Chapter 3
A Research Method for Integrative Transition Simulation

Silvia Ulli-Beer, Stefan Groesser, and Ruth Kaufmann-Hayoz

> *We seem to have been living for a long time on the assumption that we can safely deal with parts, leaving the whole to take care of itself. But now the news from everywhere is that we have to begin gathering up the scattered pieces, figuring out where they belong, and putting them back together. For the parts can be reconciled to one another only within the pattern of the whole thing to which they belong.*
> *Wendell Berry*

Abstract System dynamics (SD) simulation supports the identification of interacting feedback processes guiding system behavior in social systems; but its contribution to theorizing on multi-level alignment processes of socio-technical transition is unclear. Our purpose is to clarify the benefits and limitations of an SD-based research strategy for theorizing on sustainability transitions. First, we explicate why and how the linkage of SD simulation with the multi-level perspective (MLP) helps to overcome some limitations of narrative approaches. Second, we offer for such integrative transition simulation (ITS) journeys a tailored method that provides methodical guidance. We found that the structural analysis methods and tools offer the unique value proposition of ITS. They help to explicate dominating causal circularities of multi-level alignment processes and to test the behavioral consequences. We illustrate how this approach has supported the development of a process theory about iterating cycling through sequences of innovation, diffusion, and standardization in energy-efficient (ee) housing. We conclude that the method supports cross-case comparison and generalization of single findings.

S. Ulli-Beer (✉)
General Energy Dynamics of Innovative Systems, Paul Scherrer Institute, PSI Ost, 5232 Villigen, Switzerland
e-mail: silvia.ulli-beer@bluewin.ch

S. Groesser
General Energy Dynamics of Innovative Systems, Paul Scherrer Institute, PSI Ost, 5232 Villigen, Switzerland

Institute of Management (IfB), University of St. Gallen, Dufourstrasse 40a, 9000 St. Gallen, Switzerland

R. Kaufmann-Hayoz
Interdisciplinary Centre for General Ecology (IKAÖ), University of Bern, Schanzeneckstr.1, 3001 Bern, Switzerland

S. Ulli-Beer (ed.), *Dynamic Governance of Energy Technology Change*,
Sustainability and Innovation, DOI 10.1007/978-3-642-39753-0_3,

In addition, we suggest that ITS may enhance discussion on circular causalities and sequences in sustainability transitions; this kind of knowledge is important for the coordination and timing of policy and strategy making in sustainability transitions.

Contents

3.1 Introduction 50
3.2 Benefits and Challenges of Combining the MLP Heuristic with SD Simulation 52
3.2.1 MLP Approaches: Strengths and Limitations 52
3.2.2 SD-Simulation Studies: Strengths and Limitations 54
3.2.3 Benefits and Challenges of the ITS Approach 57
3.3 The Research Method 57
3.3.1 Problem Specification 59
3.3.2 Dynamic Hypothesizing 60
3.3.3 Operationalizing, Model Testing 61
3.3.4 Model Analysis 62
3.3.5 Experimenting with Policy and Strategy Levers 63
3.4 An Illustrative Case of Integrative Transition Simulation of Energy-Efficient Housing 63
3.4.1 The Project Road Map 64
3.4.2 Explication of the Research Steps 65
3.5 Discussion 74
3.6 Conclusions 76
References 77

3.1 Introduction

Innovation researchers have found the system perspective useful to study the structure and performance of innovation systems and technology change (Fagerberg 2009). Eventually, different perspectives with a broader problem focus have been developed that include the use of technologies and its institutional context (Coenen and Díaz López 2010; Smith et al. 2010). The *multi-level perspective* (MLP) is one of the most discussed analytical frameworks for studying sustainability transitions of so-called socio-technical systems (Geels 2002; Geels et al. 2008). However, criticism of this approach concerns the lack of a unifying systematic in conducting case studies and the operationalization of the MLP (Genus and Coles 2008; Smith et al. 2010).

In parallel to this narrative conceptual approach, the field of *system dynamics* (SD) has developed in the last five decades. This scholarship provides a methodology on how to systematically reduce empirical complexity of social systems in order to build simulation models (Forrester 1961; Sterman 2000). SD modeling is based on the assumption that system behavior arises endogenously from information feedback loops (Richardson 1991). Therefore, SD theory has been acknowledged as a research field that offers a method for "helping to understand the dynamic behavior of complex systems" (Davis et al. 2007; Aghion et al. 2009: 691). This provides a promise that an SD-based research strategy for conducting case studies on socio-technical transitions may improve the operationalization of multi-level alignment processes, on the one hand. On the other hand, best practice guidelines on how to implement an SD-based research strategy may provide a unifying systematic in the form of a method of analysis. Such a method would be of particular importance, because it facilitates cross-case comparison and the accumulation of knowledge. However, a constructive dialogue on the contribution of SD is mainly missing in the innovation systems literature. In order to clarify the scope and nature of the postulated potential, this paper addresses the questions: Does SD modeling help to substantiate theorizing on sustainability transitions? Why has SD modeling a large potential? What is the potential? How then should the research process be designed?

The contribution of this study is twofold. First, we explicate the strengths and limitations of an SD-based research strategy. We are not referring to an approach of deductively operationalizing a simple theory (Davis et al. 2007). We refer to a case study approach on socio-technical transitions that apply SD methodology for theory enhancement and policy analysis. It applies *constant comparing of data and fragmented knowledge* acquired from different perspectives, and includes ongoing mapping of insights in a simulation framework. Simulation is used to test Popperian statements on system structure behavior assumptions. We term this approach *integrative transition simulation* (ITS). In general, the case study approach is acknowledged as “a research strategy which focuses on understanding the dynamics present with single settings” (Eisenhardt 1989: 534). In particular, ITS focuses on two kind of dynamics: (1) processes in the sense of circular causalities, and (2) system behavior change over time, i.e., transition from one system state to another over a specific time horizon.

Our second contribution is to offer guidelines on how such a research strategy should be implemented. We introduce a *method* that helps to organize and manage the complex research task of ITS. The method builds on extant guidelines for simulation and theory building (Strauss and Corbin 1998; Poole et al. 2000; Sterman 2000; Davis et al. 2007), and our own research experience. It elaborates on the specific requirements of simulation-based theory building about socio-technical transitions. Due to multiple involved levels and perspectives in these contexts, there exists no single clear problem perception and single simple theory that allows identifying an intriguing research question guiding theory development. The problem situation is messy and the extant knowledge is diverse and fragmented. Therefore, deliberate research techniques are necessary to account for internal and external validity in the analysis of processes that drive or hinder sustainability transitions. The ITS method provides the basis for a systematic and effective approach that specifically considers these aspects. It also clarifies the logic of important research steps and decisions in the course of the research process. For illustrative purposes on how the suggested method can be implemented, we draw on a simulation study that addresses the socio-technical transition toward *energy efficient* (ee) housing in Switzerland.

The paper is organized as follows. Section 3.2 summarizes separately the strengths and limitations of the narrative MLP approach and SD. We explicate the unique value proposition from applying SD for theory building about multi-level alignment processes in sustainability transitions (i.e., what we term ITS). Section 3.3 develops a method that answers the questions of how such a socio-technical transition simulation task should be organized and conducted. In Sect. 3.4, the practicability of the developed method will be demonstrated with an ITS study on the socio-technical transition toward ee housing in Switzerland. The benefits and limitations of ITS are discussed in Sect. 3.5. Section 3.6 summarizes the overall argument and insights of the paper and concludes with suggestions on further research.

3.2 Benefits and Challenges of Combining the MLP Heuristic with SD Simulation

The argument we are addressing is that simulation-based case studies on sustainability transitions help to substantiate theory building on multi-level alignment processes. It is based on the assumption that SD simulation promises to be most useful to enhance our understanding of dynamic complexity and to derive causal theories of social systems behavior (Pool 1992; Sterman 2007; Schwaninger and Groesser 2008). In this subsection, we explicate the scope and nature of the promise and address the questions: Why has a SD-based case study approach a large potential? What is the potential? Based on a review of the innovation systems literature, we elaborate the strengths and limitations of the MLP and SD and derive implications about likely benefits and challenges of a tailored ITS approach.

