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Silvia Ulli-Beer *Editor*

Dynamic Governance of Energy Technology Change

Socio-Technical Transitions Towards Sustainability

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Silvia Ulli-Beer
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Dynamic Governance of Energy Technology Change

Socio-Technical Transitions Towards Sustainability

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Editor
Silvia Ulli-Beer
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Abstract

Formulating effective responses to the global challenges of mitigating climate change and securing a sustainable energy future require a clear understanding of the interdependent causalities between institutions, local decision making, strategic alliances, and eco-innovations as well as policies. It has been acknowledged that the linear "Manhattan project" model is not an adequate governance model for mastering the dynamic complexity of socio-technical transitions; therefore, this book discusses more adequate transition models and governance principles. It brings together tailored theorizing on sustainability transitions and system dynamics modeling. It offers qualitative and quantitative analyses of socio-technical transitions in road transportation and housing. It highlights the interconnected causal feedbacks that are required to overcome the lock-in situation in road transportation and housing fuelled by fossil energies. Showing which concerted actions and framework conditions are required in the transition phases in order to initiate and sustain socio-technical transition, it serves as a guide to model-based strategy making and policy design and analyses in support of sustainable futures.

Preface

This work has been motivated by the quest to better understand how industrialized countries can prosper *and* decisively decrease CO_2 emissions at the same time.

We know that profound human behavior change is crucial for reaching critical CO_2 emission targets in time to avoid irreversible climate change. Behavior change is facilitated/hindered by technology, infrastructures, formal and informal norms. Therefore, the widespread use of eco-technologies is seen as a promising approach for an effective climate change mitigation strategy. However, the ubiquity of fossil-based technologies in our socio-technical lifestyles makes it hard to replace them with eco-technologies. In addition, the decision-making process concerning the choices of (eco-)technologies takes place in a self-organized manner in a fragmented context. Therefore, the linear innovation model, as it was exemplarily applied in the Manhattan project for the application of nuclear technologies in World War II, does not provide adequate guidance for the governance of technology change towards green economies. Nevertheless, the linear innovation model is still dominant in the thinking of many leading innovation and technology researchers, managers, and policy makers.

Only recently, actors and research institutes have started to explore different approaches that include stakeholder dialogues with national and local authorities, utilities, private entrepreneurs, associations, and citizens, in Switzerland specifically. The assumptions behind these joint efforts or the characteristics are often implicit, not reflected or communicated. The logic why, how, and when the new approach should work is not transparent. Likewise, the most important governance principles of such systemic governance approaches are less clear. Who should be responsible/accountable for such joint efforts? Who should be the captains that navigate the endeavor through the cliffs of power plays and acceptance problems if social and private benefits do not fully overlap? Who should be the entrepreneurs that manage trade-offs between investments made today and returns gained the day after tomorrow?

While these social experiments serve as an alternative innovation model for eco-innovation or socio-technical transition towards sustainability, the causal effects in society and outcomes regarding emission mitigation are hard to analyze with traditional research approaches. Linear regression models, linear optimization models, or narrative explanations do have limitations for analyzing the dynamics of socio-technical transition experiments. However, simulation modeling, a young approach in social science, is most promising for eliciting and testing causal assumption about acting processes and the impact of socio-technical behavior change. But in the innovation literature, there are only few articles that provide piecewise knowledge or know-how about simulation approaches on socio-technical transitions. Comprehensive and well-tailored information about simulation modeling of socio-technical transitions is missing.

Therefore, in this book we provide a rich description of theoretical grounds, methods, and case studies that should support ambitious innovation researchers, analysts, or strategic advisers as well as novice researchers in their simulation modeling endeavors on socio-technical transition. In addition, a summary about most promising governance and management principles has been prepared.

The book is the product of an interdisciplinary research group of 13 researchers including economists, psychologists, physicists, chemists, and geographers. They all have been fascinated by the power of simulation modeling for better understanding the underlying processes of socio-technical transitions and their impact. They are the authors and coauthors of single chapters. In several cases, the reported research was part of doctoral theses, but no single researcher could have fulfilled one research task alone. Ongoing reflection and lively discussion between different disciplines and perspectives have been most important for a well-founded and validated research outcome.

It is with great pleasure that I express my deep gratitude to many farsighted persons who have supported the research group.

I am deeply indebted to Prof. Dr. em. R. Kaufmann-Hayoz from the University of Bern and Prof. Dr. em. M. Schwaninger from the University of St. Gallen. They have provided direct support to many subprojects with their guidance, feedback, and encouragement. Likewise, I am very honored and thankful to have had the chance to work together with Prof. Dr. Wokaun from ETH Zurich. He provided goal-oriented guidance and the inspiring research environment at the Paul Scherrer Institute (PSI). In this environment, many interesting discussions about eco-technology development and the social selection environment took place. I would like to specifically thank Dr. S. Walter, Dr. F. Gassmann, Dr. P. Dietrich, U. Elber, and Dr. S. Hirschberg and his research team. In addition, I am grateful to many persons who supported the research endeavor in different research phases. I am very thankful to Dr. S. Bruppacher for her friendship and teamwork in many research tasks. Also, I would like to thank Dr. M. Jakob, Dr. M. Zimmermann, Dr. H. Gugerli, Dr. P. Schwehr, and many participants of workshops in Zurich and Langenthal. Their wisdom helped us to pay attention to the most important aspects of socio-technical transitions in the building section. I am also very thankful for the collaboration with Prof. Dr. J. Heywood and his research team at the Massachusetts Institute of Technology (MIT). The collaboration has been very fruitful for the analysis of eco-technology options in the context of road transportation. In addition, I would like to thank the anonymous reviewers of earlier drafts of the manuscripts. They helped the authors to improve the different chapters in significant ways.

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Villingen Silvia Ulli-Beer
Mai 2013

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Chapter 1
Introduction to the Research Task on Governance Dynamics of Energy Technology Change

Silvia Ulli-Beer

> *Innovation is not an individual activity –it is a collective achievement*
>
> (Van de Ven 1986:597)

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1.1 Action Context and Research Scope

Today, many entrepreneurs and policy makers are concerned with developing responses and competitive strategies to anthropogenic climate change and energy supply issues. Their efforts are critical for socio-technological transitions toward "greener" economies with less energy consumption and lower greenhouse gas (GHG) emissions. Technological eco-innovations such as energy-efficient passenger cars or building designs, based on alternative technologies and renewable energy carriers, could play an important role in this process, if society were to

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

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use them widely. However, in fossil-based industries and economies, systemic barriers such as lock-in effects hinder their timely and successful commercialization. Misperceptions of systemic barriers lead to strategy and policy failures that result in excessive energy consumption and GHG emissions relative to sustainable levels (c.p. Sterman 1994; Moxnes 2000). Therefore, in our book, we assume that the governance of socio-technical transitions toward "greener" economies requires a systemic understanding of three analytical dimensions.

Main assumption: The challenge of socio-technical transition requires an adequate understanding of first, interdependent causalities between eco-innovations, physical (infra-) structure or the corresponding capital stock, and governance including the actors, which create and recreate the rules of the game. Second, it requires an adequate understanding of the dynamics, i.e., the rate and direction of innovation and its diffusion, which depend on dynamic phenomena such as lock-in and inertia. Third, the most promising governance principles that help to cope with systemic sources of policy failures (i.e. policy resistance), and help to avoid overshoot dynamics need to be discovered.

This book introduces a research approach and illustrative case studies that provide this kind of understanding. It brings together tailored theorizing on sustainability transitions and system dynamics modeling. It offers qualitative and quantitative analyses of socio-technical transitions in road transportation and housing. It highlights the interconnected causal feedbacks that are required to overcome the lock-in situation in road transportation and housing fuelled by fossil energies. The overall quest of this book is twofold: First to contribute to the development of helpful approaches for analyzing socio-technical transition toward sustainability. Second to improve our understanding of most promising socio-technical governance and management principles. In this vein the book serves as a guide to model-based strategy making, policy design and analyses of sustainability transitions.

Key terms: The focus is on socio-technical systems that are designed to satisfy our basic societal needs (e.g. housing and transport). Such systems include all system elements and interdependencies that are relevant for both satisfying our needs and the resulting environmental impact. Specific systems elements are infrastructures, knowledge, technology, capital resources, and market shares of products, as well as the actors, which develop and redevelop the patterns of interaction. The term governance refers to feedback patterns that coordinate the interactions of multiple actor groups or self-organized subsystems (e.g. markets) that control the development of resources, technologies, product markets, and infrastructure. Discrepancies between desired and effective states of the socio-technical system indicate the need of corrective actions that may be hindered by dominating feedback causalities creating undesired path dependencies. Purposeful interventions by the government or other actor groups that support socio-technical transitions are also addressed by the governance notion applied in this book. Finally, the term governance dynamics refers to steering mechanisms that involve activities of multiple actor groups influencing directly or indirectly the resulting outcome i.e. environmental impact over time. For example, discrepancies between desired and effective CO_2 emissions from transportation exert pressure on the guiding rules of actor groups to pay more attention to environmental attributes in the decision making process.

1.2 Approach and Objectives

The research presented in the book falls within the field of management science in a broad sense. It focuses its analysis not only on the firm, or on an industrial system but on a socio-technical system with an explicit emphasis on energy technology change. It covers aspects related to strategy, innovation and technology management and focuses on technology, product and market development from systemic and interdisciplinary perspectives. The book is based on the foundational disciplines of economics, sociology, psychology and complex systems. It combines concepts from several disciplines to investigate the determinants and mechanisms that govern the innovation, adoption, and diffusion of energy-efficient products. Promising strategies for the analysis and governance of such systems are discussed based on a systemic understanding of governance.

The different chapters report on systemic modeling approaches combined with established social science and marketing methods. This allows for analyses of the interdependencies between the sub-systems of technology development, supply, and demand as well as political regulations and their dynamic implication. Statistical data are used for validation and calibration. Numerical, white-box models of socio-technological change enhance the understanding of systemic barriers and drivers, as opposed to one-dimensional models of market failure, technology failure, or human failure. This specific research perspective is also distinct from energy economics modeling and technology-assessment studies. The research does not aim at identifying optimal social welfare goals, as it is not based on assumptions of perfect foresight and rationality but on bounded rationality and uncertainty.

1.2.1 Toward a Causal Understanding of Governance

One overall objective of the book is to offer an enhanced understanding of the multiplicity of feedbacks governing sustainability transitions toward highly energy efficient socio-technical systems, road transportation and housing in particular. Specifically, the book enhances knowledge about the determinants (including social and political norms, knowledge, and infrastructure) that govern the innovation, adoption, and diffusion of energy-efficient products. It highlights the role of path dependence and creation as well as overshoot behavior in complex socio-technical transition tasks. This allows for a comprehensive analysis of policy and strategy. In this manner it informs political and entrepreneurial

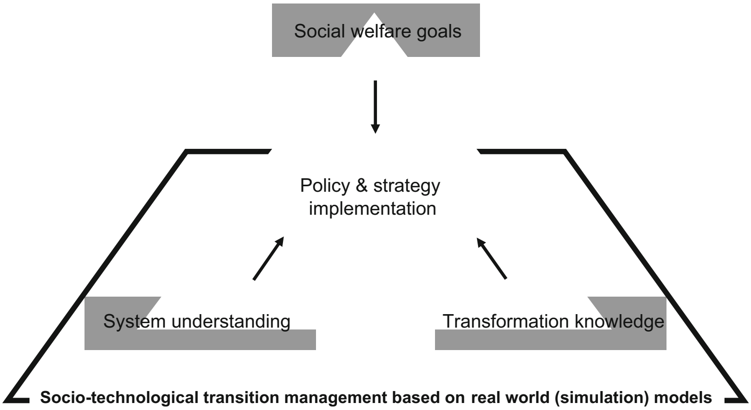

Fig. 1.1 Toward an encompassing information triangle for policy and strategy implementation. Real world (simulation) models provide system understanding and transformation knowledge as highlighted by the quadrangle. They are complementing economic energy system modeling that support policy making on cost effective technologies to reach social welfare goals. An encompassing information triangle may emerge if all three knowledge characteristics were combined. This provides the necessary foundation for mastering the governance challenge of socio-technical transitions toward greener economies

decision makers about promising technological substitution pathways for meeting policy targets on time.

