2015a) suggest that transition management and similar reflexive governance approaches can offer such a guiding framework, as they can link the application of participatory methods to an overall transition process including actor networks and the current phase of transition dynamics.

This paper continues this strand of research by following two objectives. First, the paper aims at assessing the ability of transition governance frameworks to guide the application of participatory modeling methods in a way that fosters effective change towards sustainability. Second, the paper aims at the identification and assessment of participatory modeling methods and tools with respect to their application in transition governance processes. Due to the various benefits of a modeling approach in transition research (cf. Holtz et al., 2015), we put a focus on participatory modeling methods, but also consider complementary tools and frameworks. The term “transition governance” is used in this article as an umbrella term that include conceptual frameworks 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 paper is structured as follows. First, process phases and pertaining objectives of transition governance frameworks are identified and compared. Second, we present and assess participatory modeling methods and tools that can be useful in achieving the objectives of process phases. Finally, the discussion reflects on the potential of the three frameworks to act as a guiding framework for effective participatory processes, and provide some future research ideas.

2. Process phases and pertinent objective of transition governance frameworks

Reflexive governance is a broad conceptual framework that fits into this category. Reflexive governance transcends the notion of an external supervisor or 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). In addition to the general reflexive governance framework, Voß and Bornemann (2011) consider adaptive management as a specific design of reflexive governance, which particularly deals with managing change towards sustainability in social-ecological systems. Transition management is another specific reflexive governance approach that aims at the pro-active facilitation of socio-technical sustainability transitions (Loorbach 2007). Various papers describe linkages between these frameworks mentioned above. Foxon et al. (2008, 2009) detect various opportunities for a fruitful dialogue so that transition and adaptive management can be seen as complementary approaches to understand and handle the complexity of transition processes. Thus, we regard reflexive governance, adaptive management and transition management as promising frameworks to guide effective participatory modeling process in the context of sustainability transition.

Various academic papers have described the conceptual frameworks of reflexive governance (Voss and Kemp, 2006), transition management (Loorbach 2010) and adaptive management (e.g., Williams 2011; Pahl-Wostl 2008) in detail. Thus, a further detailed introduction to the concepts is not necessary. Instead, we succinctly describe the different process phases and related objectives that are conceptualized in each framework. As all frameworks deal with complex systems, process phases cannot be considered as clearly separated from each other. Different phases and related activities usually proceed in cyclical and iterative terms. They often operate simultaneously and are hardly distinguishable 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 purpose and a particular timing in the process.

2.1 Reflexive governance

The concept of reflexive governance developed against the background of a rising disappointment about the limited practical success of sustainability strategies (Voss and Kemp, 2006). 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: First, problem analysis comprises (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 through participatory scenario development in order to reveal undesired side-effects. Second, the goal formulation dimension 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 is also a specific reflexive governance approach that aims at the pro-active facilitation of socio-technical sustainability transitions (Voß and Bornemann, 2011). Transition management comprises different activity clusters that form a transition management cycle: strategic, tactical, operational and evaluation. The *strategic activity cluster* includes participatory problem structuring to find a common language between actors and a shared conceptualization of the system at hand. This allows for the development of sustainability visions which are inspiring pictures of the future. Strategic activities usually start with a group of innovative individuals who are thinking and acting outside of conventional boxes. The *tactical activity cluster* introduce organizations, businesses, NGOs and others who are able to further promote and specify sustainability visions. This involves the development of concrete transition images (e.g., for public transport or solar energy) that fit to the overall sustainability vision. Transition paths are specified, which are a series of 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 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 continuously assess and adapt actions (Loorbach 2007, 2010).

A focus on experiments is also applied by the related framework 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 is more focusing on technological innovation and thus not mentioned as a general transition governance framework. However, we also consider the approach in section 3.1.5, as strategic niche management is a key approach in the implementation and coordination of experiments that aim at facilitating sustainability transitions.

2.3 Adaptive management

While the reflexive governance and transition management frameworks developed in the 2000s, the proliferation of adaptive management approaches already started 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 an experimental approach that allows for continuous learning from past actions (Lee 1999; Berkes et al. 2002; Pahl-Wostl 2007). Various adaptive management frameworks are available that usually share many commonalities, but use different terminology (Plummer, 2009). Pahl-

Wostl (2008) provides a general adaptive management framework that distinguishes between five steps in an iterative adaptive management cycle, which all require strong stakeholder participation and transparent decision-making: (1) *Problem definition and goal setting* phases need to take multiple perspectives into account; (2) *Policy design* should consider different scenarios to assess policy performance under different possible futures; (3) Correctability of decisions should be considered in *policy implementation* (e.g., by considering the costs of reversing decisions); (4) *Monitoring and evaluation* should include different kinds of knowledge; (5) *Policy assessment* should be accomplished in a transparent way.