3.2.1 MLP Approaches: Strengths and Limitations

The MLP offers a helpful heuristic in the form of analytic concepts, which point to typical alignment processes at the niche, regime, and landscape levels of socio-technical transitions (Smith et al. 2010). It defines what basic subsystems and elements should be considered of a socio-technical system, including actor groups and organizations with their decision rules (institutions) of both the production side and application domain (Geels 2004). The MLP seeks to avoid an oversimplification that often comes along with one-directional and dimensional causality concepts in transitions: *"There is no simple 'cause' or driver. Instead, there are processes at multiple dimensions and levels simultaneously. Transitions come about when these processes link up and reinforce each other ('circular causality')"* (Geels 2005b: 453). In the last decade, research concerning the MLP has made strong progress in consistently conceptualizing a framework as narrative explanations grounded in case studies and interdisciplinary theories (Geels 2010). Different case studies have supported the development of a typology of transition pathways (e.g., Geels 2002; Belz 2004; Geels 2005a, b; 2006a, b; Vleuten and Raven 2006; Geels and Schot 2007; Raven 2007). Most recent studies demonstrate how the MLP can be enriched by complementary theories to analyze adjustment dynamics of transitions (Markard and Truffer 2008; Nill and Kemp 2009; Elzen et al. 2011).

Although the leading authors of the MLP do not provide a specific method of analysis, they provide hints about how the analytical concepts have been developed or how they can be substantiated. Typically, they apply a deductive theory building approach stemming from sociological dynamics and evolutionary economics, and use historical case studies to illustrate their conceptual contributions (e.g., Geels 2006a). Geels (2002) relates the approach to Nelson and Winter's (1982) notion of "appreciative theory." It is described as a tool that provides a broad theoretical structure for a phenomenon and helps to organize case analysis. In later work, Geels categorizes the resulting findings of this approach as a narrative explanation. This is distinct to storytelling or empiricism because it intends to develop an integrated story (e.g., Geels 2005a, b), and to explain patterns and pathways that are the result of interactions. Therefore, Geels and Schot (2007) see the conceptual status of the MLP as a "process theory." This theory type has been elaborated independently from the MLP (Pettigrew 1997; Poole et al. 2000; Abbott 2001) and explains outcomes as the result of temporal sequences of events (i.e., phases), and timing (i.e., in which phases and which activities are crucial). Geels (2006a) argues that the specific narrative MLP approach helps to reduce historical complexity. The different levels can be used as analytical and heuristic concepts to understand the dynamical complexity of socio-technical change (Geels 2002).

Besides the growing acknowledgment of the benefits of the MLP approach from various researchers (Coenen and Díaz López 2010; van Bree et al. 2010; Kern 2012; Weber and Rohracher 2012), it has also been criticized for several limitations. These include the lack of an unifying practice of case study construction and analysis, and the lack of practice on how to justify important decision in the research process (Genus and Coles 2008). In addition, it is argued that methodologies for operationalizing MLP concepts are missing; subsequently dynamic effects of alignment processes cannot be substantiated (Carlsson et al. 2002; Berkhout et al. 2004; Bergek et al. 2008; Smith et al. 2010; Papachristos 2011). Voss et al. (2009) argue that MLP studies are suitable to only a limited extent to enhance reflexivity in governance[1] of socio-technical transition. A further observation about the MLP – yet not mention in literature – is that the performance and effectiveness of policy interventions cannot be systematically analyzed.

[1] In our paper we use the term 'governance' in a broader sense than is often used in political science. We refer with this term to decentralized and often self-organized steering of heterogeneous multi-actor systems. Subsequently, governance mechanisms refer to feedback loops that coordinate activities through socially constructed rules. In other words, governance describes the interplay of agents and rules in a system that produces the behavior of interest.

In summary, the MLP has attracted many researchers interested in improving the understanding of complex socio-technical change processes toward sustainability transitions. It provides a framework of ordering and simplifying the analysis of alignment processes of dominant practices between different regimes (markets, industries, technology, policy, science, culture) as a response to macro-level landscape changes and path-braking radical innovations. It provides a language that helps to elaborate a narrative account of the big picture of transitions (Smith et al. 2010). However, systematic reflections and guidelines on how to organize and conduct case study analysis are missing in this literature. Also, it has shortcomings concerning operationality and dynamical impact assessment.

3.2.2 SD-Simulation Studies: Strengths and Limitations

In parallel to this narrative conceptual approach on the analysis of socio-technical systems, the field of SD has independently developed over the last five decades (Sterman 2007). It does not offer any (grand) content theory, but rather a (grand) structural theory about how social system phenomena that are unfolding over time might be explained (Lane 2000). The scholarship provides a methodology on how to systematically reduce empirical complexity of social systems and how to build simulation models for a wide array of applications (Forrester 1961; Sterman 2000). It includes guidelines about good practice in using particular techniques for modeling dynamic systems (Mingers and Brocklesby 1997). Dynamic complexity is explained by information feedback loops that reflect a closed loop understanding of the world (Forrester 1968). Forrester (1968) describes the understanding of time-dependent adjustment processes as sequences of intertwined loops of *"perceived action pressure*$_{(t)}$ *– response – state adjustment – perceived action pressure*$_{(t+1)}$ *–. . ."*. With this understanding, actors are continually (re)acting to information about actors' past actions and system state adjustments (e.g., capacity levels, infrastructure states, standards, resource, or pollution levels). It means that system behavior arises endogenously from information feedback loops (i.e., circular causalities as perceived by heterogeneous actor-groups within the system). This understanding of causality applies to social phenomena that refer to invariant social patterns and rules that can be observed at an aggregated level and not at the level of individual decision making (Lane 2000). Lane (2000) argues that SD should not be described as a deterministic approach but rather a system approach that offers Popperian statements on system structure-behavior assumptions. He highlights that SD fits well with social theories, which integrate agency and structure by giving an account of the processes, which mutually shape them both. Today, SD is considered as a specific approach of systems thinking that has a particular philosophical perspective, termed *critical realism*. This perspective is characterized by the epistemological balance between objectivism and subjectivism and the integration of agency and structure (Mingers and White 2010).

SD-simulation frameworks have increasingly been used to conduct policy and scenario analyses addressing the impact of radical innovation pathways (Janssen et al. 2006; Weil 2007; Struben and Sterman 2008; Stepp et al. 2009; Ulli-Beer et al. 2009; Harich 2010; Park et al. 2011; Yücel and van Daalen 2011). Early on, SD-simulation has been discussed as a promising approach for theory building (Forrester 1961; Hanneman 1988). In the last decade, it has been increasingly applied for the development of process theories in management science (e.g., Black et al. 2004; Rudolph et al. 2009). Schwaninger and Groesser (2008) elaborate useful characteristics of the concept of model-based theory building. Those include improved operationality and refutability that comes along with explicit testable propositions translated in mathematical equations. Simulation facilitates the selection and falsification of hypotheses explaining system behavior. They deem the process design as crucial to the quality of the resulting theory. Other authors have explicated and enhanced participative modeling as a problem-structuring method (Andersen et al. 2007).

Papachristos (2011) illustrates how SD modeling can be used to formalize and test assumption about substitution pathways derived from narrative accounts of the MLP. He argues that this deductive model-based theorizing approach enhances the credibility of assumptions and assures the internal validity of the proposed explanation. These promising characteristics of simulation-based theorizing do not apply to SD models only – other modeling approaches also have great potential to make existing theorizing more precise (Davis et al. 2007; Safarzynska et al. 2012).

Davis et al. (2007) argues that simulation is most beneficial for theory development if nonlinearity, longitudinal behavior pattern and processes are involved or when empirical data are limited. This focus on theory development links simulation to process theory development. A process is defined as "a sequence of individual and collective events, actions, and activities unfolding over time in context" (Pettigrew 1997: 338). While these benefits may be inherent to every simulation study, the more specific strengths of an SD approach to study multiple interacting processes at different levels stem from the underlying structural theory and the related analysis method with its specific representation tool-sets:

1. *Identifying the reference variables:* The behaviors of interest of the socio-technical system can be specified by longitudinal reference variables (e.g., energy consumption of the housing system, number of houses perceived as energy efficient). They guide the specification of the model boundary. Trigger events or landscape pressure are included as exogenous variables, while the evolution of changes at the niche and regime levels are specified by endogenously changing variables. Variables that do not influence the behavior of interest are excluded.
2. *Mapping feedback loops:* SD offers a concise mapping syntax for highlighting feedback loops that control the rate of change of state variables. It allows postulating hypothesis on circular causalities that drive system change over time.
3. *Identifying feedback loop polarities:* SD goes beyond the identification of one-dimensional (positive or negative) causalities; it also differentiates two kinds of feedback loops: these can be either reinforcing (R), producing exponential change, or balancing (B), enacting goal-seeking behavior toward an

(implicit) system objective. In addition, the concept of feedback loop dominance is used to analyze and understand qualitative changes in system behavior. The behavior over time depends on which feedback loop is highly influential. As the system evolves, loop dominance often shifts due to nonlinearities. Ineffective loops may gain strength, causing bifurcation, exponential change, or transition to new (equilibrium) states (Richardson 1995).