The application of (simulation) models is one important aspect in the construction of an inter-subjective understanding of causalities and testing their dynamic implications and the effectiveness of policies. The construction of an adequate model of a problem is a fundamental management task for effective responses in a changing environment. An apt quotation by Conant and Ashby (1981), “The result of a management process cannot be better than the model on which it is based, except by chance!” indicates that we need adequate models for the governance challenge of socio-technological transition with respect to all three scientific dimensions of knowledge: defining goals that maximize social welfare, systemic understandings and transformational knowledge. The work therefore aims at complementing existing research on cost-effective technology choices based on energy economic modeling. It adds a problem-oriented analysis of socio-technical transitions based on system dynamics modeling. It provides an adequate understanding of the system structure and transformational knowledge to derive the most effective implementation strategies. In the end, a comprehensive picture of the governance task emerges, which reflects all three scientific dimensions of decision support. Figure 1.1 visualizes how the chosen approach contributes toward an encompassing information triangle for policy and strategy implementation.

1.2.2 Guiding Research Questions and Main Contribution

To enhance understandings of the system, the following general research question is addressed in the several case studies. “What determinants, mechanisms, and actors foster or hinder the spread of clean and energy-efficient technologies”?

The elaboration of transformational knowledge is guided by the question: “How should a socio-technical transformation be governed”?

In sum, the overall task addressed in the book is the following. *Real world* decision support models for mastering socio technological governance challenges at the strategic level of the socio-technical system are developed for the following purposes:

- Overcome lock-in effects and misperceptions,
- Remain competitive, and
- Reach emission reduction targets in a sustainable way.

The reader will obtain an improved understanding in four different domains:

1. Integrative transition simulation (see Chapter 3), which is introduced as an investigation approach that combines scientific theorizing and data analysis with simulation.
2. Critical structures of the adoption and diffusion dynamics of specific eco-innovations for sustainable (energy) futures.
3. Generic control structures for the governance of sustainable socio-technological transitions.
4. The impact of ecologically driven innovation strategies toward green energy consumption in housing and road transportation.

1.3 GHG Emissions: Technology as a Source and Solution

A historical analysis of technology and global change (Grübler 1998) highlights the dual role of technology as a source of and solution to global environmental change. This technology-environment paradox is nicely illustrated with the historical replacement of horse-powered vehicles with automobiles a 100 years ago. The feed required for urban horses and the presence of their manure in the streets was a problem, and the automobile had generic environmental advantages over the horse in terms of higher energy-efficiency and the quantity of local emissions such as solid and liquid waste (Grübler 1998: 320). In the short-term, the urban environment improved due to this transition, but in the long-term and with the wide-spread use of internal combustion engine vehicles (ICEVs), new (local and global) environmental issues became pressing (e.g., CO_{2-}, CO-, NOx-, SO_2-emissions, as well as particulate and noise-emissions). Many of these issues were solved using new technological solutions (e.g., three-way catalytic converters reduce the CO- and NOx-emissions of petrol driven ICEVs).

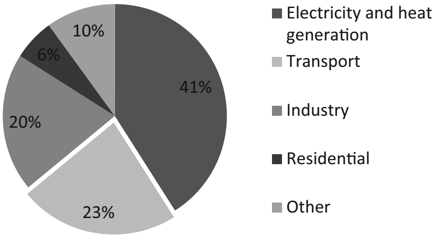

Fig. 1.2 Global CO_2 emissions by sector in 2009 (IEA 2011b: 11). In 2009, global anthropogenic CO_2 emissions from all sectors amount to approximately 29 Gt CO_2. The overall share of transport is 23 %, and that of road transport alone is 17 %

1.3.1 GHG Emissions from Transportation

GHG emissions from transportation still remain a significant source of climate change. Today, the transport-sector is the second-largest contributor to anthropogenic GHG emissions from industrial sectors, and 23 % of global CO_2 emissions are produced from transportation (Fig. 1.2). The vast majority thereof (75 % or 4.900 Gt CO_2) stems from road transportation. Consequently, highly energy-efficient automobiles and alternative fuels are considered important for climate change mitigation (IEA 2011a).

1.3.2 GHG Emissions in the Building Sector

Another important energy end user and source of CO_2 emissions is the building sector. It consumes energy from the electric and heat generation sectors and directly consumes primary energy in singly buildings for decentralized heating. As an energy end-user, the building sector produces approximately 8.6 Gt CO_2, (not including non-CO_2 GHG gases such as CH_4, N_2O and halocarbons), this represents approximately a quarter to a third of the total CO_2 emissions by sectors (Fig. 1.3). Fuel substitution and highly energy-efficient building designs and conversion technologies are also seen as important for lowering energy use and CO_2 emissions. For example, a substitution away from the current fuels used for direct combustion toward electricity and highly energy-efficient technologies such as heat pumps have high mitigation potential. According to the 2007 IPPC Report, there is the potential for a 70–80 % reduction in GHG emissions if a large number of the presently commercially available and tested technologies were to be implemented. In addition, they may provide the same services and confer additional benefits. The 2007 IPPC Report also acknowledges that there are multiple barriers and that the pace of policy making is slow, which lead to higher energy use in buildings than is necessary. Consequently, the rapid development of a low-emissions building system remains a major challenge (Levine et al. 2007: 391).

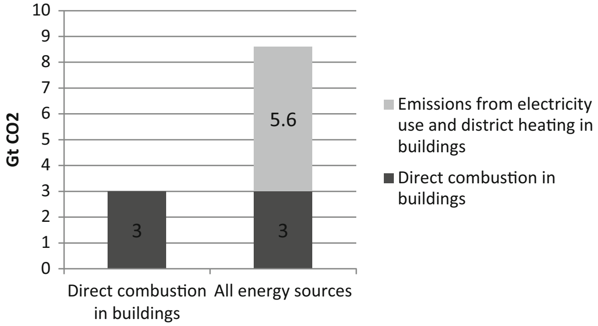

Fig. 1.3 Building sector emissions (Levine et al. 2007). Total CO_2 emissions from buildings, including electricity use and district heating, were approximately 8.6 Gt. These values are estimates but robustly demonstrate the significance of these sectors

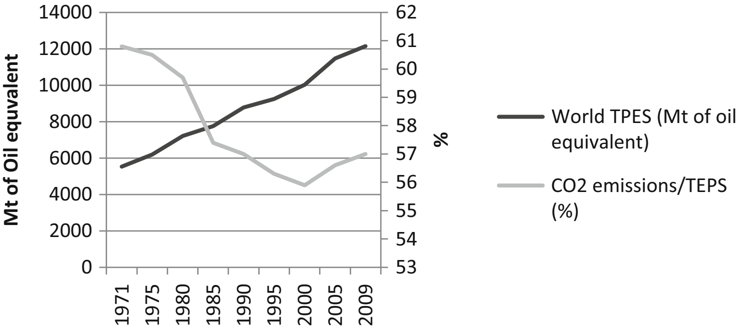

Fig. 1.4 Total Primary Energy Supply (TPES) and its share of CO2 emissions (IEA 2011). After 2000, CO_2 emissions per unit of energy supplied begins to increase again after a long-term declining trend

The building and transportation sectors combined produce nearly 50 % of global greenhouse gas emissions by sectors. In both sectors, eco-innovations (i.e., energy-efficient technologies) and low carbon fuels are seen as promising ways to mitigate climate change in a cost-effective way (Levine et al. 2007). However, Fig. 1.4 illustrates that the steadily increasing demand for energy services and primary energy supply decreases the effect of eco-innovations and limits their contribution to the effective reduction of GHGs and averting abrupt climate change. Overcoming such steady-state growth trends requires broad governance efforts at multiple levels.

1.4 Governance of GHG Emissions

The book addresses the need for basic scientific discussions concerning the governance of climate stability, i.e., discussions of the most promising governance systems and the impacts they will have on sustainable emission and energy consumption levels over time. The following remarks on established climate governance systems highlight the main challenges of the socio-technical transition that result from the dynamic complexity of the governance task. Specifically, the challenge of reaching an agreement in the UN climate change negotiations (Dimitrov 2010) and the regulation and implementation issues in the EU are addressed as illustrative examples.

In the book, we will argue that in the development of effective governance systems, robust emissions targets to limit global warming “at different levels” are a necessary but not sufficient condition. We also need a better understanding on causal governance processes that help to reach them.

1.4.1 Critical GHG Emission Reduction Targets

Since the early 1960s, scientists have collected data to test the hypothesis that increasing GHG emissions produced by burning fossil fuels causes global warming (Harding 2007). Sophisticated analysis of the historical changes in global average temperature (e.g. Mann et al. 1998 with its illustrative hockey stick graph) provides evidence for a rapid temperature increase since the industrial revolution. Within the last decade, a widespread scientific consensus has been reached that abrupt climate change (evinced and enforced by the melting of the Greenland ice sheets or the disappearance of the Amazon rainforest) may occur if carbon emissions continue unabated (IPPC 2001/2007). Furthermore, scientific evidence indicates that limiting global surface warming to 2 °C relative to pre-industrial levels is a reasonable goal to prevent abrupt and irreversible climate change. However, uncertainty remains concerning which cumulative GHG emissions limit in the 2000–2050 period would limit global warming to below 2 °C in the twenty first century (Meinshausen et al. 2009). This scientific analysis suggests that cumulative emissions of 1400 Gt of CO_2 (1000 Gt CO_2) within the 2000–2050 period results in a 50 % (75 %) probability of not exceeding the 2 °C threshold in the twenty-first century. This means that less than half of the proven economically recoverable fossil fuels reserves should be emitted before 2050. Alternatively, the politically discussed targets of halving global GHG emissions by 2050 relative to 1990 levels[1] would result in a 12–45 % probability of exceeding 2 °C.

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[1] With 39.4 $GtCO_2$-eq (21 $GtCO_2$ of sectors) global emissions in 1990, the 50 % reduction level in 2050 corresponds to 19.7 $GtCO_2$-equivalent (10.5 $GtCO_2$ of sectors) global emissions, http://www.iea.org/co2highlights/co2highlights.pdf, http://www.ipcc.ch/pdf/assessment-report/ar4/syr/ar4_syr.pdf.

While emissions levels for 2050 are seen as robust indicators, those for 2020 are less robust. Studies estimate that the probability of exceeding 2 °C increases to 53–87 % with reductions targets of less than 25 % of 2000 levels in 2020[2] (Meinshausen et al. 2009).

Assumption: While this type of scientific discussion of climate warming and thresholds is necessary for the governance of climate stability,[3] it is not sufficient for providing guidance to politicians and entrepreneurs. This proposition conflicts with a comment from IPPC scientist John Schellnhuber (cited by Schiermeier (2009)): "We have now a politically accepted and science-based threshold that allows us to calculate precisely how much greenhouse gas we can still afford to emit if we don't want to exceed a given probability of getting into dangerous territory".. He goes on to say: "[s]o much for science – the rest is up to politicians and voters" (313).

1.4.2 Multi-Lateral Governance Approaches

The UN climate change conferences and negotiations illustrate the significant challenge in reaching a global accord between all nations and their political and entrepreneurial leaders. This challenge includes several dimensions, ranging from acceptable climate targets, global as well as national long- and medium-term emission levels, absolute emission reductions to the governance of climate finance and the specific numbers, or the governance of emission auditing (Dimitrov 2010). The fourth IPCC report describes this challenge as follows.

> "The numerous mitigation measures that have been undertaken by many Parties to the UNFCCC and the entry into force of the Kyoto Protocol in February 2005 . . . are inadequate for reversing overall GHG emission trends. The experience within the European Union (EU) has demonstrated that while climate policies can be – and are being – effective, they are often difficult to fully implement and coordinate, and require continual improvement in order to achieve objectives. In overall terms, however, the impacts of population growth, economic development, patterns of technological investment and consumption continue to eclipse the improvement in energy intensities and decarbonization. Regional differentiation is important when addressing climate change mitigation – economic development needs, resource endowments and mitigative and adaptive capacities – are too diverse across regions for a 'one-size fits all' approach (*high agreement, much evidence*)" (Rogner et al. 2007: 97).

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[2] With 23.4 GtCO2 of sectors global emissions in 2000, the 25 % reduction level in 2020 corresponds to 17.5 GtCO2 sectors global emissions, http://www.iea.org/co2highlights/co2highlights.pdf.

[3] The term climate stability refers to "the stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system" as addressed in the UN, 1992: United Nations Framework Convention on Climate Change, United Nations, New York.

While the global UN negotiation approach seems insufficient on its own,[4] the manifold, multi-level, climate science-based responses of entrepreneurs and policy makers may have the power to trigger a global transition to greener economies that may be comparable to the Industrial Revolution with respect to the magnitude of change and the time frame (see also Dimitrov 2010). Furthermore, the fourth IPCC report supports the appraisal that multi-lateral climate governance needs to be supported by multi-level governance approaches to technology change.