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). Models are important tools for understanding consequences and associated uncertainties of different management actions or policy designs. Thus, the adaptive management field has gained some experience in the use of participatory methods, such as participatory modeling approaches (e.g., van den Belt et al., 1997). Learning can occur by comparing modeling results with observed data from well-designed monitoring programs (Williams, 2011). Adaptive co-management also highlights the importance of horizontal and vertical integration in resource governance systems (Armitage et al., 2008) in the coordination of stakeholder actions (Olsson et al., 2004). This requires the conscious and continuous analysis and assessment of stakeholder participation throughout the process (Foxon et al., 2009).

2.4 Overview of process phases and objectives

The three transition governance frameworks 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, the framework comparison shows some form of conceptual consolidation with respect of process phases required for a pro-active facilitation of sustainability transitions. We synthesize the following sequence of six process phases from the three transition governance frameworks:

Process phase 1: Integrated knowledge production for 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: Stakeholder analysis, problem definition and goal formulation are closely related, and thus have to be conducted in parallel. 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 facilitation of stakeholder involvement is required.

Process phase 3: Participatory visioning and goal formulation: Common goals must be discussed that integrate various perspectives and interests of stakeholders. The objective of this process phase is to bring different interests together, and to develop a vision that motivates stakeholders and functions as a reference point for action. A potential process goal could also comprise the testing of different hypothesis to learn about the system.

Process phase 4: Interactive strategy development that anticipates long-term systemic effects: In this process step, the outcomes of different strategies are 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: Coordinate the implementation of experimental actions of multiple actors: Multiple experiments can be 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 allow for learning of participants and lead to a revision of problem definition, stakeholder selection, goal formulation, strategy development and implementation of experiments.

The similarity of process phases in all transition governance frameworks is a favorable condition for transferring findings and experiences on the use of participatory methods from the more mature adaptive management and other related research fields to transition governance frameworks (cf. second objective of the paper) that have been developed more recently. However, the identified process phases might be too general to guide effective participatory processes (cf. first objective of the paper). Thus, the subsequent section takes a closer look at the differences and synergies of transition and adaptive management in order to identify further, more specific aspects of these frameworks that could guide the application of participatory methods.

2.5 Commonalities and differences between transition and adaptive management

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 frameworks 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). Foxon et al. (2008, 2009) identifies differences of transition and adaptive management with respect to six aspects: (1) Goal-setting: adaptive management aims at maintaining system functions while transition management aims at their transformation through the development of innovations; (2) Extend of participation: adaptive management usually includes a broader diversity of stakeholders while transition management has been criticized to risking dominance of actors from the existing regime; (3) Role of diversity: unlike transition management, adaptive management explicitly considers diversity in systems and structures as a central approach to achieve resilience towards shocks; (4) Consideration of spatial scale and timescales for change: experiments in adaptive management consider scaling-issues, while transition management does not address the opportunities and limitations of large-scale implementation of successful experiments in niches; (5) Governance approach: adaptive management focuses on polycentric and multi-level governance systems (which pertains to the landscape in transition management), while transition management uses the multi-level framework; (6) Institutional change: in adaptive management, institutional change is stimulated by learning from experiments, while transition management also have a strong goal-oriented approach towards institutional change.

Based upon the comparison of transition and adaptive management frameworks, we will have a closer look at the following aspects that have been identified as factors for mutual learning by Foxon et al. (2009). The six key factors will be addressed in related process phases, as indicated below. Thus, we will have a closer look at the role of participatory modeling methods for:

- **Analysis and facilitation of innovations (Key Factor 1)**: This aspect will be specifically addressed in process phases 1-4, as innovations can be addressed in the problem definition (phase 1), stakeholder selection (phase 2), goal formulation (phase 3) and strategy development (phase 4).
- **Systematic analysis and selection of stakeholders (Key Factor 2):** this is particularly relevant in phase 2 (stakeholder analysis and selection).
- **Analysis of diverse systems and structures that provide functions (Key Factor 3):** This aspect can be related to phase 3, as different future visions can be considered that include a diversity of structures to provide system functions.
- **Assessment of barriers and drivers of upscaling innovations (Key Factor 4)**: This aspect is particularly relevant in phase 4 in which future effects and potential pathways are interrogated, as well as phase 5 in which experiments are implemented.
- **Using the multi-level perspective for system analysis (Key Factor 5):** This aspect is mainly relevant for an integrated analysis of the system in phase 1.
- **Analyze institutional change from a more goal oriented perspective (Key Factor 6):** This aspect is mainly related to visioning and goal formulation in phase 3.