4. *Refining a causal loop diagram toward a dynamic hypothesis:* Interacting processes of a real system are mapped by a causal loop diagram. A causal loop diagram synthesizes and displays the main stocks of a system and the interacting (reinforcing or balancing) feedback loops controlling them. It summarizes the dynamic hypotheses incorporated in the simulation model, which are the assumptions about the main real-world processes that explain the behavior of the reference variables.
5. *Simulation for policy and strategy analysis:* The conceptualization, operationalization, and formulation of the simulation model allow testing of different policy and strategy approaches. Most important, they provide insight concerning the social-political feasibility of socio-technical transition targets.

In the recent literature on innovation system studies, we have rarely found any new and specific critics on SD-based studies. We attribute this to the missing constructive dialogue. However, in the past, there was one debate addressing the limits to growth study (Meadows et al. 1973; Streatfeild 1973). In addition, there was a debate about (wrong) assumptions on determinism incorporated in SD-simulation (Lane 2000). We also found some more general criticisms on structural approaches or complex system approaches to study socio-technical transitions. Geels (2010) criticizes complex system approaches as weak in operationalizing actors and states that their value in social domain application still needs to be proven (Horgan 1995; Morel and Ramanujam 1999). Also, the references to causal interactions are characterized as abstract and metaphorical. Specifically, the structural determinism is perceived as unsuitable to address power struggle or sense making within social systems (Geels 2010). In addition, we have noticed that mainstream innovation scholars tend to show skepticism toward computerized model building in the social science. This may be partly explained by elements of "paradigm war" about perspectives and means of studying social systems (Aghion et al. 2009; Morlacchi and Martin 2009). Aghion et al. (2009) suggest that the objective of simulation should be "a simplified model or map with just enough detail to enable effective decisions to be made" (692). Often, simulation approaches are not well received, because they seem to be as complex as the real world, or because basic assumptions are not made transparent.

3.2.3 *Benefits and Challenges of the ITS Approach*

We conclude that the structural analysis method and tools of the SD scholarship form the decisive attributes, which provide the unique value proposition of ITS studies. These allow systematically explicating the causalities of core aspects of socio-technical transitions, such as multiple interacting alignment processes, nonlinearities, path dependencies, thresholds, and path creation. Finally, a process theory may emerge about sustainability transition pathways. The theory may differentiate important sequences in a transition and identify the dominant circular causalities.

The summarized critics indicate some challenges of an ITS approach. We would like to point out the challenge of conceptual heterogeneity. Because SD does not assume that there exists a well-specified system out there, it does not offer any content theory that prescribes which concepts and variables should be included. SD modeling is normally centered on an issue and is therefore contingent on the perceived problem situation of decision makers who want to deal with it (Lane 2000). This has two important consequences. An ITS approach inherently takes a normative stance that applies problem- and action-oriented perspectives. These orientations may lead to an increased heterogeneity in explaining socio-technical transitions. In reference to the problem owners' and researchers' lenses, as well as abstraction context, specific concepts and interactions may be highlighted that are only transferable to a limited extent to further socio-technical transition contexts.

3.3 The Research Method

The management of these challenges may be facilitated by a research method, which is presented in this subsection. The development of the method was guided by the following research question: How should the research process be designed to deploy the benefits and to master the above identified challenges?

The field of SD applies best practice approaches to modeling. These approaches are also critical for model-based theory building. They trigger the selection of hypotheses and the falsification of premature propositions (Schwaninger and Groesser 2008). Sterman (2000) proposes a research design with five iterative steps. In the first step, the dynamic problem situation and the system boundary is specified with crucial time series characterizing the behaviors of interest. In the second step, prevailing theoretical explanations of the problematic behavior are challenged by a dynamic hypothesis. The new formulated dynamic hypothesis explains system behavior as an endogenous consequence of the feedback structure. It should provide a more accurate picture of the problem situation than previous theoretical explanations. In the next steps, the dynamical hypothesis is operationalized within the simulation model. The modeling activities include rigorous specification and parameterization, as well as structure and behavior testing. Step five is dedicated to policy development and analysis. One important objective is to identify robust policy recommendations under different scenarios and given uncertainties.

This well established research design highlights the iterative nature of modeling. Here, in this subsection, this iterative process picture is complemented with a method that highlights the convergence toward a scientific model. It visualizes the progress, and emphasizes the phase-specific mapping challenges of an ITS study. It is *the triple challenge* of (1) resolving a messy problem situation; (2) constant comparing of data and interdisciplinary theory, well known from grounded theory methodology; combined with (3) the conceptualization and formulation of a "scientific" model. We define a scientific model as one that offers a dynamic theory for "the family of systems to which the specific one belongs" (Forrester 2003: 4) and fulfills a set of criteria for high-quality theories as suggested by Schwaninger and Groesser (2008).

The offered method is more specific than the general roadmap for developing theory based on simulation as suggested by Davis et al. (2007). The method for the ITS approach focuses on the question: How should distributed knowledge be integrated to enhance theorizing on sustainability transitions and guide action? Subsequently, the method emphasizes the *double objectives of ITS*, which are to contribute to theory building and enhance the management of a socio-technical transitions. This task is distinct to the understanding of simulation-based theory development of extant simple theories, as suggested by Davis et al. (2007). While the MLP can be considered a premature theory, it does not represent a simple theory but rather a heuristic that points to important alignment processes between multi-dimensions and multi-levels. Subsequently, the main objective of the ITS method is to guide coherent and congruent integration of different levels, dimensions, and perspectives, the practitioners' perspective, in particular.

The suggested research frame has been developed and applied in different studies on dynamics of innovative systems (e.g., Ulli-Beer et al. 2006), and has been inspired by Beer's methodology of typological maps and scientific modeling (Beer 1984). Previous work on methods for theory building, including grounded theory (e.g., Strauss and Corbin 1994), building theories from case study research (Eisenhardt 1989), and simulation for theory development (Davis et al. 2007) have been most helpful to substantiate and reflect the different suggested procedures.

The framework is visualized in Fig. 3.1. It highlights the challenge of the researcher to design a research strategy that supports congruency and coherency between the real-world problem situation and scientific theorizing. The framework reflects the idea that the perception and data reduction process, as well as the language used by practitioners and researchers, is distinct, in a complex governance situation specifically. The real-world "theories in use" are typically implicitly derived and tacit, whereas in research the reduction process should be deliberate and create a well-understood detail of a scientific view. The evolving simulation model actually reflects the state of constant comparison of data and theory. In order to test the behavioral consequences of conceptualization, they are tested by simulation. This requires that researchers always work with a running model. Ongoing

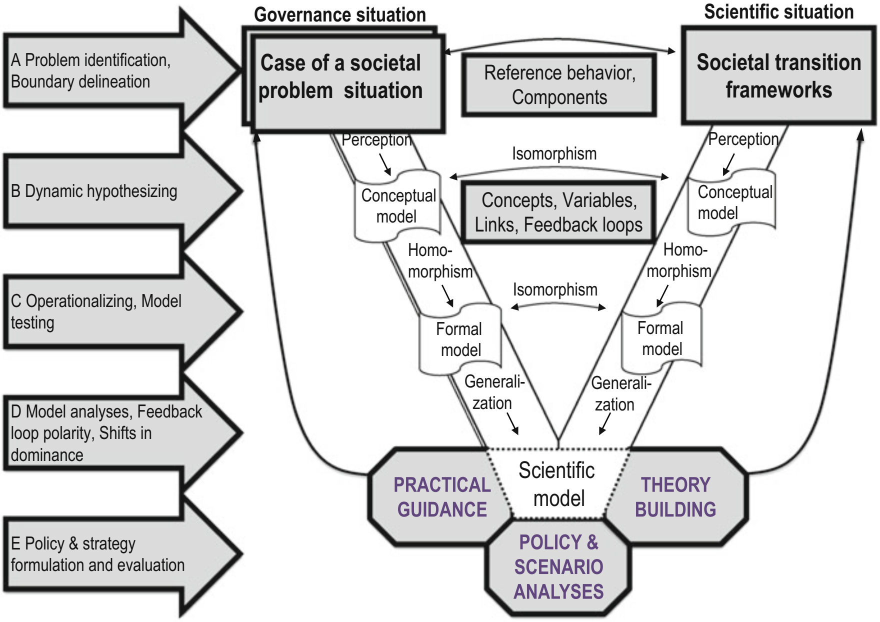

Fig. 3.1 The research method for integrative transition simulation (Adapted from Beer 1984; Ulli-Beer and Wokaun 2011) Note: Homomorphism is a map from one group to another but the operation is preserved; in doing so the information is reduced. Isomorphism is a unique pairing of each element of a set with an element of another set

mathematical formalization also indicates logical and data gaps, which the researcher needs to address. In addition, it helps to cope with the amount and diversity of information, as well as the ongoing interpretation, on how comparing data and knowledge forms evidence for conceptualizing and simulation.