> "It would be economically impossible without technology research, development, demonstration, deployment and diffusion (RDDD&D) and induced technology change (ITC), to stabilize GHG concentrations at a level that would prevent dangerous anthropogenic interference with the climate system. Government support is crucial at the development stage, but private investment will gradually replace the former for deployment (creating necessary market transformation) and for diffusion (successful market penetration)" (Rogner et al. 2007: 112).

As multi-lateral UN negotiations have thus far been insufficient because of the challenges of reaching a global accord, pro-active multi-level governance approaches such as those observed in the EU become critical for climate stability. However, these efforts also have to address further challenges on other dimensions. These challenges concern setting dynamic targets and standards for GHG emissions and energy-efficiency for different nations, sectors or products, as well as the implementation and administration of CO_2 emissions trading systems. Since the ratification of the Kyoto Protocol, the EU has achieved remarkable progress in climate policy. Between 1990 and 2007, GHG emissions in most sectors have decreased by 15 %. Only in the transport sector have emissions increased, by 36 %. Increasing personal and freight transport volumes have actually counteracted improved vehicle efficiency (EC 2011d).

1.4.3 *Climate and Energy Governance in the EU*

Since 2009, the EU has had an enhanced climate and energy governance system that is legally binding. This governance system should be effective in reaching the so called '20-20-20' targets (EC 2010a). They refer to the following targets that are to be reached by 2020:

- 20 % reduction of GHG emissions below 1990 levels in the EU.
- 20 % of EU energy consumption coming from renewable resources of EU energy consumption.
- 20 % reduction in primary energy use compared with projected levels.

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[4] In 2010, global GHG emissions increased by a record amount but the Kyoto Protocol has shown its effectiveness. Those countries that ratified the 1997 Kyoto Protocol have achieved their goals of cutting emissions to approximately 8 % below 1990 levels. http://www.guardian.co.uk/environment/2011/nov/04/greenhouse-gases-rise-record-levels.

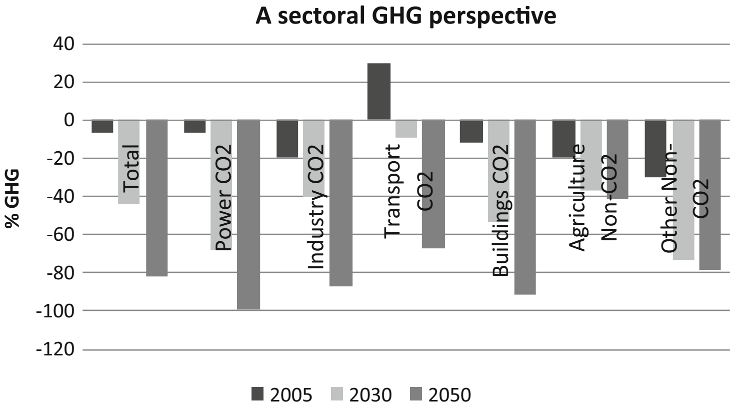

Fig. 1.5 The sectoral GHG emission reduction perspective of the EU (Adapted from EC 2011c). This perspective is based on an impact assessment study that applied multiple energy system modeling tools to project changes in supply and demand in a coherent manner (EC 2011c). The overall aim of the modeling project was to specify cost-effective reduction levels that consider the technological and economic potential of each economic sector

The EU governance system comprises four pillars to achieve these targets: The Emissions Trading System (ETS) for industrial GHG emissions, national targets to increase the share of renewable energy to 20 % by 2020, the carbon capture and storage framework, and, finally, the 'Effort Sharing Decision' package (ESD) that addresses emissions not covered by the ETS, including transport, buildings, waste and agriculture. The overall goal of the EU governance system is to transform Europe into a low-carbon economy and to increase its energy security (EC 2010c). The implementation of the ESD package needs to be particularly highlighted because it has resolved the coordination problem between the member states. Each member state has specific, binding GHG emissions targets that are a function of their relative levels of wealth. For example Luxemburg's target is a 20 % reduction in GHG emissions compared to 2005 levels. Conversely, Bulgaria is required to constrain their emissions growth to 20 % (EC 2009a). Each Member State is responsible for the implementation of goal-achieving policy packages. Another major effort of the EU climate action program is the sector-specific target-setting approach. Within the scope of a roadmap study, a cost-effective emission reduction pathway has been elaborated for each sector. The dynamic reduction targets for each sector are displayed in Fig. 1.5. The overall goal of the roadmap is a reduction in domestic emissions by 80 % below 1990 levels by 2050 with intermediate reduction targets of 40 % by 2030 and 60 % by 2040 (EC 2011c).

Historical data and Fig. 1.5 highlight that sectors other than transportation have more technological and economic potential for decarbonization. In the building sectors, there is the potential for a 90 % improvement by 2050. In the transport sector, CO_2 emissions are still increasing despite improved vehicle energy-efficiency, and an improvement potential of approximately 70 % is considered cost effective. A primary contributor of CO_2 emissions is the passenger car fleet with

12 % of the overall EU CO_2 emissions by sectors. Therefore, the EU adopted legislation in 2009 that set emission performance standards for new passenger cars to ensure that the average emissions from new passenger cars in the EU do not exceed 130 gCO_2/km in 2015, or 120 gCO_2/km for alternative fuels. Additionally, a long-term target of 95 gCO_2/km takes effect in 2020. A penalty payment scheme sets the incentives for automakers to comply with the legislation (EC 2009b, 2010b).

The above outlined integrated climate and energy policy approach is a very ambitious policy strategy. It may become a model for a global, low-carbon economy strategy, if it is implemented successfully. Given the urgency of effective climate action that has been accentuated by the release of the latest CO_2 emissions record in 2010 (IEA 2011b), successful socio-technical governance examples are key for overcoming both the cooperation and implementation challenges, specifically for multi-lateral UN negotiations.

Therefore, an improved understanding of the barriers to and drivers of successful socio-technological transitions is required that transcends one-dimensional analysis of either policy implementation or eco-innovation and diffusion approaches. There are many climate and energy system-modeling tools (e.g. Edenhofer et al. 2006; EC 2011c) that inform politicians, entrepreneurs and voters on goals in terms of targets and technology choice. However, there exist far less realistic pictures of the essence of socio-technical change in terms of the determinants and mechanisms that foster or hinder the spread of clean and energy-efficient technologies clearing the way for greener economies. Similarly, the dynamic implications of ingrained and evolving governance structures for sustainable emissions and energy consumption levels are unclear. Finally, socio-technical governance principles about the most promising and concerted policy and eco-innovation strategies still need to be substantiated to effectively reach the targets.

As a response to the perceived global challenge, this book intends to contribute to the development of helpful analytical approaches to the complex and dynamic problem in order to provide most helpful transformational knowledge for concerned political and managerial entrepreneurs at a local level. The local decision making context is where agency begins to transform the rules of the game and account for environmental aspects in the decision process. This is also the level where clean technologies are tested in the context of daily life and begin to make a change toward greener livelihoods, industries or even whole economies.

1.5 Organization of the Book and Chapter Contents

The book contains ten chapters that are grouped in three main parts. Each part provides a crucial pillar for the overall approach to the governance dynamics of induced technological change toward sustainability.

- The First Pillar presents theoretical and methodological discussions about the governance dynamics of socio-technological transitions.

- The Second Pillar provides illustrative case studies focusing on specific governance aspects of "green" road transportation and housing.
- The Third Pillar emphasizes how generic insights can be deduced and applied for related research questions in distinct fields.

Each chapter is a stand-alone paper that emphasizes a specific aspect concerning the analysis of socio-technical transitions at the local level.

Chapter 1: Ulli-Beer provides the introduction to the research task on governance dynamics of energy technology change. It clarifies the motivation that has triggered the investigation into the book's topic: Governance dynamics of energy technology change: Analyzing socio-technical transitions toward sustainability. The overarching objectives and targets of the book are explicated. The global challenge of reducing greenhouse gases in road transportation and housing are summarized.

Chapter 2: Ulli-Beer provides a directed synopsis of promising theoretical approaches of socio-technological transition studies. The aim is to clarify the decision-making challenge in the real world action context and the theory selection challenge for illuminating the decision making task. It answers the research questions: How should distinct theorizing be understood in the context of related theorizing? What are the sources of tensions and confusions between related theorizing? How can the tensions and ambiguities be resolved? The following core terms and concepts are explained: Technology change, socio-technical systems, as well as governance dynamics. Tension and their sources between different analytical perspectives are highlighted. Finally, the chapter identifies research opportunities for a system dynamics perspective, for resolving tensions in sustainability studies and the elaboration of causal decision support tools.

Chapter 3: Ulli-Beer et al. introduce the method of integrative transition simulation that guides the integration of theory building, data analysis and simulation as applied throughout the book. System dynamics modeling is introduced as a promising simulation approach that helps to operationalize and substantiate theorizing on socio-technical transitions. It is an analysis method that is particular helpful for identifying causal governance mechanisms that explain path dependence, path creation and lock-in. Its applicability for socio-technical transition phenomena has been illustrated by a case study addressing the transition toward energy-efficient housing.

Chapter 4: Müller et al. address the methodological challenges of collaborative research in highly fragmented socio-technical systems. Collaborative research plays an important role in operational research, strategic management and systems thinking. The chapter argues that the incorporation of a strong organizational focus into many soft operational research (OR) approaches is inadequate when studying socio-technical systems, which are fragmented and have no clear boundaries. In addition it also shows that methods for the identification of individuals, which are adequate for representing the perspectives of heterogeneous actors and sufficient for research into socio-technical transitions are absent from the literature. In response to this gap in the literature, the chapter proposes a terminology that differentiates between actors, experts, and agents. Based on this terminology, an iterative method to guide the assembly of an expert group to undertake collaborative research into governance dynamics of a socio-technical transition is proposed.

Chapter 5: Bosshardt et al. present a theoretical discussion about social norm building and its relevance for modeling green product diffusion. Social interaction effects of distinct technology adoption patterns are conceptualized as social norm competition. The method of simulation based theory building is applied to test the system behavioral implications for the case of two and three competing (eco)-technologies in vehicle fleets. The results indicate that social norm competition provides an endogenous explanation of tipping behavior in s-shaped diffusion models. The tipping point is explained by the built up of a critical mass of users that signal a new socio-technical norm fostering transition to irreversible substitution. The offered approach and perspective is intended to be useful for effective long-term policy making and to enhance the intuition about feedback rich sustainability transitions.

Chapter 6: Boksberger et al. develop and apply a road transportation model to analyze the interaction between demand and supply sides of the auto industry, as well as policy regulations. The main governance processes guiding technology change in the automobile industry are summarized as well as their behavioral impact on diffusion paths, CO_2-emissions and capital stocks. The model analyses provide evidence that anticipated regulations and early responses on the supply side induce economically and environmentally advantageous transition paths. The paces of infrastructure development and production capital adjustment are critical determinants of the transition paths toward near zero emission vehicles.

Chapter 7: Müller et al., focus on the inertia of the existing building stock that is a challenge for a socio-technological transition toward a near-zero emission sector as is sought by the EU. Their work highlights a concerted interplay of the governance mechanisms of market, technology, civil society and state that are necessary for a timely transformation of the existing housing stock. The elaborated model is used to identify most promising policy strategies. Policy analyses show that the renovation process of the existing building stock can be accelerated by a modest degree. However, an improved level of energy-efficiency of renovation practices has a remarkable effect on energy savings over the long term. The policy analysis also shows that command and control strategies for near-zero emission heating technologies are the most urgent to meet the CO_2 emissions targets in the building sector.

Chapter 8: Ulli-Beer et al., discuss a generic acceptance-rejection model structure that accounts for changes in the guiding rules. Social behavior patterns are often guided by stable values such as social norms and preferences. They also define a social equilibrium state. However, changing environmental conditions (e.g., climate change, resource scarcity) may induce behavioral changes and the acceptance of new technologies. Antecedents of aggregate behavioral change are value changes that predetermine when new behavior patterns emerge and a new social equilibrium state can be reached. The paper addresses these phenomena and discusses a model structure that represents the dynamical characteristics of paradigm change processes. The simple model structure is generic in the sense that it can be applied in adoption and diffusion studies, where effects of paradigm change are of interest.