3 Application of participatory tools and methods in transition governance processes

This section describes the results of a literature review that aimed at the identification and assessment of specific participatory modeling methods and related tools and frameworks that are potentially applicable in transition governance processes. Due to the involvement of multiple stakeholders, we particularly focus on modeling methods and tools that can serve as boundary objects (cf. Black 2013). Boundary objects have the following characteristics (Carlile 1997, 2002, cited in Black 2013): “they are “concrete”; they represent dependencies among actors; and they are transformable by all actors”. The HarmoniCOP project defines four general principles of successful participation processes (i.e., openness, protection of core values, speed and substance), which have implications for participatory methods and tools (HarmoniCOP, 2005). The principle of openness requires that the process content and outcomes are not predefined but can be influenced by participating stakeholders. Thus, all information and decisions should be made transparent, which also include the choice for methods and tools that are applied in the process. This also means that methods and tools are comprehensible for lay people. Another principle requires that the core values of stakeholders are acknowledged and protected. Thus, methods and tools should not only build upon scientific knowledge, but also incorporate alternative knowledge systems, such as local knowledge. The principle of speed requires continuous progress and momentum. For methods and tools this means that their application can be accomplished in a reasonable amount of time and support collaboration between stakeholders. The principle of substance requires that strategies and agreements are technically feasible and realistic. Thus, methods and tools should support the integration of knowledge to shed light on various aspects that could constrain the applicability of strategies. The application of methods and tools themselves need to be realistic too, which means that only a moderate amount of resources (e.g., finances or expertise) is required.

3.1 Assessment of participatory methods and tools for each process phase

In the following, participatory modeling methods and tools are described for each process phase that applies to these characteristics and principles mentioned above. A detailed assessment of methods is beyond of the scope of this paper. Thus, we only mention some particular characteristics of methods that constrain and promote their application in transition governance processes. Most of the presented methods and tools have been originally developed in other research fields (e.g., operational research or resource management). However, we also provide references to transition studies that applied these methods and tools, if available.

3.1.1 Phase 1: Integrated knowledge production for problem definition

Facilitated problem structuring methods are mainly qualitative modeling methods that deal with the challenge of multiple plausible problem perspectives held by stakeholders. Conceptual modeling is particularly appropriate approach to develop a common holistic understanding of a problem situation, and thus supports communication and learning between modelers, decision makers and other stakeholders (cf., Liu et al., 2008). Various methods are available to develop conceptual models. Systems thinking is a method for the qualitative analysis of systems (i.e., Causal Loop Diagrams) that visualize multi-causal relationships and feedback processes (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 1999). In this process, participants explain the concepts and rationales underlying variables, which reduces linguistic uncertainty (Brugnach et al., 2008) and supports the development of a shared problem understanding.

Cognitive mapping is another approach for problem analysis that has been developed in operational research (Eden 1988; Ackerman and Eden, 2010) and can be defined as “a model of action-oriented thinking about a situation” (Eden, 1994, p. 265). While the systems thinking approach analyzes causality between variables, cognitive mapping aims more at the representation of a belief system and its linkage to values (Eden, 1994). Cognitive mapping is a more flexible method than causal diagrams as it does not necessarily differentiate between causality and events (Hall et al, 1994).

Participatory mapping methods focus more 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). Such conceptual modeling and mapping methods can also be combined by a diagnostic scoring procedure. Stakeholders can prioritize the importance of different aspects of a problem by using simple voting techniques (cf., Sheil and Liswanti, 2006).

Conceptual modeling is already applied by some transition scholars. Videra et al. (2014) applies conceptual modeling in a participatory process of 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. Auvinen et al. (2015) also use causal loop diagrams to analyze important feedback processes between conventional and innovative transportation systems. Halbe et al. (2015b) applies causal loop diagrams and the concept of Viability Loops (Hjorth and Bagheri 2005) to link innovations as part of a solution strategy to a particular problem perspective (cf. Key Factor 1 in section 2.5). Sustainability innovations for water, energy and food supply are analyzed by conducting a participatory modeling process with implementers of these innovations. Another approach that provides a focus on innovations in problem analysis (cf. Key Factor 1) includes the definition and analysis of functions in technological innovation systems (Bergek et al., 2008). The methodological framework allows for a case-specific analysis of barriers and drivers of vital functions in innovation systems that can also be conducted in a participatory setting (Breukers at el., 2014).

The second key factor (cf. Key Factor 5 in section 2.5) implies the application of the multi-level perspective for system analysis. Auvinen et al. (2015) go in this direction by using the multi-level perspective (Geels, 2004) to analyze the existing transportation system of the Helsinki metropolitan area in Finland and potential transition pathways towards an emission-free transport system. The authors consider the multi-level perspective can be a suitable tool to support stakeholder processes in understanding transition processes, due to its intuitive nature.