The visualization of the method highlights the value of cross-case comparison toward a scientific model by the two-plus indicated pathways. Cross-case comparison of ITS studies helps to identify the potential of single studies for generalizing the insights, and to lift the level of abstraction toward more generic societal transition frameworks.

3.3.1 Problem Specification

The challenge of integrative modeling is to reflect adequately the real-world governance situation against established theorizing in the scientific community. Thus, the problem identification phase becomes an iterative process that includes clarifying the system behavior of interest, the model boundaries, and analyzing data, as well as identifying the important dimensions of the relevant components and interactions. In general, these are actor networks, their decision rules, as well as formal rules of different regimes, relevant artifacts, and infrastructures, which are specified along decisive attributes, and their causal relationship.

ITS includes the challenge of unraveling the implicit understanding or mental model of the practitioners that have to cope with the complex governance situation of a transition challenge. The goal is to elaborate a conceptual model and understanding that mirrors the problem situation as perceived by practitioners. However, in a messy governance situation, where it is not clear which actors are involved, a knowledgeable system expert must be identified who may inform the research team (Mueller et al. 2012). Hence, problem structuring methods from management science (Mingers and Rosenhead 2004) may be enhanced to capture the essence of the fragmented multi-actor system. Practically, many combinations of different social science methods and techniques may be chosen to develop a better understanding of the problem situation, for example, desktop research, including internet and literature research; historical approaches; (expert-)interviews; network analysis; workshop techniques; soft-system methodologies, including cognitive mapping; and group model building (Mingers and Brocklesby 1997; Kopainsky and Luna-Reyes 2008). However, effectiveness and efficiency in the research process of ITS depend on choosing the most helpful techniques in the particular situation and enhancing methodological consistency. In view of identifying interactions between system components and building SD models, cognitive mapping and group modeling are promising methods (Vennix 1996; Howick et al. 2006).

3.3.2 Dynamic Hypothesizing

Based on an empirically grounded understanding of the problem situation and the important actors, a scientific argument needs to be developed on how this situation relates to extant theorizing and how it may enhance theorizing. Therefore, a profound knowledge of potentially relevant theorizing for the problem situation is necessary. It may include the MLP but needs to go beyond in order to differentiate between different variables, interactions, and feedback loops. The MLP may provide a heuristic for deductive structuring of the case. However, there exists a wealth of disciplinary theorizing that helps to delve deeper into important concepts and causal relationships within and between action regimes. This is an important precondition for a richer understanding of multiple interacting causal circularities guiding socio-technical transitions. This corresponds to the quest of a process analyst to identify the underlying mechanisms as the causal agent of a process theory (Pettigrew 1997). Also, it helps to identify tensions between different theoretical propositions and to formulate an intriguing research question (Davis et al. 2007).

According SD scholarships, the researcher needs to translate the problem situation in a coherently nested map of feedback loops to capture the causal circularities of the transition context. This results in a dynamic hypothesis. This is a statement about relevant system variables and multiple circular causalities that explains transitions over time in the socio-technical system states of interest (Sterman 2000). We would like to emphasize that it is this phase that requires a great deal of creativity, theoretical sensitivity, and expertise (Strauss and Corbin 1994; Pettigrew 1997), in order to suggest initial propositions grounded in empiric observation and multi-disciplinary theory. For this purpose, the *grounded theory approach and theoretical sampling* offers helpful guidance to analyze the empirical data, for analytic induction,[2] and for triangulation (Eisenhardt 1989; Pettigrew 1997; Strauss and Corbin 1998). The aim is to identify relevant theorizing, important concepts, and relevant dimensions (open coding) that allow for adequately linking the concepts at the level of their dimensions (axial coding) (Corbin and Strauss 1990; Groesser 2012). The process of iteratively comparing theory and data is advanced by mapping the emerging insights into a dynamics hypothesis. Also, *soft system methodologies* (Checkland 1993; Checkland 2000) may provide general methodical guidance on how to conceptualize a messy problem situation. These approaches may complement the best practice approach of SD (Müller 2012). The researcher should seek to formulate a dynamic hypothesis about how the perceived problem structure results in action pressure influencing decision variables and rules of the system (i.e., system behavioral rules) (Sterman 2000). For this purpose, the SD field offers the simple syntax for visualizing causal loops, as well as stock and flows within a system. It enables the researcher to develop a qualitative white box model in the form of a causal loop diagram (Richardson and Pugh 1981; Coyle 2000; Sterman 2000). This qualitative model should be as congruent as possible regarding the real-world context and as coherent, as indicated by existing theorizing.

3.3.3 Operationalizing, Model Testing

The skillfully selected concepts help to reduce the dynamic complexity and gain focus. For the formalization, i.e., the development of a quantitative model with mathematical equations, adequate variables that have perceived real-world counterparts have to be identified. Each variable needs to be operationalized with data and units, as well as adequate formula and units. This involves congruently mapping of different real-world variables to one concept (homomorphism). However, the formulation of causal proposition found in the real world should be reflected one to one in the theorizing process and the formulation of mathematical equations (isomorphism). This is to ensure external validity or secure that the “right

[2] In grounded theory, the notion analytic induction describes the process by which the researcher applies induction and deduction iteratively while practicing the method of constantly comparing data and extant knowledge (Strauss and Corbin 1998).

output behavior is generated for the right reason" (Barlas 1996: 186). Stringent formal model testing, including simulation (Barlas 1989), allows iteratively refuting and refining the formulated propositions that link model structures to model behavior. Subsequently, this quest may induce theory refinement and enhancement (Schwaninger and Groesser 2008). It is in this phase where conceptual ability,[3] technical modeling skills, and simulation together create the ground toward a better understanding of sustainability transitions (Homer and Oliva 2001).

3.3.4 Model Analysis

The tested simulation model of a specific case provides a solid base for model analysis.

There are different aims and ways for model analysis. It involves experimentation with the model to produce novel theory (Davis et al. 2007). By changing the mathematical equations and parameter values, alternative versions of a theory, but also behavior modes, can be tested, i.e., testing the sensitivity of specific variables and frame conditions (Rudolph et al. 2009).

With regard to enhancing the understanding of important circular causalities in socio-technical transitions, the identification of feedback loop polarities and shifts in dominance helps to deploy the value proposition of ITS. This can either be done by mathematical model analysis (Mojtahedzadeh et al. 2004; Kampmann and Oliva 2006; Bosshardt 2009; Ulli-Beer et al. 2010; Mojtahedzadeh 2011) or by tracing the causality of single links and logical reasoning and experimentation of loop dominance behavioral analysis (Ford 1999; Groesser 2012). In the case of feedback- and detail-rich models, the former approach is limited, while in the latter the intuition developed through persistent model analysis is crucial. The result of this analysis may be an even more abstract explanation that allows developing more general propositions for a class of transition challenges. It suggests a causal process theory (Pettigrew 1997) about phase-specific determinants and causal circularities that explain changes over time. The theoretical interpretation of the model analysis outcome, then establishes the main evidence for formulating theoretical implications. The addressed research questions and the chosen concepts indicate the relevant reference frames to which the ITS study may contribute. Specifically, it may explicate causal relationships of extant process theories in single fields. But more promising are insights on interacting processes that can be gained from the integration of different process theories (Rudolph et al. 2009). Often, one specific ITS study may provide a building block to further research. This may include cross-case comparison, or comparison with further theorizing on similar transition phenomena. This provide evidence about limits for generalizing the substantive theory

[3] Under conceptual ability, we understand the skillful application of the coding procedures guided by theoretical sensitivity.

derived from the single study (Eisenhardt 1989). A moderate achievement would be if the simulation model provides an explanation that is idiosyncratic to the particular case without generating general insights about socio-technical transitions.

3.3.5 Experimenting with Policy and Strategy Levers

Finally, the simulation model can be used for experimentation, i.e., for developing different kinds of policy and strategy scenarios (Zagonel et al. 2004). Those may address questions such as: Under what policy and strategic behavior assumptions is the achievement of sustainability objectives plausible? Under what boundary conditions have certain radical technologies the potential to reach GHG reduction targets in time? What leverage points and policy packages are most effective? What are the challenges and opportunities of socio-technical transition for the actors? The endogenous model structure – adequately reflecting delays, nonlinearities and thresholds – is particular suitable for assessing social-political feasibility transition pathways (Van den Bergh et al. 2011)? This complements the one-dimensional "efficiency criteria" of an economic perspective or technological feasibility of technology-oriented system engineering studies.

In summarizing the output of the phases D and E (in Fig. 3.1), we highlight the dual benefits of ITS studies: On the one hand the final product of an ITS study may be the input to further theory-building studies on socio-technical transition or sustainability transition in general. On the other, the elaborated simulation tool may be applied for policy, strategy, and scenario analysis, in order to derive practical guidance.