Chapter 9: Kopainsky et al. illustrate how the application of the generic acceptance-rejection model regarding seed from improved varieties in African countries helps to better understand the transformation of agricultural sector from subsistence farming to small-scale commercial agriculture. Such a transformation path is seen as desirable, because it contributes to food security. The applied simulation framework highlights the role of historically accumulated trust and actual trust building processes for both, lock-in into subsistence farming and transition to commercial agriculture, respectively. The model simulations demonstrate that under current practices of cultivating improved maize seed varieties, all policies aiming at increasing yields are offset by the costs of fertilizer and seed. Effective adoption stimulation policies focus on measures that build trust in improved maize seed varieties and in this way contribute to food security.

Chapter 10: Ulli-Beer summarizes the main contributions of the research on governance dynamics and socio-technological transition with respect to the three guiding research questions:

- What determinants, mechanisms, and actors foster or hinder the spread of clean and energy-efficient technologies?
- How should a socio-technical transformation be governed?
- How can integrative transition simulation (ITS) support sustainability transitions?

The insights are summarized in the form of main governance and management principles that have been derived from the single case studies. The chapter claims that ITS supports coherent reasoning about effective governance mechanisms and adequate implementation plans within actor networks.

1.6 Audience of the Book

This book is written for researchers and managers, as well as policy makers who are interested in local responses to the global challenges of reducing emissions and securing the supply of energy. We specifically address researchers and consultants working for national and local government agencies (e.g., Swiss Federal Office of Energy), as well as for corporate enterprises and lobby groups or associations.

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Part I
Theory and Methods

Chapter 2
Conceptual Grounds of Socio-Technical Transitions and Governance

Silvia Ulli-Beer

> *As for the future, your task is not to foresee, but to enable it.*
> Antoine de Saint Exupery

Abstract This chapter provides an overview of theorizing on technology change and socio-technical transition. The first contribution of the chapter is to clarify how distinct theoretical framework should be understood in the context of other related theorizing. The second contribution is to clarify the sources of theoretical tensions, and to resolve ambiguities in terms. This is important because tensions and ambiguities hinder the accumulation of an inter-subjective theoretical ground. We observe that sustainability transition research increasingly relies on process theorizing. It stresses the role of feedback mechanisms and systemic barriers as a new rationale for concerted strategy and policymaking. On the other hand, it does not answer the questions of which and how causal structures influence system behavior, e.g., in terms of reaching emission reduction targets in time and/or dynamical competitiveness. We have identified two reasons for this tension. First, sustainability transition research traditionally employs descriptive theorizing. Behavioral consequences remain obscure due to lacking causal propositions. Second, there exists a variety of categorization schemes that use ambiguous technical terms for describing linkages, processes, and performance characteristics. Consequently, we propose a standardization of system technical terms based on system dynamics methodology. This is important to facilitate a shared understanding on the factors and processes of (un-)desired transition trends. Further, we propose to apply system dynamics mapping tools to conceptualize socio-technical systems as a causal feedback system. This mapping approach provides the structural elements of critical behavior phenomena, like inertia, lock-in, and path creation, in socio-technical systems. We assume that this is particularly supportive for governance-based steering, because causal beliefs about effective governance structures are a necessary condition for the acceptance of concerted action programs in heterogeneous actor groups.

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

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2.1 Introduction

In this chapter we critically discuss conceptual grounds of technology change and sustainability transition research. Innovation researchers have to deal with a multifaceted reality, therefore they develop *analytical perspectives* for building internally consistent theories that reduce the dynamical complexity in such a way that a "useful" picture emerges. A variety of analysis approaches have emerged, which shows a broadening in the problem framing and unit of analysis (Smith et al. 2010). Their common research interest is to describe the structure or performance of systems. In other words, they aim to clarify the factors and processes that explain the rate, direction and patterns of (radical) innovation adoption, diffusion and use. However, tensions between different theorizing approaches may arise depending on the chosen perspective, conceptualization, and terminology (Poole and Van de Ven 1989). While such tensions are confusing for (novice) researchers and practitioners, they also offer opportunities to advance sustainable transition theories, as the flourishing discussion in the literature shows (Edquist 2004; Hekkert et al. 2007; Bergek et al. 2008; Smith et al. 2010; Foxon 2011).

The overarching aim of this chapter is to enhance the clarity of the real world context and theoretical approaches of *energy technology change and socio-technical transitions*. We provide answers to the three guiding research questions:

- How should distinct theorizing be understood in the context of related theorizing?
- What are the sources of tensions and confusions between related theorizing?
- How can the tensions and ambiguities be resolved?

After providing a better understanding about the terms technology change, socio-technical transitions and governance, we elaborate distinct characteristics of different modes of theorizing. This provides the underlying logic for discussing the synopsis on theorizing on technology change and socio-technical transitions. We will specifically focus on the modus of theorizing and the applied technical terms to describe important factors and processes. Finally, we propose *a system dynamics perspective* that allows resolving some of the tensions and integrating insights from distinct theorizing.

We believe that this theoretical discussion is specifically helpful for novice innovation researchers that aim to develop theoretically grounded decision support tools for policy and strategy support in (messy) socio-technical problem situations.

2.2 The Real World Socio-Technical Governance Situation

> The formulation of a problem is often more essential than its solution, which may be merely a matter of mathematical or experimental skill. Albert Einstein, cited in (Van de Ven 2007: 71).

In this section, the real world challenge of the governance of sustainability transitions in socio-technical systems is elaborated. A better understanding of the specific challenges helps researchers to identify and integrate the relevant knowledge concerning technology change and sustainability transition research for policy and strategy making.

Consequently, the perspective taken in this chapter and throughout the book departs from a managerial situation of entrepreneurs and policymakers at the local level that proactively try to respond to global changes, such as climate change. Motivations for their actions arise not only from the established action paradigms of securing competitive advantages or economic growth, but also from enhancing resource productivity and from mitigation opportunities of global threads (Porter and Van der Linde 1995; Smith et al. 2010). These motivations come along with additional challenges, such as the establishment of new action paradigms within socio-technical systems. These may induce broader change within existing regimes of science and technology, industries, markets, and politics, but also the built environment (Geels and Schot 2007). This means that segmentation and decentralized decision making in socio-technical systems increases the complexity of the management task.

This creates a specific management situation. It turns from a well-structured problem situation that is amenable by well-known problem-solving technologies (in the broadest sense) into a messy problem situation. Such a situation is defined as “a dynamic situation that consists of complex systems of changing problems that interact with each other” (Ackoff 1979: 99). Müller, Grösser et al. (see Chap. 4) specify the messy action context of a socio-technical transition challenge as a societal problem situation. They characterize such transition challenges as “*highly fragmented situations, where it may not be clear what exactly the problem is, what kind of actors are involved in it, and who is responsible for addressing the problem. In particular, fragmentation means that actors in the problem situation may not be aware that they are participants in a societal problem situation*” (Müller et al. 2012: 498). This messy transition challenge also involves dynamic decision-making tasks. These are tasks that require managing rates and states of a system, such as selling/scrappage rates of (energy-efficient) cars and its corresponding fleet stock, or the decay and renovation rate of the stock of buildings with the objective to achieve a cost-effective CO_2 emission reduction trajectory. Experimental research and practice has shown repeatedly that such tasks are managed with low performance results, yielding costly, unsustainable, or undesired outcomes (Sterman 1989; Sterman 1994; Diehl and Sterman 1995; Moxnes 2004). The poor performance is explained by misperception of circular causalities (i.e., biased perceptions of delays, nonlinearities, or feedback complexities) that results in deficient management rules. Such a messy and dynamic complex situation hampers the deployment of eco-innovations and policy making. It calls for the development of adequate perspectives, frameworks and analysis methods for elaborating helpful guidance and decision support for the concrete problem situation (Sterman 2011).

Such tools should help entrepreneurs and policymakers to overcome their own misperception when dealing with dynamical decision tasks. Specifically, they should give guidance in dealing with systemic barriers and drivers, such as historically grounded lock-in effects and path creation toward a greener economy. Therefore, the tool should be applicable for strategy and policy making in the concrete action context, i.e., support the discussion of competitive advantages and compliance with CO_2 emission targets.

2.3 The Notion of Socio-Technical Transition and Governance Dynamics

The overarching topic of the book is summarized by the title: *governance dynamics of energy technology change toward more sustainable futures: analyzing and substantiating socio-technical transitions*. In this subsection we elaborate the understanding of the applied terms.

Technology change: With the notion technology change, we refer to the rate and direction of technology development and its economic impact. Relevant theorizing on technology change can be found within the disciplinary fields of technology and innovation management, industrial dynamics, and evolutionary economics, as well as the systems of innovation literature. The technology change literature is strongly linked to economic growth and competition issues.

Socio-technical transition: Socio-technical transition refers to reconfiguration processes between technology development and broader adjustment processes in science, industry, markets, policy, and culture (Geels and Schot 2007) that are necessary for the creation of new trajectories (Geels 2002; Geels and Schot 2007). Socio-technical system encompass the subsystem of production, diffusion and use of technology (Geels 2004). In contrast to technology change research addressing traditionally economic growth issues, the broader focus of research on socio-technical transition towards sustainability is interested in understanding how shifts in societal undesired trajectories of technological developments towards more sustainable trajectories come about in sectors such as transportation or housing (Kemp et al. 1998). This specific kind of research is also called sustainability transition research. The term sustainability indicates the normative quest of the direction and rate of change. It explicitly acknowledges the need to secure all three aspects in the socio-technical governance task, i.e., economical, ecological and societal aspects.

Governance: In the literature, the notion governance is described in many different ways and often used as an imprecise term that is related to policy interventions and institution building by the government (Meadowcroft 2007; Florini and Sovacool 2009). Government is a crucial but not the only means through which governance or coordination is achieved between actors. According to Florini and Sovacool (2009), "governance refers to any of the myriad processes through which a group of people set and enforce the rules needed to enable that group to achieve desired outcomes" (5240). In the context of societal problem situations, arrangements of public and private actors for solving societal problems are referred to as social-political governance (Kooiman 2000). Meadowcroft (2007) applies the notion "governance for sustainable development." He refers it to socio-political processes and interactions between public authorities, private business, and civil society oriented toward the attainment of sustainable development. It is a form of long term 'societal self-steering' that is goal directed and involve the coordination of activities of decentralized actors. Meadowcroft (2007) emphasizes that "a critical component of the steering involved in governance for sustainable development are the societal interactions which can help define 'clear goals' and develop better causal theories" (307). Because of this orientation on societal learning within governance, the term interactive or reflective governance is used (Hendriks and Grin 2007; Walker and Shove 2007). Voss et al. (2009) refers to the design of transition management as a promising mode of reflexive governance and long-term policy planning.

In our book we use the term governance in reference to socio-technical steering mechanisms understood in the sense of (circular) causalities, which coordinate the interactions of multiple actor groups or subsystems, as stated in Chap. 1. We assume that intertwined circular causalities between action rules control the power of actor groups with similar values and beliefs, the development of their resources, technologies, product markets, and infrastructures. Discrepancies between desired and effective system states create pressure for corrective actions within the socio-technical system; however, such purposeful responses may be overruled by historically established steering mechanisms and actor groups. This creates systemic resistance to change and results in undesired path dependencies and lock-in.[1] Not only purposeful interventions by the government and other actor

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[1] Path dependence refers to self-reinforcing processes that accelerate the development direction within a system. Lock-in refers to a historically evolved system state that can only be changed with great effort.

groups to achieve a desired outcome are considered, but also counteracting steering mechanisms, which reflect power asymmetries and path dependence in the system.

The term *governance dynamics* refers to both the variation in socio-technical steering mechanisms and its direct or indirect influence on measurable trajectories of change, such as CO_2 emission trajectories. For example, discrepancies between desired and effective CO_2 emission rates from transportation exert pressure on the guiding rules of actor groups to pay more attention to environmental attributes in the decision-making process.

With this understanding, we emphasize structural and behavioral causalities of governance. In this manner, we relate micro-scale activities to changes over time in selected system indicators. This is a linkage that has not gained much attention in the literature about governance in general, and about governance of socio-technical transitions in particular.