3.1.2 Phase 2: Stakeholder analysis and selection

Various methods and approaches for stakeholder analysis exist that can be differentiated between methods for (1) identifying stakeholders, (2) differentiating between and categorising stakeholders, and (3) investigating relationships between stakeholders (Reed et al., 2009). A brainstorming process can be a good starting point to develop an initial list of stakeholders based upon a literature review, interviews, or focus group discussions (Inam et al., 2014; Prell et al., 2011). Subsequently, these stakeholders can be asked to identify further stakeholders (cf. Brugha and Varvasovszky, 2000). Stakeholders can be categorized by assigning roles, such as decision-makers, users, experts or implementers (European Commission, 2003). A prioritization of stakeholders can be conducted by assessing their interest, power, legitimacy, and urgency linked to a particular problem situation (Mitchell et al., 1997).

Social network analysis is a widely used approach for the empirical investigation of relations between actors (Scott, 2013) (Key Factor 2). Participation of all stakeholders is usually not manageable in processes that deal with broad societal issues (Loorbach 2007). For instance, Prell et al. (2011) describe the challenge of selecting stakeholders for a site visit. One the one hand, a small group was preferred to allow for effective deliberation processes in a more intimate atmosphere. On the other hand, findings from the process should be communicated broadly to achieve societal impact. Social network analysis can analyze several network aspects, such as the strength of ties between stakeholders, to guide the selection process (cf. Prell et al., 2009). 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 in case that they have a broker role between different networks, and thus, might include new ideas and a more holistic view (Prell et al., 2009). While various flexible and tested methods for stakeholder identification and analysis exist, the study of relational aspects can be challenging due to the huge data requirements and mathematical formalization (cf. Scott 2012). Prell et al. (2011) observe a high appreciation for the role of social networks in social learning and adaptive management processes, but a lack of formal methods that allow for the practical implementation of social network analyses. In particular, iterative methods are required for transition governance processes that start with simple methods and tools, and are expandable towards more detailed analysis, if this turns out to be necessary for the process. A pragmatic approach can be to limit the number of actors in an initial social network analysis to well-known stakeholders or stakeholders representing different categories (Prell et al., 2011). Even such an initial social network analysis can provide a preliminary picture on relational issues, provide input in subsequent stakeholder discussions and provide a basis for more detailed analyses (Prell et al., 2011). Net-Map is another low-tech, low-cost, interview-based mapping tool that allows qualitative and quantitative analysis of social networks (Schiffer and Hauck, 2010). 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. First, actors are defined and their linkages are drawn. In a next step, influence towers are built that represent the influence of an actor with respect to the issue at stake. The goals of actors are subsequently defined. The resulting network can be analyzed using graph-theoretical indices, such as centrality or density (Schiffer and Hauck, 2010).

Social network analysis is very relevant for transition governance processes, as this method allows for a purposeful selection of participants. The consideration of information flows and influence structures is also related to process phase 5 (Coordinate the implementation of experimental actions of multiple actors). Social network analysis can specify which stakeholders should be included in the process in order to coordinate their actions through a unifying goal or vision. In particular, innovators in different sectors could be identified so that the process could initiate broad societal change by supporting various socio-technical innovations (cf. Key Factor 1). Participatory network analysis, by using the Net-Map tool for instance, could allow for the exploration of barriers and drivers of transitions from a network perspective. The important role of networks is highlighted by several transition scholars (e.g., Cohen et al., 2012), but the current application of social network analysis is limited. Binz et al. (2014) use social network analysis to analyze the spatial dimension of technological innovation systems.

3.1.3 Phase 3: Participatory visioning and goal formulation

A sustainability vision can be defined as “a shared vision that is both desirable to the vast majority of humanity and ecologically sustainable” Costanza (2000). Thus, sustainability 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. Visions can include a combination of socio-technical innovations (cf. Key Factor 1 and 6) or alternative system designs that fulfill societal functions (cf. Key Factor 3).

There are different approaches for the development of joint future visions in the scope of collaborative processes. Wiek and Iwaniec (2014) describe visions (desirable future states) as a subgroup of scenarios (possible future states) clearly different to predictions (likely future state). Vision modeling can visualize visions, ensure that the vision conforms to social, ecological and economic sustainability criteria, and assess trade-offs and plausibility of visions (Wiek and Iwaniec, 2014). Methods for developing joint visions can be sorted into four groups, which can be combined in participatory visioning processes. First, visions of desirable future system states can be created through the use of *non-technical methods* that tap into the creative potential of participants, such as written vision statements (e.g., National Civic League, 2000; Kallis et al., 2009; Auvinen et al., 2015), collages (e.g., Kok et al., 2006), or even role plays (e.g., Oels, 2002). In addition, 3D computer-generated visualizations can be prepared by researchers to visualize visions (Robinson et al., 2011).