3.4 An Illustrative Case of Integrative Transition Simulation of Energy-Efficient Housing

In this section, we present the illustrative case of ITS of the socio-technical transition toward ee housing in Switzerland. We use the case to explicate the implementation of the method. The research journey will be summarized along the different integration steps. A detailed account of the case study is beyond this article but can be found in Groesser (2012).

The research design of the project called "Diffusion dynamics of energy efficient buildings DeeB[4]" has been strongly informed by the best practice approach of SD modeling and the case study approach of ITS. The initial research question of the simulation study was: "Which factors and processes have played a role in the diffusion of energy-efficient housing designs in the Swiss building sector?"

[4] Project Nr 405440–107211 of the National Research Program 54 of the SNSF.

We have selected this case because it reports on a typical socio-technical transition case, which has influenced the energy consumption of the societal function "housing" in a more sustainable direction. The project was part of the National Research Program 54 "Sustainable Development of the Built Environment" of the Swiss National Science Foundation.

In Switzerland, environmental and energy politics are anchored in the Swiss Constitution. In 1997, Switzerland signed the Kyoto Protocol and consequently approved the CO_2 law, which prescribes that the CO_2 emissions need to be reduced by 10 % below the reference value of 1990 until the year 2010. Although this federal legislation has been complemented with the vision of the 2000-W society[5] in 1998 and several national and cantonal policy programs, the achievement of political targets regarding energy efficiency and reduction of greenhouse gases proves to be very challenging. This indicates the need for further "governance" efforts, specifically in the domain of transportation and the built infrastructure. In contrast to this general observation, energy efficiency in new buildings has shown a very positive development in the last five decades (c.p. Jakob 2008). A better understanding of this success story and its governance mechanisms would help to transfer it to further domains in need of action.

3.4.1 The Project Road Map

In order to analyze the historical transition toward ee housing, a transdisciplinary and interdisciplinary modeling approach were each chosen (Ulli-Beer et al. 2006), referred to as ITS. A concrete project road map was guiding the research journey, as illustrated in Fig. 3.2. Its left-hand side represents the steps of "desktop research." The right-hand side highlights the transdisciplinary character of the project as a mutual learning process and knowledge transfer between researchers and target groups. This has been realized within four workshops. System experts (i.e., public and private decision makers of the housing system) were involved in the ITS journey. They were selected based on an iterative method of actor identification (Mueller et al. 2012).

Two models were developed and tested: (a) a (static) model of behavioral antecedents of the choices at the point where the path to an energy-efficient or non-energy-efficient construction process was entered, and (b) a (dynamic) building stock simulation model. For the static modeling approach, psychological, managerial, and economic theories, as well as results of empirical investigations about antecedents of behavior choices, were analyzed by a structural equation model (Lauper 2009). These causal relations were partially integrated as decision functions in the housing simulation model for a middle-sized Swiss city.

[5] "The vision of the 2000-W society per person calls for a continuous reduction in energy needs to 2000 W pro person" http://www.novatlantis.ch (accessed 8 August 2011).

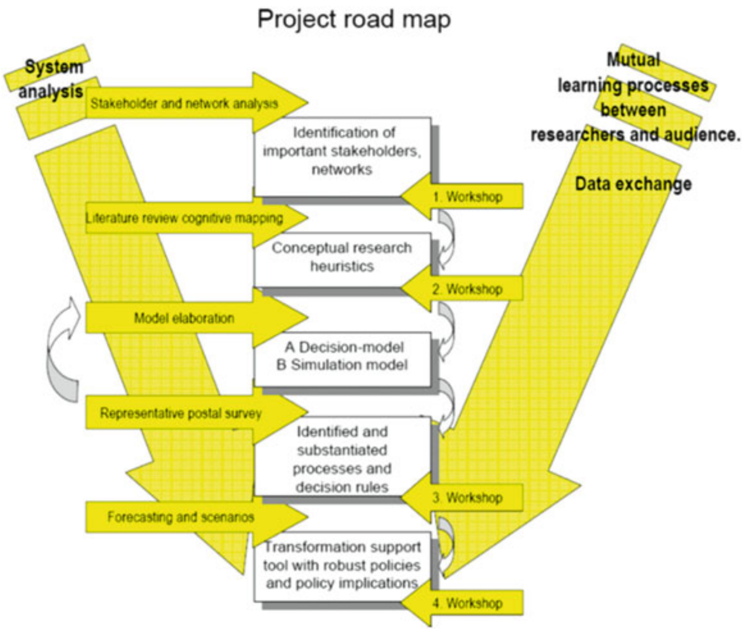

Fig. 3.2 The project road map of the simulation study (Kaufmann-Hayoz et al. 2005)

The research journey proceeded along different steps, but involved iterative cycling between data gathering and conceptualization, as well as operationalization and simulation. Preliminary insights were tested in workshops with the system expert group. This ensured a phase-specific external comparison of preliminary conceptualization and the reference frames offered by the system expert group. The four elaborated workshop documents had the characteristics of field notes (Yin 2003). The researchers summarized what was done, learned, and how to proceed. In the following, we use the ITS research frame to describe the different steps and resulting outputs in more detail.

3.4.2 *Explication of the Research Steps*

3.4.2.1 Problem Identification

At the outset of theorizing, a better understanding of the problem situation was elaborated either by internet research, literature research, or informal expert interviews. We considered this an important prerequisite to developing an understanding of context conditions, important actors, and the identification of experts that may represent them (Mueller et al. 2012). It provides the empirical starting point for ITS. The following research question was leading the study: Which

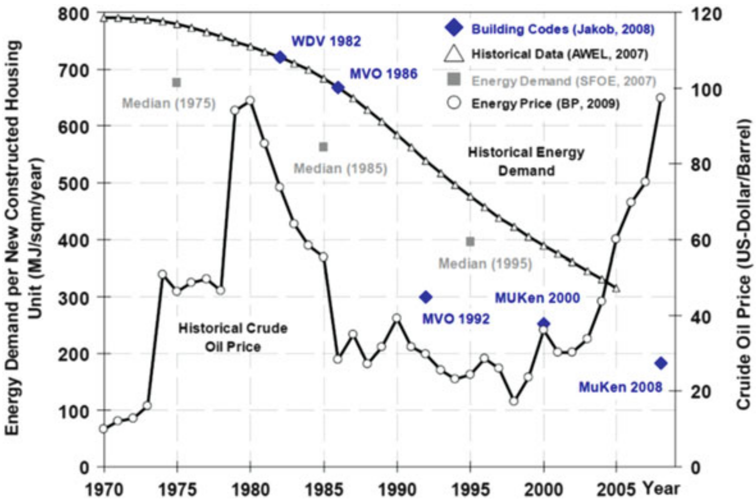

Fig. 3.3 Comparison of energy demand of new buildings in Switzerland and the crude oil price development (Groesser 2012)

governance mechanisms have controlled the historical improvement in the energy efficiency of newly built houses? The following description provides the broad understanding of the *context conditions* and the *behavior of interest*.

The building sector is an important end-consumer of energy and contributor to GHG emissions (IEA 2011). The 2007 IPPC Report acknowledges a large reduction potential if a large number of the presently commercially available and tested technologies were to be implemented. However, a rapid reduction remains an important governance challenge for multiple reasons (Levine et al. 2007: 391). Most interestingly, the GHG abatement cost in the building sector would even be negative, also in Switzerland (McKinsey and Company 2009). This is a global ambiguity that needs a better understanding, since not only the governance context is messy, but often important data are missing. An empirical study showed that the gathering of exact longitudinal data on energy consumption from newly built houses is a challenging task in Switzerland (Brühlmann and Tochtermann 2000; Dettli et al. 2003). Figure 3.3 summarizes the available information and illustrates the continuous decrease of energy demand of newly built housings from 1970–2010 in Switzerland. While, in 1970, a newly built home consumed around 800MJ/m^2*year for heating and warm water, energy consumption has been decreased by a factor of four, resulting in an average of 200MJ/m^2*year in 2010. However, these values may differ strongly, depending on regional location, type of housing, and implemented energy standard. In the same time horizon, the price of oil showed a different development. We can observe a decade with high oil prices from 1974–1984 due to the oil crisis, and two decades with relatively low energy prices from 1985–2005. While the oil crisis may explain the initial improvement in energy efficiency, the strong decline in energy consumption in the following two decades cannot be explained by the oil price trend.