2.4 Heterogeneity in Theorizing

Synopsis: In order to address the first research question, “How should distinct theorizing be understood in the context of related theorizing?” we provide a synopsis about relevant theorizing. The focus is on theory-building approaches in the technology change and sustainability transition literature that characterize important factors and processes of governance dynamics in socio-technical transitions. For our synopsis, we have selected illustrative and most important stepping stones that address aspects of competitive ability and sustainability transitions. This means that we have not considered all research that enhances the understanding of important determinants. An encompassing account of the different theoretical approaches is beyond the scope of this work. Thematically focused reviews can be found in the literature (e.g., Garcia and Calantone 2002; Jordan 2008; Markard and Truffer 2008; Coenen and Díaz López 2010; Smith et al. 2010; Markard et al. 2012). We acknowledge that we need to remain sensitive to more peripheral and new research lines within the broad field of sustainability transition studies. Here, we would like to emphasize specifically the new literature on determinants of eco-innovations that are based on panel data models and analysis (e.g., Cainelli et al. 2011; Horbach et al. 2012; Kesidou and Demirel 2012).

In our synopsis we give a brief idea about the content and scope of the selected perspectives. We show how theory development has increased the variety in the used perspectives and terminology for explaining the determinants of innovation, technology change, and sustainability transitions. We are interested in better understanding the sources of variety in used technical terms (i.e., factors, structure, elements, processes, forces, dynamics, interactions, alignments, feedback, motors, functions). How are the technical notions used in theorizing? How are determinants of innovation systems, transitions, and performance conceptualized? In this manner the reader may become confused concerning the variety of terms. But this is exactly the main argument of our contribution: The conceptual ground of socio-technological transition is confusing, specifically for the novice innovation researcher. Our synopsis should provide an orientation and facilitate the selection of further literature.

Modes of theorizing: In order to better understand the different approaches to theorizing in socio-technical transitions, some features of theorizing need to be distinguished. It provides the basis for answering the second research question, "What are the sources of tensions and confusions between related theorizing?"

Descriptive theory: Conceptual frameworks and analysis heuristics that do not specify causal relationships between concepts are not considered explanatory theory but descriptive theory. Descriptive theory aims at improving categorizing schemes in order to better identify the relevant attributes of a phenomena (Christensen 2006).

Explanatory theory: Explanatory theory formulates assumptions with theoretical terms (often based on categorizing schemes) about relationships, and conditions when they apply (Van de Ven 2007). Explanations may be provided at different levels of abstraction using theoretical or observable terms. Theoretical terms (i.e., concepts and constructs) allow a higher level of abstraction and are used to formulate grand and middle range theories. Derived statements about relationships are termed propositions. Observable terms are variables that allow testing hypotheses derived from operational theorizing. An adequate understanding of causal relationships is important to derive policy or strategy implications for action managers (Christensen 2006).

Van de Ven (2007) highlights two modes of scientific reasoning: *(1) variance theorizing* and *(2) process theorizing*. Variance theorizing focuses on variance in factors. It is based on the scientific logic of answering questions like, "What are the antecedents or consequences of the issue?" (145). Variance is explained in terms of relationships among independent and dependent variables or concepts.

Process theorizing applies a different theory-building perspective that focuses on changes over time. It asks questions like, "How does the issue emerge, develop, grow, or terminate over time?" (145). Outcomes are explained by sequences of events. Consequently, a process analysis investigates sequences of change and how they occur. An often-used process analysis method is the narrative approach, which uses a conceptual framework to describe how things develop and change. Another applied process approach is based on event analysis. Actions and activities are classified to a category of concepts or variables that are deemed relevant to understand variation in some outcome criteria.

Differentiating between these distinct modes and approaches of scientific reasoning is important to understand the variety in theory and term conceptions. Also, it helps to classify why and how different findings of theorizing relate to each other, i.e., to understand when they are complementary rather than competing.

2.4.1 Disciplinary Perspectives on Technology Change

There exists a wealth of theorizing on technology change and it has a 76-year-long history (Garcia and Calantone 2002). Specific determinants (e.g., factor prices, knowledge generation, and diffusion), characteristics of innovation (e.g., incremental and radical, disruptive and sustaining innovation) and impact of technology change (e.g., creative destruction of firms, economic growth, and environmental change) have been researched from different perspectives. These include supply, demand, or organizational perspectives, as well as evolutionary perspectives on technology change (Box 2.1).

Supply side or demand side perspectives: One prominent innovation model for explaining technology (supply) push innovation is the so-called linear or pipeline model. Innovation is explained by a linear succession of basic research that generates new knowledge that leads to new applied research, resulting in invention, prototyping, and development, and eventually to innovation with a successful business model that allows widespread diffusion. This innovation model was guiding the Manhattan project and many other technological innovations, particularly during and after the World War II era (Rosenbloom 1981; Weiss and Bonvillian 2009). The demand side perspective highlights innovations processes that are induced from the economic or selection environment (Ruttan 2001). It assumes that changes in the direction of technology development are caused by changes in the markets (e.g., increasing or decreasing factor prices) or policy environment (e.g., standard setting). It has been often applied to theorize on innovation in agricultural development.

Firm- and industry-level theorizing: Early on, the importance of linking technology management to further arenas of organizational development has been emphasized (Rosenbloom 1981). This includes theorizing on the relationship between technological dominant designs and innovation, as well as organizational change, competition of firms, and whole industries (Abernathy and Utterback 1978; Abernathy and Clark 1985; Tushman and Anderson 1986; Freeman and Perez 1988; Utterback 1994, 1996; Christensen and Rosenbloom 1995; Christensen 2002; Furman et al. 2002).

For example, the management of technology and innovations has been investigated at the firm level as an important determinant of competitive advantage (Utterback 1971; Cohen and Levinthal 1990; Adner 2006). Likewise, technology change became a very important topic for whole industries, because it has the capacity to disrupt the leadership structure of the industry and destroy big companies (Henderson and Clark 1990; Utterback and Suárez 1993; Utterback 1996; Adner 2002; Christensen 2006). Utterback (1994, 1996) specifically highlights the role of dominant product designs and technological innovations that imply “changes in system relationships” in the industry. He argues that, “architectural knowledge of products tends to become embedded in the structure and information-processing procedures of established organizations” (195). Critical are discontinuities that break market and manufacturing linkages and call for different kinds of business models (Utterback 1994, 1996; Christensen 2006). In sum, the literature emphasizes that specific characteristics of technological innovations and associated business models (e.g., incremental, radical, sustaining, or disruptive innovation) have distinct impacts, even on economic cycles (Freeman and Perez 1988; Henderson and Clark 1990; Christensen 2006).

Most of the theorizing described above went through the phase of descriptive theory building with different categorization schemes on characteristics of innovation and degree of innovativeness of a product, firm, or industry (Garcia and Calantone 2002). Eventually, disruption theory, as an example, entered the phase toward explanatory process theorizing, and the identification of the causal mechanism between technological innovation and the success or failure of leading companies (Christensen 2006). Newer panel data model and analysis specifically focus on the determinants of environmental innovations and firm-level performance (e.g., Horbach et al. 2012; Kesidou and Demirel 2012).

Endogenous variety creation: Dosi (1982) has suggested a micro-level framework of technology change that offers an endogenous explanation of paradigm changes in technology development; it accounts for incremental and radical technological change processes. In this, it explains how changes in the direction of technology change come about in the sense of a "mutation generating" mechanism. Radical changes in the direction of technological progress are attributed to paradigm change in the search processes. Important determinants are "scientific advances, economic factors, institutional variables and unsolved difficulties of established technological paths" (147). Incremental improvements follow the same search paradigm and therefore follow the established improvement trajectories.

Selection processes: Dosi's interpretation of technology change complements evolutionary economic models of technology change pioneered by Nelson and Winter (1977, 1982). They developed formal economic models with endogenous processes of technological change where the economic and social environments select between both the direction of mutations and the mutations themselves (Dosi 1982). Evolutionary thinking, with the core concepts of variation, selection, and differential replication, has become an important research field to better understand dynamics of changes in economies. In evolutionary economics modeling, innovation processes are conceptualized as the main driver of diversity creation in technology and practice (variation). Competition, regulations, and institutions are understood as mechanisms of selection. Imitation behavior is associated to differential selection. Eventually, different formal modeling approaches have been elaborated to analyze the outcome of these interacting processes (Safarzynska and Van den Bergh 2010). The potential of evolutionary modeling approaches to contribute to socio-technical transition theorizing has been highlighted more recently (Safarzynska et al. 2012).

Evolutionary economic modeling is an example of formal explanatory theorizing on a rather abstract level. It offers formal theorizing on causal mechanism and system behavior development over time. It has the potential to test propositions about micro-level processes and macro-level behavior.

Behavior patterns of technology change: With the growing importance of environmental and global changes, a kind of paradigm change toward a dynamic perspective on eco-technology change can be observed (Porter and Van der Linde 1995; Grübler 1998; Grübler et al. 1999b; Grübler et al. 2002). Grübler (1999a) provides ample empirical evidence that technological choices have long-term impact on the characteristics of industrial societies and the natural environment. Based on long-term historical analyses of time series, he identifies stylized stages of technological development and typical characteristics as a basis for the improvement of technological change modeling. In Table 2.1, six stages in the life cycle of a technology are differentiated: invention, innovation, niche market commercialization, pervasive diffusion, saturation, and senescence. For each stage, key mechanisms and measures (cost, market share, learning rates) are identified that relate its finding to extant technology change research. He concludes that, despite the extant wealth of technology change research, it remains an important area of research to elaborate processes of radical technological changes endogenously. This is deemed important to improve economic modeling approaches and to provide guidance on how to deploy the opportunities of eco-technology change (Grübler et al. 1999; Grübler et al. 1999).

This line of theorizing is an exemplar of process theorizing on behavior characteristics and underlying causal mechanisms. It provides both conceptual as well as more operational input to formal economic modeling approaches.

In summarizing this synopsis on technology change theorizing, we recognize that theorizing has advanced from, initial descriptive categorizing to explanatory theorizing. Also, variance theories have been complemented with process theories. Those either focus on behavioral sequences, on causal mechanisms, or even on proposition about what causal mechanisms explain observed behavior patterns over time. Hence, it is noteworthy that changes over times concerning structural relationships and system behavior aspects are addressed by the term dynamics of innovation in industries (Utterback 1994, 1996). Figure 2.1 illustrates stylized behavior patterns during phases of technology change that have been identified by firm- and industry-level theorizing. Most interesting is the number of firms that exhibit a boom-and-bust pattern during the stages of niche market commercialization and pervasive diffusion of radical (or disruptive) innovations.

Due to field specific boundaries, different levels of abstractions, and analysis, there exists a heterogeneous understanding about core determinants (either as factors or linkages between factors) of technology change. This may hinder the advancement of more formal modeling and operational theorizing approaches. In addition, the integration of this extant knowledge into theorizing on sustainability transition may be hampered.

Table 2.1 Stylized stages of technological development and typical characteristics (Adapted from Grübler et al. 1999a: 249)

Stage	Mechanisms	Cost	Market share	Learning rate
Invention	Idea & knowledge generation, breakthroughs; basic research	Difficult to attribute to a particular idea/product	0 %	Hard to measure
Innovation	Applied research, development, and demonstration (RD&D) projects	High, increasingly focused on particular, promising products	0 %	Hard to measure, high in learning (e.g.,> 50 %)
Niche market commercialization	Identification of special niche application; investments in field projects; close relationships between suppliers and users, learning by doing	High, but declining, with standardization of production	0–5 %	20–40 %
Pervasive diffusion	Standardization and mass production; economies of scale; building of network effects	Rapidly declining	5–50 % Rapidly rising	10–30 %
Saturation	Exhaustion of improvement potentials and scale economies, arrival of more efficient competitors into market; redefinition of performance requirements	Low, sometimes declining	Up to 100 %	< = 0 % severe competition
Senescence	Domination by superior competitors; inability to compete because of exhausted improvement potentials	Low, sometimes declining	Declining	< = 0 % severe competition

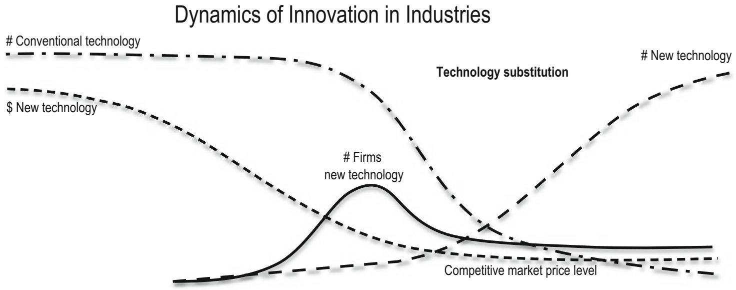

Fig. 2.1 Stylized behavior patterns of technology change in industries

Box 2.1: Definitions of Distinct Characteristics of Innovations

Definitions of important terms: In the literature, distinct innovation notions are used with often differing understanding (e.g., van den Hoed 2007). For our short overview, we refer to the original definitions of the key authors in the field.