Second, future visions can be developed in a more guided process supported by *conceptual frameworks* or *reference scenarios* (cf. Elle 1992). Such frameworks and reference scenarios assure that visions cover specific elements (e.g., different sectors or locations) and include key concepts. Thereby, participants are guided through the visioning process, which can imply some potential advantages, such as more structuration and comparability, as well as disadvantages, such as constrained creativity and less ownership. Auvinen et al. (2015) propose the application of the multi-level perspective (Geels 2004) to guide the analysis visions and vision paths. Thus, the multi-level perspective can structure participatory processes and the application of multiple tools that target on different aspects of transitions. The definition of functions in technological innovation systems and related blocking mechanisms by Bergek et al. (2008) can also function as a framework to support the setting of goals and sustainability visions in stakeholder processes (Breukers et al., 2014) .

Third, *qualitative modeling approaches* can be applied to achieve a more systematic vision (e.g., Iwaniec et al., 2014). These methods share similar benefits and constraints as conceptual frameworks. Qualitative modeling approaches are still accessible for lay stakeholders due to their qualitative nature, but still require willingness to getting involved with a method that is likely to be unknown. For instance, conceptual modeling can be used for envisioning of innovative system designs (Halbe et al., 2014), to analyze barriers and drivers of innovations (Halbe et al., 2015b) or institutional structures, such as alternative paradigms (Halbe et al., 2013).

Fourth, *quantitative modeling approaches* can be applied to develop visions that are systematic and testable in quantitative terms. Due to the complexity of visions, it becomes difficult to include all different aspects into a single quantitative model. With respect to sustainability issues, Liu et al. (2008) points out that "neither achievable nor desirable to aim for a single computational "super-model" that attempts to represent a consolidated view of all available knowledge". Thus, models can be designed that include the overall structure of visions in a more abstract way. In this respect, system dynamics modeling can be a useful approach to embracing different elements of a vision (Iwaniec et al., 2014). Another opportunity is the separate application of multiple, more detailed models 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 (multi-criteria assessment).

There is currently a low number of studies that use participatory modeling in stakeholder process to develop and analyze sustainability visions (e.g., Trutnevyte et al., 2011, 2012). In addition, we see a high potential of key transition frameworks, such as the multi-level perspective and functional analysis, to be used in goal-setting and the development of sustainability visions (cf. Breukers et al., 2014; Auvinen et al., 2015). The participatory development of visions usually also requires non-technical methods to tap into the creative potential of stakeholders. Modeling approaches can be applied subsequently to conduct a more detailed analysis of visions, test their plausibility and assess outcomes.

3.1.4 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 towards its implementation. Scenarios are a suitable approach to analyze and design implementation processes that comprise several intermediate steps towards a long-term vision. Various uncertainties need to be addressed that can influence the chosen transition pathway towards the sustainability vision. Exploratory scenarios (also called forecasting scenarios) start from the current condition and describe different plausible futures depending upon uncertain processes and events (cf. MA, 2005). Anticipatory scenarios (also called backcasting) are more normative by starting with a desired or feared vision in order to define effective policies (cf. Mahmoud et al., 2006). Backcasting starts with the detailed description of the desired system state as well as intermediate system states that connect the current condition with the desired one (Robinson, 1990). The combination of exploratory and anticipatory scenarios can be a fruitful approach to facilitate stakeholder processes with methods that urge different thinking styles and identify robust policies from the application of different methods (Kok et al., 2011).

In particular, backcasting approaches are suitable to analyze pathways for implementing a sustainability vision in transition governance processes. Similar to visioning processes, anticipatory scenarios can be designed by using non-technical approaches, conceptual frameworks or reference scenarios, as well as qualitative and quantitative modeling methods. These different types of methods can be combined to make use of their particular advantages (cf. Alcamo, 2008; van Vliet et al., 2010). Narrative scenarios are an example for a non-technical approach where stakeholders develop narratives of possible transition pathways (e.g., Vergragt and Brown, 2007). The SCENES project applied GEO-4 scenarios (UNEP, 2007) as a sort of reference scenarios to speed up the participatory process. Stakeholders were explained that the general assumptions of scenarios should be coherent to the reference scenario, while the text, key arguments, and triggering events of narrative scenarios should differ (Kok et al., 2011). Auvinen et al. (2015) combine qualitative modeling (i.e., causal loop diagrams) with the use of a conceptual transition framework (i.e., 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.