System thinking and preliminary analytical concepts (from the decision and strategy making as well as innovation and diffusion literature) were guiding the scientific perspective. We sought to *identify attributes guiding actors' actions*. For *actor identification,* we developed and applied an iterative method and selected a system expert who could represent them (Mueller et al. 2012). We chose actors who were engaged in the recent construction of three to four reference buildings, and actors of the broader housing system (including buy-owners, architects, craftsmen, investors, regional energy consultants, and representatives of the national, cantonal, and municipal authorities). The selected reference buildings differed according to their energy efficiency (buildings with a high voluntary ee standard vs. buildings with a formal ee standard). This ensured that pioneers and early adopters of innovative ee designs, as well as late majorities and laggards, were represented in the system expert group (Rogers 2003). The identification of important actor populations indicated the institutional level of analysis, being organizational fields (DiMaggio and Powell 1983). It includes all relevant actor-populations of the housing system, and not merely a single population, such as demand- or supply-side actors. In order to analyze the importance of different actor groups concerning ee in the construction process, we applied a power interest diagram (Eden and Ackermann 2004; Mueller et al. 2012).

In the first workshop we sought to *justify selection of the case, focus, and actors*. Different discussion lines emerged (Müller 2006). For example, the following two issues manifested.

> One important issue was the focus on new housing construction, because retrofitting of the existing building stock was considered more relevant for ee debates in housing. While the research team agreed on this assessment, it maintained that, to elaborate an improved understanding of transitions to ee buildings, a historical case analysis of new ee housing construction might be a most rewarding first step.
>
> Another issue concerned the choice of the behavior of interest. The practitioner considered the choice of ee improvements for energy services (i.e., for heating and warm water generation) as very narrow. The researchers acknowledged the trade-off between a concise problem statement and the neglect of other important aspects regarding ee deliberations in housing (e.g., grey energy in construction or increased energy consumption for traveling, induced by urban sprawl).

The workshop helped to verify the importance of the *concept eco-innovativeness of niche actors*. Further on, the actor identification process and boundary delineation task resulted in a first *conceptual framing of human action in context* for the housing system (Ulli-Beer et al. 2006; Mueller et al. 2012). It emphasizes the feedback processes between actors' actions (strategies) and their perception (expectation) of societal structures and context conditions (Fig. 3.4). It shows how institutional structures (formal and informal rules) and physical structures (the build environment and artifacts) guide human behavior, but also how they are created by agency (Giddens 1984; Geels 2004; Kaufmann-Hayoz 2006).

Further data were gathered in order to identify *personal and contextual factors influencing the focus on ee in housing*. Therefore, extant empirical data, expert interviews, and cognitive mapping techniques were applied to better understand crucial characteristics of the residential build environment, as well as decision and strategy making of the involved actors. About 30 interviews were conducted with system experts that helped to develop a better understanding of "theories in use" and "mental models" of practitioners. The individual cognitive maps were

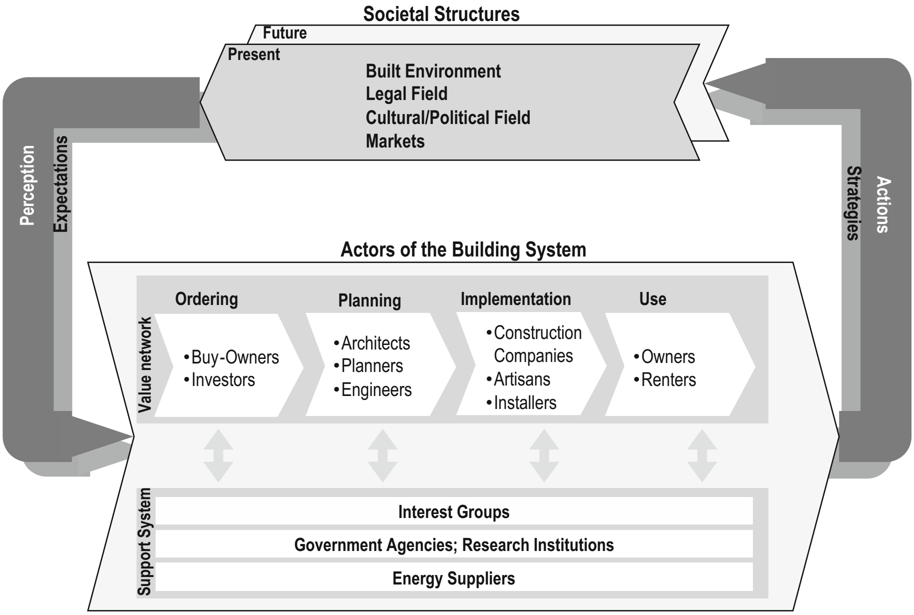

Fig. 3.4 Conception of human action in context for the housing system: basic feedback processes between action and structure (Adapted from Mueller et al. 2012)

aggregated in order to develop first theses, e.g., on personal and contextual factors that promote or hinder the adoption of energy-efficient building designs. Therefore, either psychological or managerial perspectives have been applied for private and professional actors (Groesser et al. 2006). This information input was used to elaborate first tentative circular causalities. They were mapped in causal feedback loop diagrams. The applied terms and language did mainly reflect those applied by the practitioners.

In a second workshop, we *refined the first qualitative conceptualizations* of the built environment (the causal feedback loop diagrams) together with the system experts. We applied participatory modeling techniques (e.g., Andersen et al. 1997; Howick et al. 2004). This helped to clarify the mental models about perceived substructures. However, a comprehensive, coherent picture of important feedback loops was still lacking. This actually revealed the governance challenge of the housing system. It is perceived as a very fragmented system, which is influenced by multiple heterogeneous actors and informal rules, as well as regime-specific formal rules and contextual conditions. It has self-organizing properties and thus the overall system behavior is perceived rather as emerging than as controlled and planned.

The emerging characteristics of the housing system were summarized from a system-thinking perspective; being:

- fragmented and heterogeneous actors (e.g., innovativeness of building owners)
- timescale of change (e.g., building lifecycle time)
- multiple causal circularities (e.g., learning by doing)
- history dependency (e.g., cumulative experience, implicit standards)
- exogenous changes (e.g., oil and gas prices)
- nonlinearity (effect of availability of ee building designs on adoption decisions)

3.4.2.2 Dynamic Hypothesizing

The task of the researchers was to develop a comprehensive model based on the available empirical input and the relevant *analytical concepts*. Therefore, a combined procedure of *open and selective coding* was followed in order to identify most coherent and congruent analytical concepts. Three foci for theorizing were initially chosen:

1. Strategies and decisions of the actors involved in the supply chain of energy efficient buildings – forming the system behavioral rules within the system.
2. Distinctive characteristics of adopter categories.
3. Causal circularities as structures that explain system behavior patterns over time (e.g., diffusion of ee housing and increase in ee of the energy service heating and warm water generation).

In the course of the empirical system analysis and literature research based on open coding procedures, further relevant research and theory strands were identified; being research about dominant design, innovation diffusion, co-evolution and the MLP.

This extant theorizing helped to justify the case study selection and ground it in relevant analytical concepts (selective coding).

> The case illustrates how the development of ee standards for buildings and eco-innovations is an important co-evolutionary process guiding socio-technical transitions. To elaborate, an endogenous explanation (i.e., in terms of feedback loops) about how this specific improvement trajectory was started and evolved over time became the envisioned contribution of the study.

After having identified the models' agents and the most important physical artifacts, a further next step was to formalize the direct and indirect system behavioral rules. System behavioral rules link the relevant attributes of the system components and determine their influence on important system states. This corresponds with the activity of *axial coding*. In the following example, attributes of standards and attributes of political agents were linked and formalized as important arguments of the system behavioral rule of how standards are changed or adapted.

> The system state "Energy Efficiency of Legal Building Code" is endogenously controlled by the rate that formalizes the system behavioral rule "improving ee of legal building code" as a function of the variable "relative advantage of an innovative standard regarding ee" and "willingness to improve ee of legal building codes."

For developing the comprehensive *dynamic hypothesis,* this procedure of axial coding was continued. All relevant system behavioral rules were conceptualized. They were endogenously linked in feedback loops that mutually control the evolution of the stocks of the dominant and new, evolving regime. The two were differentiated by their specific focus on energy efficiency.

In a third workshop, the dynamic hypothesis has been validated together with the system experts (Groesser et al. 2008). Therefore, techniques of group model building were applied again (Andersen et al. 1997). These include discussing feedback loops and the corresponding behavior of variables of interest. This kind of *dynamic coding* links circular causalities to system behavioral characteristics. This procedure of dynamic coding has resulted in a process theory with two distinctive contributions: First, different sequences in the evolution of building standards have been proposed. Second, triggering activities and important feedback loops for each sequence have been proposed. The output of this step was a white box model that visualizes the main circular causalities that explain the behavior of interest. It is displayed in Fig. 3.5.

> The dynamic hypothesis postulates that heterogeneous agents and different factors from the technical, industrial, political, market, and technical domains are linked by balancing and reinforcing feedback loops that control ee of the building stock. The case shows that competition between multiple housing designs and ee-standards results in a symbiotic co-evolutionary process Specifically, it shows that formal standardization depends on the development of technology, innovations, and diffusion that helps to build up political support and legitimacy for improving the ee of the legal building code. This suggests that long-term socio-technical transitions in housing have been based on sequences of innovation, diffusion, and formal standardization (IDS Cycle) (Groesser 2012).