Dominant design: "A dominant design embodies the requirements of many classes of users of a particular product, even though it may not meet the needs of a particular class to quite the same extent as would a customized design" (Utterback 1994, 1996: 25).

Incremental and radical innovations: "Incremental versus radical innovations can be reinterpreted in terms of 'normal' technical progress as opposed to new emerging 'technological' paradigms" (Dosi 1982: 158).

Sustaining innovation: "A sustaining innovation targets demanding, high-end customers with better performance than what was previously available. Some sustaining innovations are the incremental year-by-year improvements that all good companies grind out. Other sustaining innovations are breakthrough, leapfrog-beyond-the-competition products. It doesn't matter how technologically difficult the innovation is... Because this strategy entails making a better product that they [incumbents] can sell for higher profit margins to their best customers, the established competitors have powerful motivations to fight sustaining battles. And they have the resources to win" (Christensen 2003: 34).

Disruptive Innovations: "Disruptive innovations, in contrast, don't attempt to bring better products to established customers in existing markets. Rather, they disrupt and redefine that trajectory by introducing products and services that are not as good as currently available products. But disruptive technologies offer other benefits – typically, they are simpler, more convenient, and less expensive products that appeal to new or less-demanding customers" (Christensen 2003).

2.4.2 Systemic Perspectives on Sustainability Transitions

In the last three decades, research on *innovation systems* evolved around issues of technology change, economic growth, competitiveness, and sustainability transitions. Smith et al. (2010) explains the development of innovations studies on sustainability transitions as adjustments of analytical frameworks to the broadening of the problem framing – from clean technologies to industrial ecology, and to system innovation for sustainability. This development has been inspired by different research strands that include research on technological paradigms (e.g., Dosi 1982), on technological regimes (e.g., Nelson and Winter 1977), complex system research (e.g., Kauffman 1995) and national innovation systems research (e.g., Freeman 1988), as highlighted by Markard et al. (2012). The authors have identified the following four core research strands in the field of sustainability transitions studies: transition management (TM), strategic niche management (SNM), multi-level perspective (MLP) and technological innovation system (TIS). The authors also highlight that, for the maturation of the field of sustainability transitions studies, it becomes important to reach out beyond these approaches.

In this subsection, we intend to give a brief overview on the content and scope of most relevant systemic school of thoughts on technology change and sustainability transition, being the NIS (national innovation systems), TIS, TM and SNM, and the MLP approaches. In particular, we are interested in understanding how "determinants" of innovation system transitions and performance are conceptualized and what "system technical" notions are used. To remind, we neither intend to provide a detailed account of each approach, nor do we mean to give a systematic comparison of the approaches. These kinds of review can be found in the literature (e.g., Coenen and Díaz López 2010).

National systems of innovations (NIS): Since Freeman (1987, 1996), who first developed the system perspective to study conditions of innovations in nations, many innovation researchers have found the system perspective useful for studying *structures* and *processes* of innovations. Eventually, different systems of innovation have been defined depending on the specific scope and focus of analysis (e.g., national, sectoral, regional, technological, or socio-technical systems). The focus of a system perspective emphasizes *interactions* between technology, actors, institutions, and activities beyond the boundary of the firm (Geels 2004).

Freeman (1987) coined and defined the term national system of innovation as *"the network of institutions in the public and private sectors whose activities and interactions initiate, import, and diffuse new technologies"* (1987: 1). With the term activities, he refers to education, training, production engineering, design, and quality control, as well as R&D. These activities are organized by institutional arrangements, such as research councils, national R&D labs, or universities (Freeman 1995). Edquist (2004) provides a broader and more general definition of (national) systems of innovation. He argues that they encompass "all important economic, social, political, organizational, institutional and other factors that influence the development, diffusion and use of innovation." He points out that, at the present state of the art, the determinants of innovation are not understood systematically and in detail. Therefore, all factors that influence innovation processes should be included. This has laid the ground for further NIS research that focuses on the broader contextual factors and relationships that support technological change. For example, the "triple helix" of the university-industry-government relationship has been focused on as an important contextual relationship that supports innovation and economic growth (Etzkowitz and Leydesdorff 2000; Kim, Kim et al. 2012). Recent research has focused on factors that explain distinct patterns of technology-based sectoral change (Dolata 2009). The *transformative capacity* of a new technology has been suggested as one factor that describes the technology-based pressure for change. The complementary factor is the *sectoral adaptability* that accounts for the variance in the ability of social subsystems (e.g., institutions and actors) to anticipate and proactively manage technology pressure.

These innovation system approaches provide a broader perspective on factors and interactions (including institutions that organize different domains of activities) in support of technology-based entrepreneurship. In this, they enhance the understanding of effective structures in innovation systems concerning competitiveness. They offer a snapshot understanding of the structure. Therefore, the traditional innovation system approach may be considered as multi-dimensional variance theory. It does not address dynamic aspect, neither concerning the evolution of structures nor system behavior.

Technological innovation system (TIS): A specific focus on technological niche development has been suggested by the technological innovation system approach (Jacobsson and Bergek 2004; Hekkert et al. 2007; Bergek et al. 2008). It aims at better understanding the processes and their dynamics in the buildup of an innovation system.

This scholarship assumes that the innovation system around a technology is an important determinant of technological change. It postulates that the development of specific innovation system functions in chronological sequences is required for a successful development and deployment of cleaner technologies. Examples of such functions are entrepreneurial activities, knowledge development, knowledge diffusion, guidance of search, market formation, resource mobilization, and creation of legitimacy (Hekkert et al. 2007). A weak functional achievement or a mismatch between the achievements of different functions may explain an unsuccessful setup of an innovation system that accounts for eco-innovation failure.

This strand of research tries to identify patterns of reinforcing interactions between the functions, named motors that foster the development of the functions. With their approach, they provide a process framework about dynamics in structures and system behavior. It has the characteristics of a conceptual description framework, but does not yet qualify as a causal explanation for the emergence of structure and system behavior. It does not yet suggest consistent causal explanations about structural conditions that reinforce or hinder the performance of functional achievements. Any institution- and actor-specific dimensions are missing, as well as causal incentive or pressure concepts (Coenen and Díaz López 2010).

Strategic niche and transition management (SNM&TM): Transition management researchers use conceptions such a technological and market niches and how they enable shifts in socio-technical regimes (Kemp et al. 1998; Rip and Kemp 1998; Rotmans et al. 2001). The notion socio-technical regime has been developed in reference to the Nelson and Winter's (1982) technological regime notion. But it extends the narrow technological regime concept and includes interacting processes between heterogeneous institutions, a network that "creates the structural patterns that shape innovation and creates trajectories of social development" (Smith et al. 2010: 440).

The transition management approach particularly emphasizes strategic envisioning that supports goal-oriented modulation. The research focuses on steering from within, which refers to niche-internal processes that include networking, learning, and visioning. It can be applied as an analyses framework to describe how local (P&D) projects and global rule-sets guide actors' behavior. Transitions are described in terms of forces, interactions between niche internal and external processes (Schot and Geels 2008). The SNM literature also provides practical guidelines and tools for implementing such a governance approach (Kemp et al. 2007).

The TM approach offers a dynamic framework that enhances the understanding of system behavioral characteristics by classifying different phases of transitions (i.e., predevelopment, takeoff, breakthrough, and stabilization). Rotmans et al. (2001: 19) point out that "a transition is the result of long-term developments in stocks and short-term developments in flows." This understanding, together with the focus on structural processes, may provide a first step toward the formulation of a process theory that links structural aspects to system behavioral characteristics.

Multi-level perspective (MLP): Gradually, research on transition management resulted in the multi-level perspective (Rotmans et al. 2001; Geels 2002, 2005, 2010). It focuses on changes in institutional structures and actor networks over time. This approach distinguishes three analytical levels: niches, regimes, and landscape. The notion socio-technical regime refers to stable actor networks with well-aligned rules within and between different regimes, e.g., technological, scientific, industrial, market, governmental, and cultural regimes (see also Box 2.2). It describes the dominant modus operandi for realizing a societal function, such as housing or transportation. The dominant regime structures explain incremental change and path dependence within the socio-technical system, including also material artifacts and production resources.

Niches are protected spaces with flexible actor groups and rules. This setting explains how radical innovation can emerge and how variety is created. The landscape concept describes the external environment, which cannot be directly influenced by niche or regime actors (e.g., macro-political developments, cultural trends, and macro-economics), but may create pressure for change on the socio-technological regime. The main argument of the MLP approach is that alignment processes between and within the three levels account for both a transition from one system to another and stable trajectories. However, distinguishing context dimensions that differentiate successful transition from delayed/hindered are not yet consistently elaborated. Complementary frameworks provide further descriptive power that focuses on distinct characteristics of niches and regimes (Smith and Raven 2012).

A specific aspect of the MLP framework needs to be highlighted. It explicitly refers to the concept of reflexive agency and structure, which points to the relevance of actor-rule system dynamics for transitions (Giddens 1984; Burns and Flam 1987). The general characteristic of this conception is a feedback process that defines structures of actor networks and rule systems as both the medium and product of action. Based on this rationale, Geels (2004) suggests differentiating between the socio-technical system (i.e., material artifact, knowledge, capital, labor, and cultural meaning) and the actors and institutions (i.e., rules). The rules and activities of actors control how these resources are deployed. A drawback of the encompassing narrative of socio-technical transition is the lack of a theoretical micro-foundation for actor behavior; i.e., driving forces of eco-innovations within firms are not explicated.

In summary, we see that, up to date, a variety of conceptual frameworks are available to support the analysis of socio-technical transitions. This poses a challenge for the application selection of a theoretical perspective for a specific real world problem situation and the accumulation of a consistent knowledge stock. In a systematic literature review, Coenen and Díaz López (2010) have identified substantial conceptual differences between sectoral innovation systems, technological innovation systems and the MLP approach on socio-technical systems. Their systematic comparison reveals conceptual differences regarding the delineation of system boundary, and the conceptualization of actors, networks, institutions, and knowledge. Also, they point out tradeoffs between static perspectives and dynamic perspectives concerning the focus on system structure and system behavior. They conclude that these differences hinder knowledge integration for the investigation of drivers and barriers of sustainability transitions and improved competitiveness in socio-technical systems.

Box 2.2: Definition of Socio-Technical Regime

Definition of socio-technical regime: Kemp et al. (1998) have explicated their first definition of a technological regime as: "… the whole complex of scientific knowledge, engineering practices, production process technologies, product characteristics, skills and procedures, and institutions and infrastructures that make up the totality of technology." They explain that they refer to rules and beliefs, which "… guide (but do not fix) the kind of research activities that companies are likely to undertake, the solutions that will be chosen and the strategies of actors (suppliers, government and user)." Those are "…embedded in engineering practices and search heuristics with the rules of the selection environment" (182). Later, this understanding has been applied to describe socio-technical regimes.

2.4.3 Governance of Technology Change and Sustainability Transitions

Corresponding with theorizing on technology change and sustainability transitions, theorizing on rationales of policy interventions in support of desired development trajectories has been advanced.

Market failures rationales: The rational for policy intervention in support of (eco-) innovations and environmental protection are traditionally based on the economic arguments of externalities or market failures. These are private costs of actors or public benefits that are not compensated by price mechanisms and are called market failures.

R&D and innovation policies are based on the existence of *positive externalities of knowledge creation*, or knowledge spillovers. Knowledge can easily be copied without compensating the inventor or innovators for the costs of creation. Therefore, there emerge asymmetries between private and social returns of innovation. The incentives to private firms to invest in innovations remain suboptimal for the economy (Arrow 1962).

Environmental policies are based on both the existence of negative externalities in respect of uncompensated harmful impact on the environment (Pigou 1932) and positive externalities (e.g., clean air and noise reduction).

These neo-classical economic rationales of policy interventions are complemented by rationales of "increasing returns" that create path-dependent or lock-in externalities (Arthur 1989; Arthur 1994; Arrow 2000; Unruh 2000; Unruh 2002; Unruh and Carrillo-Hermosilla 2006). They emphasize that those policies are more efficient, which influences the natural development of economic structures than those which enforces a static outcome (Arthur 1999). Jaffe et al. (2005) differentiate three different kinds of increasing returns that are relevant for the adoption and diffusion of green technologies: (1) *learning-by-using* in the demand side refers to information feedback processes between adopters and potential adopters about the "utility" of the new eco-technology; (2) *learning-by-doing* in the supply side refers to decreasing cost with increased experience; and (3) *network-externalities* arise if the utility of a product increases with increasing adoption of complementary products or infrastructures.