Fuzzy cognitive mapping is a semi-quantitative approach 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). Quantitative models can also be built by stakeholders themselves, for instance by using a group model building approach (Vennix, 1996; van den Belt, 2004; Videira et al., 2010). Stakeholder participation in quantitative modeling aims at facilitating social learning processes and commitment to model results. However, the modeling process is usually a time-intensive process that requires advanced facilitation and modeling skills. Another option is the use of user-friendly interfaces that allow stakeholders to run simulation models in order to explore the effectiveness of policies. QUEST is such a modeling tool for regional sustainability scenarios applying a backcasting approach (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 (i.e., degree of social adaptation, technological innovation, and ecological resilience). 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). Multi-criteria analysis methods are also relevant for guiding the decision process towards a concrete set of actions that minimize trade-offs and maximize sustainability benefits. Multi-criteria analysis usually starts with the definition of goals, criteria and alternatives for action (Wang et al., 2009).

The role of socio-technical innovations in transition processes (Key Factors 1 and 4) is usually considered by scenario approaches. In particular, backcasting aims at the detection of innovative policies or technologies. However, Wangel (2011) criticizes a focus on physical/technical aspects in backcasting studies and a lacking consideration of social aspects and change agents. Halbe et al. (2015b) present a qualitative modeling approach that helps to analyse the various responsibilities of actors in sustainability transitions. Causal loop diagrams are used to define actor-specific learning requirements to support a broader implementation of innovations. Gaziulusoy et al. (2013) also detects that current scenario studies usually apply a macro-level perspective, and do not specify what this means for actors operating at the micro-level, such as companies. They present a scenario method to analyze innovation pathways in companies using qualitative modeling approach (i.e., event trees).

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

Due to the complexity of sustainability transitions, the implementation of measures and strategies has to be understood as experiments that have to be continuously monitored and assessed (see section 3.1.6). The frameworks of transition management and strategic niche management include a focus on coordinating multiple experiments. Strategic niche management research has resulted in various insights on the role of expectations, networks and learning processes in the facilitation of sustainability innovations (Schot and Geels, 2008). However, this research focused rather on ex-post evaluation of case studies than providing prescriptive advice for ongoing processes (Schot and Geels, 2008). Raven et al. (2010) point to the relevance of transition experiments and a lack of practical tools for their implementation in both the systemic niche management as well as transition management frameworks. Transition experiments can be described as “an innovation project with a societal challenge as a starting point for learning aimed at contributing to a transition” (van den Bosch, 2010, p. 58). Van den Bosch (2010) identifies three mechanisms that define how transition experiments can contribute to sustainability transitions. First, transition experiments can *deepen* the understanding of actors about the experiments and its context (e.g., values or practices). Second, experiments can *broaden* the area of influence by repeating the transition experiment in different contexts or linking it to other functions or domains. Third, the *scaling –up* mechanism leads to a gradual establishment of a new structure, culture or practices in the regime (depending on the particular focus of the experiment) (cf. Key Factor 4 in section 2.5). These mechanisms can be used as a prescriptive approach that guides the design and assessment of experiments. In addition, Weber et al (1999) provide various lessons from case study research that can help in the design of experiments. Raven et al. (2010) propose the development of a competence kit that present useful tools, skills and best practices to practitioners.

Due to the experimental character of the implementation process, adaptation of developed strategies in phase 4 might be required in the sense that another pathway is chosen or the current pathway is ameliorated to fit better to a new situation. Such an adaptation of pathways, which might have an impact on various actions, can be supported by a prior assessment of the conditions that might induce this shift. Assumption-Based Planning is a tool that is useful to assess the assumptions and uncertainties of an already developed plan (Dewar, 2002). First, the assumptions of a plan are analyzed and prioritized in order to define the most critical assumptions that might determine the plan’s success. Based upon this analysis, signposts, shaping actions or hedging actions are analyzed. *Signposts* are signs that warn against critical developments and signal the need for corrective action. *Shaping actions* aim at stabilizing the plan’s success by actively supporting the compliance to critical assumptions. *Hedging actions* try to prepare for a possible failure of assumptions, for instance by actively maintaining alternative options. Dewar (2002) proposes various qualitative and quantitative techniques for the different steps of Assumption-Based Planning. Adaptive Policymaking another approaches that is conceptually building upon Assumption-Based Planning (Haasnoot et al., 2013) and aims at the pro-active seizing of opportunities and handling of external forces (Kwakkel et al., 2010). Besides shaping and hedging actions, Adaptive Policymaking also involves *mitigation actions* (i.e., actions that reduce the adverse side-effects of a plan) and *seizing actions* (i.e., actions that increase available opportunities). Triggers are identified, which are critical values of signpost variables, that can lead to four action types, namely defensive actions (i.e., actions that support the implementation of the original plan), corrective actions (i.e., adjusting the plan), capitalizing actions (i.e., stick to the original plan but exploit unfolding opportunities) and a reassessment of the plan (i.e., in case that critical assumptions of the plan are no longer existing) (Kwakkel et al., 2010).