3.4.2.3 Operationalizing & Testing

Preliminary dynamic hypotheses provided theoretical perspectives for operationalizing and testing a quantitative model. At the same time, the simulation model was used to iteratively refine the dynamic hypotheses. For this purpose, adequate real-world variables and data needed to be selected as proxies of proposed concepts. The empirical data from the previous research steps was an important source. The links between the variables were specified by adequate mathematical equations. This step has been supported by the modeling software Vensim. It offers adequate mathematical formula for linking conceptual variables with rates and stocks, applying ordinary differential equations.

Eventually, a first detail- and feedback-rich model was developed and employed to advance the research project through the steps of model, policy, and scenario analysis. This version of the simulation model was premature with regard to conceptual parsimony and the level of abstraction. However, indicative insights occurred concerning main interacting processes and sequences of the transition to ee housing (Groesser and Ulli-Beer 2008; Groesser et al. 2009). This model version incorporated a *substantive theory on the specific case*. It provided direction and

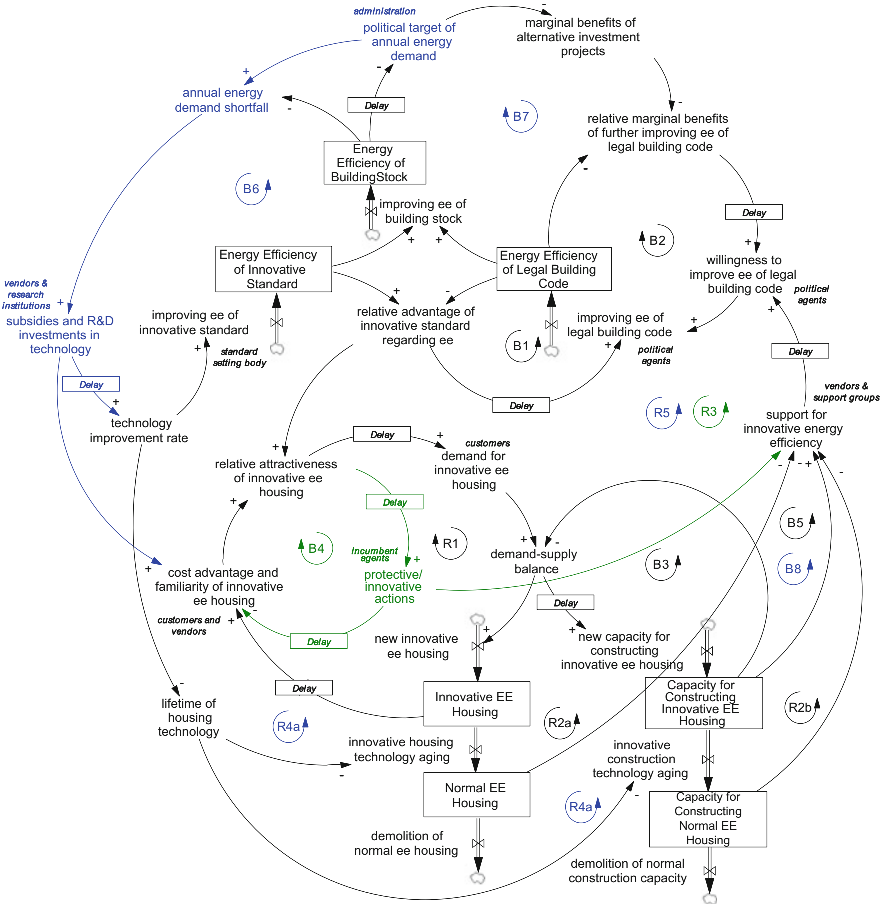

Fig. 3.5 Main causal circularities controlling ee housing (Groesser 2012) Note on the mapping syntax in the displayed causal loop diagram: A *rectangle* represents accumulations; this is a slow-changing variable. The *double arrow* with the valve depicts the rate of an accumulation (*inflow*) or degradation (*outflow*). The *single arrow* indicates a causal relationship between fast-changing variables. A "plus" stands for a rectified and a "minus" for a converse relationship. Feedback loops are indicated by the *small circle with arrows*; *B* stands for balancing and *R* for reinforcing feedback loops

stimulus in enhancing theorizing toward a more formal simulation model (c.p. Strauss and Corbin 1994).

Further theorizing efforts sought to enhance the *conceptual parsimony* of this preliminary model. The method of *constantly comparing data and extant theory* (Strauss and Corbin 1998) helped to lift preliminary variable constructs to a higher conceptual level (Martin and Turner 1986). As a consequence, detail and feedback complexity of the model was reduced. The result of this cycling through the steps of theorizing, operationalizing, and analysis was a *formal simulation model* incorporating a *grounded process theory* on the dynamics of voluntary and legal standards (Groesser 2012). About 350 variables were mathematically linked for operationalizing the suggested dynamic hypothesis. For illustrative reasons, the mathematical formulation of the central variable relative attractiveness of innovative ee housing, RA_{ee}, will be introduced.

RA_{ee} is equal to the ratio of attractiveness of ee housing $A_{ee,t}$, to the attractiveness of normal housing A_{normal}.

$$RA_{ee} = \frac{A_{ee,t}}{A_{normal}} \tag{3.1}$$

with $A_{ee,t}$ being a product of five attributes:

$$A_{ee,t} = \overline{A} * \mu_{ee,t} * \mu_{ep,t} * \mu_{ee-stock,t} * \mu_{utlization,t} * \mu_{technical,t}$$

$\overline{A}_{ee}$ $\overline{A}_{ee}$, the average of ee housing, is a norm value and is equal to the attractiveness of normal housing.

$\mu_{ep,t}$, the effect of energy price on attractiveness, is assumed to correlate positively with A_{ee}.

$\mu_{ee\text{-}stock,t}$, the effect of visibility of the ee housing stock on A_{ee}, assumes that existing ee housing increase both familiarity and financial attractiveness due to learning effects in production. This is a nonlinear effect that produces path dependencies.

$\mu_{utilization,t}$, degree of capacity utilization for constructing ee housing, assumes that increasing levels of capacity utilization results in longer waiting times and nonlinearly reduces the attractiveness.

$\mu_{technical,t}$, the effect of the technical advantage of ee housing compared to normal housing.

Changes over time in these five attributes are determined by the evolution of the linked subsystems of the model and external factors.

Different data sources have been used to calibrate the model. These include a variety of empirical studies (e.g., Jakob 2006; Ott et al. 2006; Jakob 2008; Lauper 2009) and professional databases (e.g., eurostat, STAT-TAB, Swiss Statistical Lexicon). The detailed sources used for each input data are documented in the equation script.[6] Calibration was supported by iterative behavior replication tests. Eventually, the model proved to replicate several historical behavior trends with adequate qualitative accuracy, which is illustrated in Fig. 3.6. An integrative model validation process based on different test procedures supported the quality and validity of the simulation model (Groesser and Schwaninger 2012).

However, also, different circumstances limited a precise replication of the historical trend: First, it was neither desirable nor doable to include all relevant factors in such a complex system. Second, the data sources and the research budget were scarce.

[6] The model script is available upon request. Contact: stefan.groesser@unisg.ch.

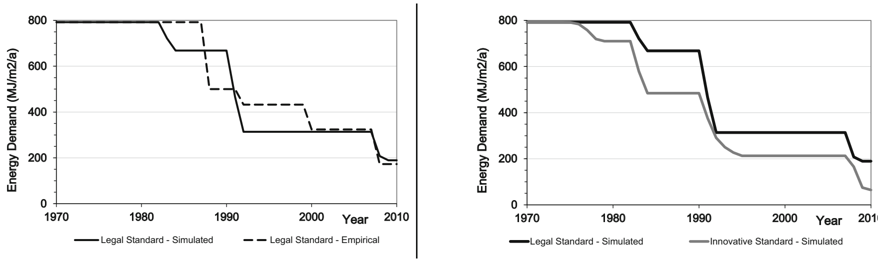

Fig. 3.6 Comparison of empirical standard intensification with simulated legal and innovative standard (Groesser 2012)

> In sum, the improvement trajectory "energy efficiency of housing designs" has been triggered by landscape developments, i.e., the oil price shocks in 1973 and a general increasing environmental awareness in society and debates on security of energy supply. Responses of innovative actors at the niche level triggered rule adjustments and a long-term transformation process toward greater energy efficiency in buildings at the level of regimes. In particular, different self-reinforcing processes well known in industrial economics (i.e., technology push, learning by doing and economies of scale, acceptance dynamics) supported the ee trajectory in the housing system. A more surprising result is that balancing feedback processes were also critical Highly important was the establishment of a politically desired "sliding goal" for energy demand reduction over time. It legitimated continued investments in eco-technology development and eco-innovations activities of niche and regime actors. Actually, the continually perceived action pressure pushed the system toward goal achievement, moderated by different balancing loops. Those involved iterating cycles of legal standard intensification. Standard intensification devaluated the comparative advantage of the ee housing design offered by niche actors. This again produced the dynamic incentive for innovative entrepreneurs to steadily elaborate the eco-innovations for buildings (technology push). These multiple interacting feedback processes actually suggest that a symbiotic competition between different housing designs, which fulfill either the voluntary or legal standard, played a major role in the observed ee transition in the Swiss housing sector (Groesser 2012). The resulting observed system behavior was an improvement cascade in energy efficiency standards.