In addition to failures of product markets, capital markets for funding technology development are also characterized by failures. These are related to uncertainty about the returns on investment and information asymmetries about the potential of a technology.

These different kinds of policy rationales and reinforcing interactions of market failures imply the need of a concerted policy-portfolio that aims to stimulate technology development and diffusion as well as the internalization of environmental impacts (Jaffe et al. 2005; Foxon and Pearson 2008).

However, policies that are directed toward the development and diffusion of specific technologies are controversially discussed. It is questioned that governments should pick technology, because more efficient/effective selection institutions may exist (e.g., public-private partnerships), which also help to minimize the danger of generating a suboptimal path dependency. In the literature, it is also acknowledged that the evaluation of policy success and efficiency of dynamic policy programs in support of sustainable transitions remains an important challenge (Jaffe et al. 2005).

The failure trichotomy in knowledge exploration and exploitation: A systematic view on different causal mechanisms of innovation failures suggest to differentiate between market failures and failures that create system inertia, as well as those that inhibit emergence (Gustafsson and Autio 2011). System inertia arises due to institutional inertia or structural deficiencies in organizations influencing incumbents' activities. Emergence is inhibited due to socially and institutionally constrained sense making. It refers to the (self-)perceived roles of actors in innovation processes: "Inhibited emergence arises from cultural-cognitive frames of institutions that guide actors' assumptions concerning their own and others' roles in innovation processes and from actors' inability to bridge activities and negotiate new roles and relations" (828).

This framework helps to understand challenges of path dependence (system inertia) and path creation (inhibited emergence). It includes the insight from theorizing on technology change and sustainability transition from both the disciplinary and systemic perspectives. TM or the TIS approaches are seen as important frameworks for designing effective policies, which foster the development and diffusion of eco-technologies and help to overcome "inhibition" failures. The MLP may provide guidance on the sequential choice of long-term policy programs in support of sustainability transitions (Geels 2006). However, further research may clarify how the tension of stability in regimes (inertia) and flexibility in niches (emergence) is resolved in real-world transition contexts. In the literature, it is suggested that incrementally implemented mixes of policy instruments, institutions, networks, and organizations become promising governance solutions. This implies the need for a transition from government to governance with constantly redefined and reinvented steering mechanisms that co-evolve with a dynamic environment (Duit et al. 2010). In correspondence to these deliberations, the guiding governance principles suggested by Foxon and Pearson (2008) should be emphasized:

> (i) Developing and applying the concept of 'systems failures' as a rationale for public policy intervention;
> (ii) Taking advantage of the appearance of 'techno-economic' and 'policy' windows of opportunity;
> (iii) Promoting a diversity of technology and institutional options to overcome 'lock-in' of unsustainable technologies and supporting institutions. (14).

In summary, theorizing on the steering of socio-technical transition has shifted to a broader systemic understanding. System failures or system barriers – both terms are often used as a more encompassing policy rationale, compared to the market failures approach, and has become the focal point of theorizing. It is complemented by a transition in the focus from government-based to governance-based steering. Theorizing on governance of sustainability transition is mainly based on structural descriptions due to a lack of causal policy frameworks. This is problematic because causal beliefs about effective governance structures underlying socio-technical transitions are one important factor to form advocacy coalitions in support of purposeful interventions (Sabatier 1998). This also limits the legitimacy and acceptance of specific governance programs and eco-technologies (Todt 2011).

There exist only a few modeling approaches that postulate and test shifts between causal steering mechanisms and their impact on system behavior characteristics. Evolutionary modeling has been suggested as a promising approach for increasing our understanding on governance structures and system behavior dynamics (Safarzynska et al. 2012). However, this line of research is quite abstract and needs to be developed further, as underlined by Faber and Frenken (2009): "Few evolutionary modeling approaches have been developed so far to describe interactions and relational structures in a system, in order to study development of a system's structure, the evolution of relations and interactions within a system, and to understand properties of emergence in relating micro-scale activities to system properties"(467).

To conclude our synopsis, we summarize our main observation with the following argument (see Box 2.3):

Box 2.3: Argument About Main Tensions in Theorizing on Sustainability Transitions

Sustainability transition research increasingly relies on process theorizing. It stresses the role of feedback mechanisms and systemic barriers as a new rationale for concerted strategy and policy making. On the other hand, it does not answer the questions of which and how causal structures influence system behavior. Therefore, the identification of effective governance structures is limited. Existing explanation frameworks do not address the following types of questions: How can emission reduction targets be met in time? How can we stay competitive during socio-technical transitions?

2.5 Toward a System Dynamics Approach for Theorizing About Socio-Technical Change

> The largest problem is not to choose among the (theoretical) alternatives but to weave them together in a way that allows each to illuminate the others (March, 1997: 10) cited by Rudolph et al. (2009: 734).

The brief literature overview gives evidence that system approaches to theory development on sustainability transitions are attractive for researchers, but also challenging. Several systemic properties are of interest and different technical terms are used to specify them. Also, we observe an emphasis on description with the elaboration of multiple categories, but few approach that focus on theoretical causation. In theorizing, this descriptive variety can lead to confusions and trigger questions like: What kind of theory is suggested? What exactly is the contribution of the theory? How do the different perspectives and approaches relate to each other? What specific technical terms indicate one-directional causalities, circular causalities, or interactions between subsystems or clusters of variables?

2.5.1 A System Dynamics Perspective

In the following, a basic system dynamics framework is presented that helps to organize the different aspects and terms that should be differentiated for an unambiguous explanation of the dynamics of socio-technical systems. This framework is based on the system dynamics school of thought on complex social systems (Richardson 1991; Sterman 2000).

Unit of analysis: The level of analysis is a socio-technical system and the units of analysis are subsystem, elements, and causalities. In the sustainability transition literature, there is a growing inter-subjective understanding that heterogeneous actor groups and networks, guiding rules (institutions), technology, resources, and infrastructures are important elements of a socio-technical system. Those can be grouped in different subsystems, depending on core activities (production, knowledge generation, use. . .). The grouping should depend on the problem framing or the focus of theorizing. For the formulation of propositions, the causal interactions between attributes or specific dimensions of the elements (e.g., level of energy efficiency of competing technologies) are of interest and not the elements themselves. Descriptive theorizing can become useful to identify the relevant attributes or dimension (e.g., innovativeness of actor groups, sustaining versus disruptive innovation, etc.).

Systemic properties: Two core systemic properties and two dimensions that are interrelated should be differentiated. The core systemic properties of interest are the structure of a socio-technical system and its behavior over time, as illustrated in Fig. 2.2. Both the system structure and the behavior may be either stable or change over time. The system structure refers to causalities between element- or subsystem-specific attributes. For example, high resources of incumbent actor networks lead to more activities than low resources of new actor networks. There may emerge qualitative change in the structure if new institutions or new actor networks are established. Circular causalities within a system are important process structures that influence system behavior over time. They help to link system structure to behavioral characteristics. Behavioral characteristics of a socio-technical system can be described by different system indicators. Their properties can be measured with time series that become the reference variable of the system behavior of interest. The work by Grübler et al. (1999a, b, 2002) is an research exemplar that provides most useful data on system behavior characteristics. Stable technology diffusion paths point to incremental innovation trajectories and stability in the evolution of the system. Contrarily, qualitative changes in the reference variables indicate radical innovations and shifts in the guiding rules.

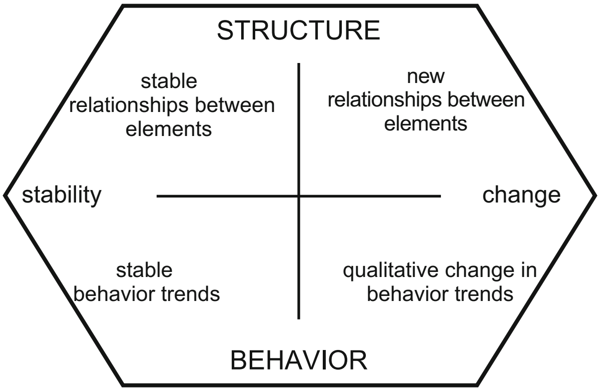

Fig. 2.2 Core properties and analysis units of a system dynamics perspective

Technical terms: In our reference literature, we have observed a plethora of technical terms that have been used to describe, analyze, and explain socio-technical transitions. We refer to terms like drivers, motors, endogenous and exogenous forces, pressure, incentives, functions, causal mechanisms, reinforcing feedback, structures, processes, alignment, and transition from one system to another. We understand that the variety in the terms can be explained by the different reference disciplines, modes of theorizing, or levels of abstraction.

We suggest developing a more standardized terminology to increase the inter-subjective clarity of their meaning. For analytical precision, we suggest distinguishing between terms that refer to the elements of a system, such as factors or variables. Variables are often used in operational models and can be specified as the dependent or independent variable in unidirectional causal relationships.

More complex relationships between factors, which are often indicated by unspecific terms such as drivers, forces, processes, and motors, should be specified concerning their causality. More precise terms are causal mechanisms or circular causalities that can be mapped as feedback loops.

Further, in order to clarify the meaning of alignment and pressure, it is necessary to specify the dimension and goal-gap constellation that are aligned or induce pressure in a system.

2.5.2 Tools for Describing Socio-Technical Governance Structures

The sustainability transition literature refers to multiple factors and processes that steer system evolution. But the question arises: How can they be explicated for a concrete action context? We illustrate that the mapping tools developed in the field of system dynamics are helpful for consistently explicating and communicating the important causal mechanism of a socio-technical system.

For illustrative reasons, we present a causal loop diagram that has been developed in a case study about transitions to energy-efficient housing (ee housing) in Switzerland (see also Chap. 6). We don't aim to comprehensively describe the developed causal loop diagram, but to illustrate how the mapping tools can be applied to visualize the relevant feedback loops.

Mapping tools: A feedback loop consists of fast-changing variables and slow-changing state variables; the latter are indicated by a box. State variables are critical to explain behavioral dynamics. They create nonlinearities, inertia, and provide systems with a memory. The circular causality hypothesis between variables is indicated by the interlinked arrows that form a loop. The loops have polarities, which means that they can be either reinforcing (positive) or balancing (negative). The loop polarity refers to the behavioral impact of a loop, producing either exponential change or goal-seeking behavior. If all relationships are rectified, then a loop is reinforcing. If there are an uneven number of converse relationships in a loop, it is balancing. For a more comprehensive description of the mapping tools, we need to refer to Sterman (2000) or Richardson (1995).

Process theorizing: In order to explicate the causal mechanism in a real-world decision context, these mapping tools can be applied for process theorizing.

In the diagram presented in Fig. 2.3, key factors and processes that have been steering the transition to ee housing in Switzerland are explicated. They postulate the dynamic hypothesis about the relevant governance structure. We see that the variables do not refer directly to the elements of a system, but to the interlinked dimensions of actors, behavioral rules, technology, designs, and resources. The diagram highlights four reinforcing and two balancing feedback loops: (R1) learning by doing by suppliers, (R2) acceptance dynamics by users, (R3) market pull by suppliers, (R4) economies of scale in the market; (B1) technology push by innovators, and (B2) limits to reduction by authorities.

The dynamical pressure for the evolution of the ee-trajectory in the housing system has been created by the gap between the average annual energy demand per housing unit and a political desired annual energy demand target. The latter has been updated over time. This sliding goal established a dynamic incentive to enhance technology development (B1). Technology improvements have created an innovative standard with lower energy demand per housing unit. This innovative standard has created competition dynamics that are indicated by the four reinforcing loops. Over time, they induced a decrease in the energy demand of the official building code. This adjustment process has been balanced by the willingness of the standard setting authority. Exogenous factors, such as marginal benefits calculations and the pressure from energy supply and climate change, have influenced their willingness.