Besides the definition of critical assumptions and signposts to address uncertainties in the implementation process, methods and tools are needed to coordinate actions of various actors. Scenarios and multi-criteria assessment methods from phase 4 can help in the selection of different sets of measures to implement a sustainability vision. However, methods are needed in the actual implementation phase to proceed from integrated analysis in phase 4 towards more detailed implementation plans in phase 5. Project management tools are widely used by organizations to deal with complex problems that involve various actors in order to achieve accountability, transparency, risk management, and consistency, among other goals (cf., Crawford and Helm, 2009). Project management tools, such as Gantt charts, are hardly transferrable to transition governance processes which imply a higher degree of unstructuredness and ambiguity due to the lack of a unifying organization. Detailed planning tools for transition governance processes are in an early phase of their development. Frameworks are needed that help to depict key elements of transition governance processes, including events, responsibilities and expected outcomes. A useful tool is the Management and Transition Framework (MTF), which is a conceptual and methodological framework that allows for the 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 process-related representation of transition processes. The static representation defines important elements of transition processes, including ecosystems, 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 reconstruction the sequence of action situations that are connected by institutions, knowledge and operational 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). Another analytical-evaluative framework is presented by Forrest and Wieck (2014) that allows for the structured analysis and evaluation of community transition processes. The framework 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, 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 planning of transition governance processes.

3.1.6 Phase 6: Systematic monitoring and assessment of actions

Systematic monitoring and assessment requires a clear understanding of the process, aspired outcomes (i.e., goals) and responsibilities. The frameworks mentioned above in section 3.1.5 can support a clear planning, evaluation and assessment of the process. The selection of suitable indicators for process monitoring can be guided by the goals defined in phase 2 or the definition of success barriers and critical assumptions as proposed in phase 5 (cf. Dewar, 2002 and Kwakkel et al., 2010). However, process goals set in phase 2 and success barriers defined in phase 5 might be too unspecific for practical process monitoring and assessment. For instance, process goals could be related to long-term processes, such as the recovery of the local economy or mitigating climate change. Thus, approaches are needed that support combining process-specific, and potentially impractical indicators with more systematic approaches for indicator selection. Reed et al. (2006) provide an overview of expert-based and participatory approaches for indicator development, 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. Bossel (2001) represents an expert approach for the definition of comprehensive indicators even though he also stresses the importance of stakeholder participation to draw upon diverse knowledge sources. Bossel’s (2001) approach take into account interactions between different system components and their viability and performance with respect of providing functions to the overall system. Four steps are proposed to detect appropriate indicators: First, a conceptual understanding of the system is required, which can be achieved through conceptual modeling approaches as described in section 3.1.1. Second, representative indicators need to be identified that are fundamental for the viability of subsystems and the overall system. Third, the performance of indicators needs to be assessed in qualitative or quantitative terms by defining specific viability and performance measures. Fourth, indicator development should be embedded in a participatory process to draw upon several knowledge sources. Bossel (2001) 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. In addition, three essential component systems are proposed comprising the human, support and natural systems. Reed et al. (2006) propose an adaptive learning process to combine expert-based and stakeholder-based indicators, which partly resembles to transition governance phases, as described in section 2.4. The process starts with a selection of system boundaries and stakeholders as well as a problem analysis. Next goals, visions and strategies are explored. Several tools can support the subsequent selection of indicators, such as multi-criteria decision analysis or different modeling techniques. Thresholds, baselines or targets need to be identified. Reed et al. (2006) point to the difficulty to define thresholds in a specific regional context, so that baselines and targets are more common in participation processes (citing Bell and Morse, 2004). In the last step of the framework, data is collected, analysed and compared to sustainability goals, which might require an adjustment of strategies (Reed et al., 2006).

Modeling methods and tools can also play a significant role in the monitoring and assessment of actions. As specified in the approach by Reed et al. (2006), models can be used for drawing scenarios and analyzing 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. A modeling approach can also support learning about complex systems, as they require the specification of a model structure and a detailed analysis of expected consequences of policies based upon current mental models (Sterman, 2000). The comparison of model results to empirical data can verify the mental models held by model builders in case that decisions have the same effect as suggested by the modeling study. Differences between expected and experienced results however should initiate a rethinking of mental models held about the respective problem situation. Thus, group model building processes can guide the evaluation and assessment of strategies and support collective learning (cf. Vennix, 1996; van den Belt, 2004).