3.4.2.4 Model Analysis

In order to further substantiate the developed process theory on eco-standard setting, the impact of different feedback processes in the sequential phases of innovation, diffusion, and standard setting were identified by detailed model analysis. Further on, simulation experiments helped to actually test the postulated impact of the *symbiotic competition* between different housing designs. Therefore, parameter values have been manipulated to test what would have happened if the perception of the voluntary standard were weaker than in the base case. The backcasting simulation output showed a much slower improvement in the energy efficiency. This result supported the dynamic hypothesis on the beneficial impact of the symbiotic competition processes (Groesser 2012).

3.4.2.5 Policy Formulation & Evaluation

The developed model allowed for policy and scenario analysis in terms of forecasting "what if" simulation experiments. For example, the endogenous Innovation-Diffusion-Standardization model structure allowed evaluating the impact of a higher willingness to improve the legal standard on the energy efficiency path and the resulting energy demand. The rather counterintuitive outcome was that legal standard setting starts to overrule voluntary standard setting. Based on the different simulation experiments directed to assess the impact of policy and strategy making, or to evaluate the impact of further landscape changes, provided the basis for the formulation of practical implications, also in terms of timing interventions (Groesser et al. 2009; Groesser 2012).

3.5 Discussion

We discuss our initial argument that the unique value proposition of ITS stems from the structural analysis method of the SD scholarship. We elaborate to what extent the presented case study on ee housing supports this argument. All of the SD analysis tools were beneficial when applied in the ITS study of ee housing: (1) identifying the reference variable, (2) mapping feedback loops, (3) identifying the feedback loop polarities, (4) refining a causal loop diagram toward a dynamic hypothesis, and (5) conducting simulation experiments. Eventually, the main circular causalities were explicated that have coordinated landscape pressure with the responses of niche actors and regime-level rule adjustments in ee housing. Iterative cycling through the sequences of *innovation, diffusion, and (formal) standardization* explains the transition to ee housing. For each sequence, the dominant balancing and reinforcing feedback processes have been identified. In addition, simulation has highlighted that the iterations of the IDS cycle over time depend on a certain *willingness threshold* to intensify the standard. A most interesting insight is the *symbiotic competition process* between informal and formal standard development – it influences the speed of standard intensifications. Higher perception of the evolving informal rule and higher willingness to intensify the standard leads to higher energy saving in housing over time. We have argued that the simulation model represents a process theory, which explains the transition to ee housing as the result of temporal sequences of dominating feedback loops pushing *innovation, diffusion, or standardization*. It explicates both *the direction and speed of sustainability transitions*. Subsequently, simulation experiments inform social-political feasibility of sustainability transition on a solid ground, considering endogenous variety creation and nonlinear rule adjustment processes. We regard this as a major achievement, because it avoids the weakness of diffusion studies and policy analysis that depend strongly on oversimplified exogenous input assumptions and linear extrapolation. This illustrates the logical precision of ITS in explicating multi-level alignment processes, which is an important contribution to theorizing about sustainability transition. Often used terms in narrative approaches, such as determinants, mechanisms, circular causalities, and accumulations, can be explicated. Also, core concepts responsible for systemic phenomena, such as path creation or thresholds, can be mapped and analyzed more specifically.

Concerning the offered analysis method, the case study has illustrated its applicability. It specifically has proven useful to better understand the nature and logic of the different research steps of the ITS journey. For example, the messy problem situation of a socio-technical transition needed to be resolved before a clear research focus could be developed. This is a very important and challenging task, which is often overlooked or bypassed without reflection. The method highlights procedures and techniques supporting homomorphic and isomorphic mapping. Both mapping types are important for the elaboration of a scientific model that has a high internal and external validity. The strengths of the method stems from providing guidance for planning, designing, and implementing ITS journeys. It supports the choice of adequate research techniques and methods. The case study has illustrated that the method offers guidance for the operationalization of multi-level alignment processes in sustainability transitions. With these features, it is qualified to offer a unifying systematic in conduction ITS studies. However, linking the findings of single ITS studies explicitly to the narrative MLP framework is important to facilitate the accumulation of inter-subjective knowledge on socio-technical transitions. Depending on the level of abstraction applied in a single ITS study, the generic boundary conditions that qualifies for application to further cases are often not clear – and still need to be determined. Questions arise such as: What further transition cases can be informed by the proposed process theory? For example, does the *innovation, diffusion, standardization cycle* thesis holds true for transitions toward ee-personal road transportation? Can the insights be transferred to sustainability transitions in which the endogenous improvement potential is not created by technology but by service or process innovation?

We observe that an ITS approach is not a straightforward mechanical analysis approach. Well-conducted ITS studies require high expertise concerning different aspects, such as theoretical sensitivity, (participative) modeling, and creativity. As a consequence of the broad scope of ITS and the strong empirical founding, there is the danger of getting lost in the amount and richness of data, and, as a consequence, links to extant theorizing may be overlooked. Researchers need to balance the trade-off between parsimony and richness incorporated in the model. Related to this challenge is the tension between achieving a good historical explanation versus making generalizations at a high level of abstraction. Hence, the craftsmanship of ITS requires skills that need to be trained in different research journeys.

There exist further general limits of ITS. Theories incorporated in the simulation model are limited in time and scope. As soon as, in reality, different conditions become dominating, the model may become outdated, since changes in reality have overrun it. This specifically refers to the mapped rules and their interactions. In the real world, those are socially constructed and some triggering events may change them abruptly (Geels 2005b: 453). Politics, power, and trade-offs between conflicting goals of heterogeneous actors are normally oversimplified. Hence, the impact of unexpected events cannot be forecasted on a solid basis. Often the (re) actions need to be studied, and basic model assumption updated in an ex post analysis. A related aspect is that often important structures of innovation system may not yet be in place, but are emerging with weak interaction ties (Bergek et al. 2008). Those are difficult to identify in an early phase of niche creation, and therefore difficult to adequately represent in a model. Yet, they may later have a decisive impact on the socio-technical system behavior. In order to assess the buildup of an innovation system, the technological innovations system approach may be more powerful (Bergek et al. 2008). Finally, we suggest to apply models not as oracles that tell the truth, but as tools that help to cope with the dynamic complexity of socio-technical transitions.

3.6 Conclusions

The aim of the study is to clarify the benefits and limitations of an SD-based research strategy for theory development on sustainability transitions. We termed such an approach integrative transition simulation (ITS), because it combines theory enhancement based on extant theory with simulation-based theory building.

We make two contributions. First, we clarify why and how the linkage of ITS with the MLP helps to overcome some limitations of narrative approaches on socio-technical transitions. We show that ITS has the potential to explicate the circular causalities of multi-level alignment processes and its behavioral implications on sustainability transitions. We illustrate that ITS provides explanations as narrow to middle range process theories about classes of transition challenges. Second, we offer a method that provides methodical guidance for conducting ITS journeys. The method points to procedures that support the elicitation of practitioners' perspectives involved in socio-technical transition journeys in order to structure the problem situation. Also, it facilitates the conceptualization and operationalization of circular causalities explaining socio-technical change patterns. The method is unique because it links different methodological research streams with the purpose to increase expertise in ITS research journeys. This is an important contribution, because other methodological studies do not sufficiently consider the specific challenge of an MLP on sustainability transitions. For example, Davis et al. (2007) do not take into account the specific challenge of a messy problem situation, and of multi-level alignment processes. In this respect, our work does not substitute earlier contributions, but instead highlights how they inform ITS. Subsequently, our method offers a tailored systematic in conducting ITS. This facilitates cross-case comparison and eventually the generalization of findings from single case studies.

We acknowledge that our two contributions are only a starting point to enhance a constructive dialogue about the usefulness of ITS. Further research is needed to substantiate and enhance this discussion. Most helpful are further exemplar ITS studies that would allow cross-case comparison. As systems innovations scholars start to emphasize dominating causal circularities and sequences in sustainability transitions, the coordination and timing of policy and strategy making may be discussed on a more solid ground.

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