4 Discussion

This paper does not claim comprehensiveness with respect to the presented methods, tools and frameworks. The aim of the paper is more to contribute to the discussion on participatory modeling approaches and their applicability the governance of sustainability transitions. Participatory methods and tools are promising approaches to achieve a more widespread application of transition governance frameworks. This requires that interested practitioners without in-depth knowledge of complex systems and transition theories are able to apply these methods (cf., Raven et al., 2010). Furthermore, methods and tools should only require limited resources and be flexible in order to allow their application even without the funding and expertise from research projects.

The review of transition governance framework shows considerable overlaps and synergies, which can be interpreted as a sign for conceptual convergence and robustness. It seems to be clear which steps are required to actively facilitate sustainability transitions. However, the frameworks do not provide clear information about which methods and tools are required for practical implementation. The six process phases identified in section 2.4 nevertheless turned out to be useful for structuring out review. We were able to detect a diverse set of approaches to fulfill the different objectives of processes phases. Some of the methods have a long legacy of application in other research fields (e.g., conceptual modeling), others turned out to be more recent and tailored to the sustainability transitions field (e.g., use of functions in technological innovation systems as tools for participatory goal setting). The key factors pointing to synergies between adaptive management and transition management provided further guidance in the selection of innovative approaches.

The review of methods and tools shows that various participatory modeling methods and tools are already applied in a transition research context. However, the number of publications is quite low and point to a high potential for future research. Our analysis identified some particularly interesting approaches:

- Social network analysis shows a high potential for the purposeful selection of stakeholders in transition governance processes. We presented some pragmatic analytical approaches that can even be applied with limited resources and time requirements. Participatory social network analysis (e.g., Net-Map) can even be used as a social learning tool and only requires basic equipment.
- We found promising examples that applied conceptual transition frameworks, such as the multi-level perspective or functions in technological innovation systems, in participatory processes. Such frameworks can reduce the complexity of transition processes and provide guidance of stakeholders in analyzing their current situation and define suitable actions.
- Methods and tools for implementation planning 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 considerable future research.

There are various further experiences from other research areas that are relevant for participatory transition modeling, such as general skills that are needed for process facilitation. Vennix (1996) list a number of skills for participatory modeling, including conflict handling, process structuration, team-building, and intervention skills. Franco and Montibeller (2010) add active listening, chart-writing, managing group dynamics and power shift, and reaching closure. Franco and Montibeller (2010) also highlight the fact that different skills are required in different phases. In problem structuring, the facilitator needs to cope well with ambiguity, multiple perspectives and qualitative data, whereas in option evaluation synthesizing skills and handling of quantitative data are required.

Future research should evaluate methods and tools along various dimensions (e.g., required expertise, financial and time requirements, etc.) to assess their applicability in transition governance processes. In addition, research is needed that test participatory approaches in various transition governance contexts, such as grassroots initiatives, transdisciplinary research projects or policy advice (cf. Holtz et al., 2015). Thereby, participatory methods and tools can play a central role in widening the application of transition governance frameworks in practice.

5. Conclusions

This article identified various participatory modeling methods and tools that are highly relevant for transition governance research and practice. Participatory methods permit the analysis of stakeholder perceptions, values and interests and their role in sustainability transitions. Participatory methods and tools also support the pro-active facilitation of transition processes, and allow for a broader application of transition governance frameworks by practitioners. In particular, we found participatory social network analysis as a promising approach to purposefully select stakeholders. This approach can also be used as a learning tool to explore the role of social networks in sustainability transitions. We detected two conceptual frameworks (the Management and Transition Framework developed by Pahl-Wostl et al. (2010), and the analytical-evaluative framework by Forrest and Wieck (2014)) that can be potentially used as a planning tool for organizing stakeholder processes and intervention strategies. Transition research can also contribute to the portfolio of participatory methods by applying conceptual transition frameworks, such as the multi-level perspective, as a participatory tool for problem structuring and development of intervention strategies.

Transition governance frameworks, including reflexive governance, adaptive management and transition management, turned out to be helpful to structure the review of participatory methods and tools. Six process phases were identified that could also be used as a guiding framework for an effective application of various methods and tools in participatory processes: 1) Integrated knowledge production for problem definition, 2) Stakeholder analysis and selection, 3) Participatory visioning and goal formulation, 4) Interactive strategy development that anticipates long-term systemic effects, 5) Coordinate the implementation of experimental actions of multiple actors, and 6) Systematic monitoring and assessment of actions. In addition, several key factors were identified that point to specific contributions of transition research to the literature on stakeholder engagement, such as a focus on innovations.

This paper is intended to contribute to the discussion about participatory methods and tools for understanding and facilitating sustainability transitions as well as for allowing wider application of transition governance frameworks in practice. We think that a comprehensive and more detailed assessment of participatory methods and tools for transition governance requires a broad community effort in the future.

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