From a system dynamics perspective on sustainability transitions, balancing and self-reinforcing mechanisms are important governance structures that explain temporal processes of societal steering. With this focus, we try to elaborate a causal understanding of alignment processes in the concrete socio-technical transition context. It is important to emphasize that the main contribution of such an analysis is not the identification of new factors or causal mechanisms. Important for useful

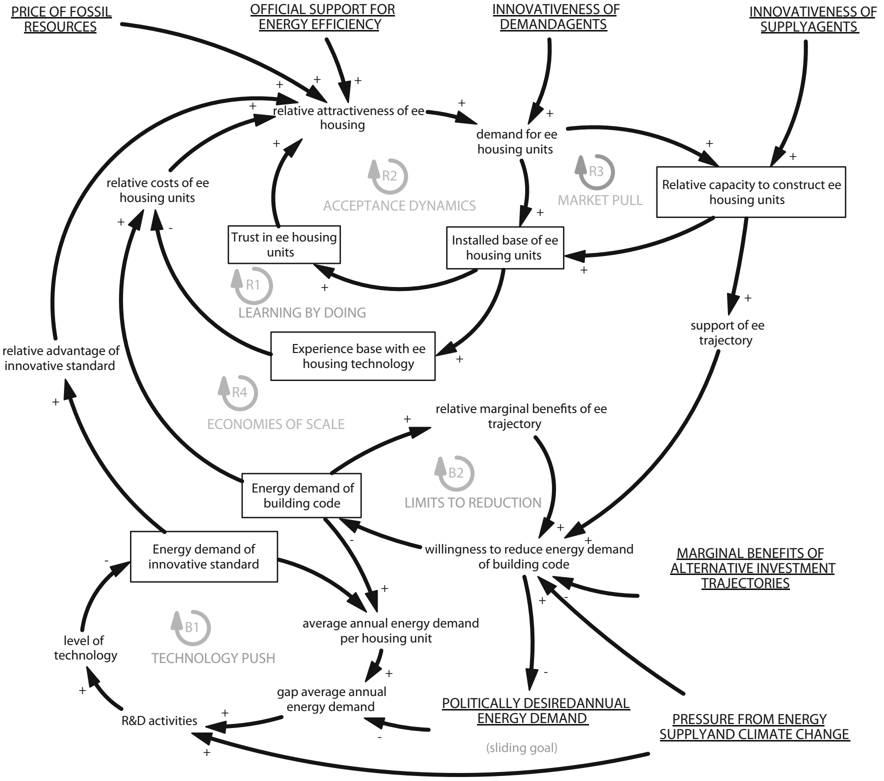

Fig. 2.3 Basic factors and processes that have played a role in the diffusion of energy-efficient housing designs in Switzerland (Adapted from Groesser and Ulli-Beer 2008)

theorizing is to identify the decisive factors and circular causalities in the concrete decision-making context, and to understand how their interactions “govern” the failure or success of transition to increased energy efficiency. However, further modeling and simulation is necessary to test the behavioral implication of the postulated governance structure, as explicated in Chap. 3.

2.6 Conclusions: Opportunities for Explanatory Models for Resolving Tensions in Sustainability Transition Studies

The aim of this chapter is to enhance the clarity of the real-world context and tensions between theoretical approaches of energy technology change and sustainability transitions. Theoretical reflection about the real-world challenge is important to develop useful decision support tools for policy and strategy making.

Understanding the real-world context is decisive to select adequate analytical perspectives.

We have started our endeavor with the assumption that tension between different theorizing approaches may exist and hamper theory integration and application.

We have elaborate answers to the three guiding research questions:

- How should distinct theorizing be understood in the context of related theorizing? The synopsis on technology change theorizing and sustainability transitions shows that extant theorizing of structural conditions and behavioral impacts of innovation on industries, economies, and the environment has only modestly inspired sustainability transition studies. Technology change research has evolved from descriptive to causality theorizing. In this, distinct conditions have been identified that explain different behavioral outcomes. Contrarily, sustainability transition studies mainly engage in the elaboration of categorization schemes and descriptive theorizing. Competitiveness deliberations are not explicitly integrated. We have also emphasized the argument that a lack of causal transition frameworks may hinder the formation of advocacy coalitions and, subsequently, acceptance of reflexive governance approaches.
- What are the sources of tensions and confusions between related theorizing? We have found evidence that the mode of theorizing, as well as the variety and application of imprecise technical terms to describe the dynamical complexity of socio-technical systems and transitions, create additional challenges of theory selection and application and enhancement. This is a specific challenge for novice innovation systems researchers, and for deducing concrete implications for strategy and policy development in concrete real-world transition contexts. We have proposed a concluding thesis about the observed tensions in theorizing on sustainability transition, highlighted in Box 2.3. It emphasizes the need for a stronger focus on causal mechanism and structure-behavior links in theorizing. This is a necessary condition to answer questions like: How can emission reduction targets be met in time? How can we stay competitive during socio-technical transitions? Therefore, we believe that there exist research opportunities for the elaboration of explanatory models, and for resolving tensions in sustainability transition studies.
- How can the tensions and ambiguities be resolved? We have suggested that a system dynamics approach for theorizing about socio-technical change helps resolve some tension in theorizing. It differentiates between two core systemic properties (system structure and behavior), that both may be stable or changing. It offers an unambiguous term frame and mapping tools for specifying multiple circular causalities of socio-technical systems that explain path dependence, lock-in, or path creation. Mapping concepts, such as feedback loop polarities, and causal loops diagrams, provide the basis for developing endogenous explanations of socio-technical transitions. These mapping tools help to weave together process theorizing from distinct perspectives for concerned decision makers in a useful way. These concepts are also a key to link system structure to behavior explanations. However, it is only by advanced simulation-based theory

building that this promise can be scientifically delivered. Only then can windows of opportunity, such as tipping points and sensitive leverage points, be identified to support socio-technical transition and the fulfillment of long-term policy objectives. How such an endeavor should be designed is addressed in Chap. 3.

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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

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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.

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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.

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[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

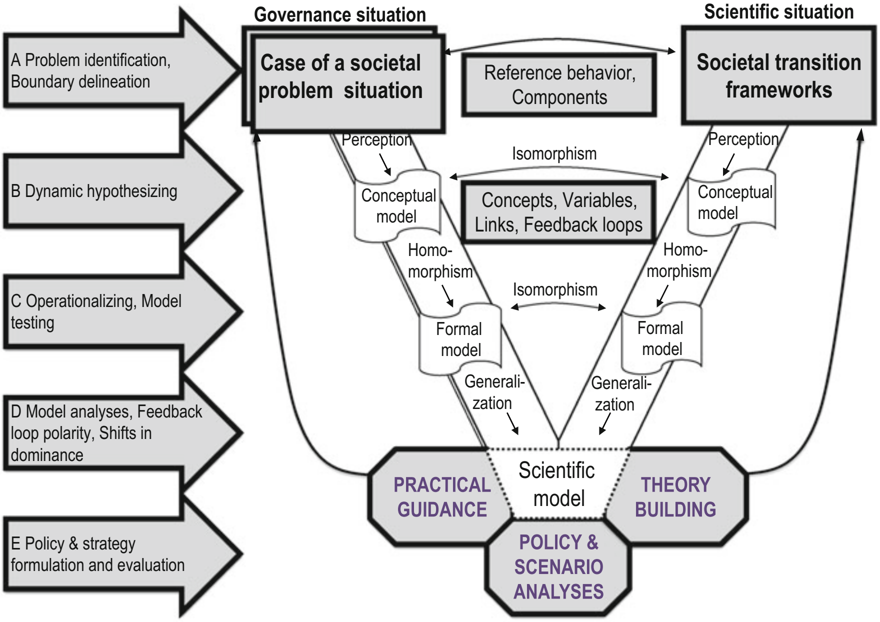

Fig. 3.1 The research method for integrative transition simulation (Adapted from Beer 1984; Ulli-Beer and Wokaun 2011) Note: Homomorphism is a map from one group to another but the operation is preserved; in doing so the information is reduced. Isomorphism is a unique pairing of each element of a set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

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[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

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[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?"

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[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.

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[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).

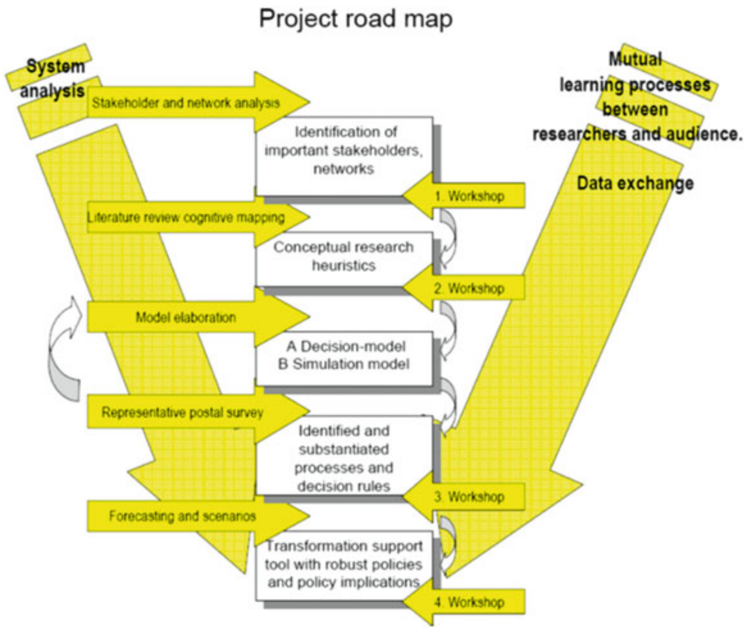

Fig. 3.2 The project road map of the simulation study (Kaufmann-Hayoz et al. 2005)

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

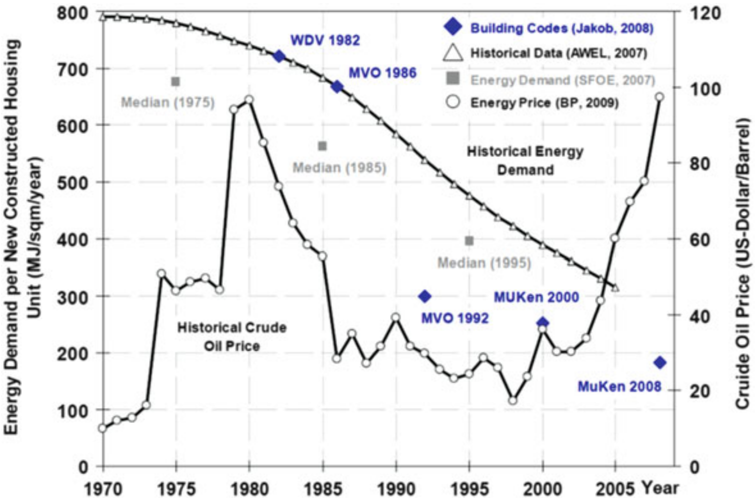

Fig. 3.3 Comparison of energy demand of new buildings in Switzerland and the crude oil price development (Groesser 2012)

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

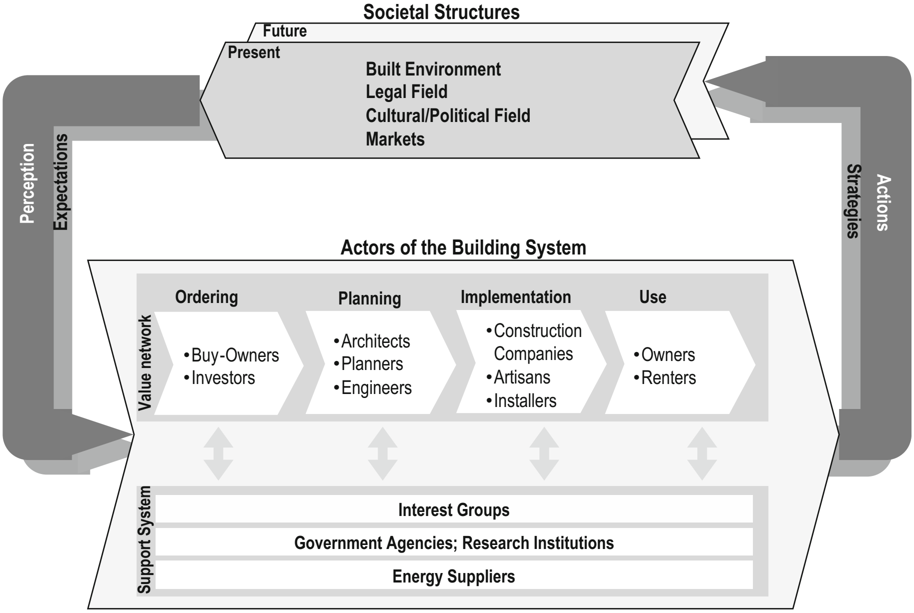

Fig. 3.4 Conception of human action in context for the housing system: basic feedback processes between action and structure (Adapted from Mueller et al. 2012)

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

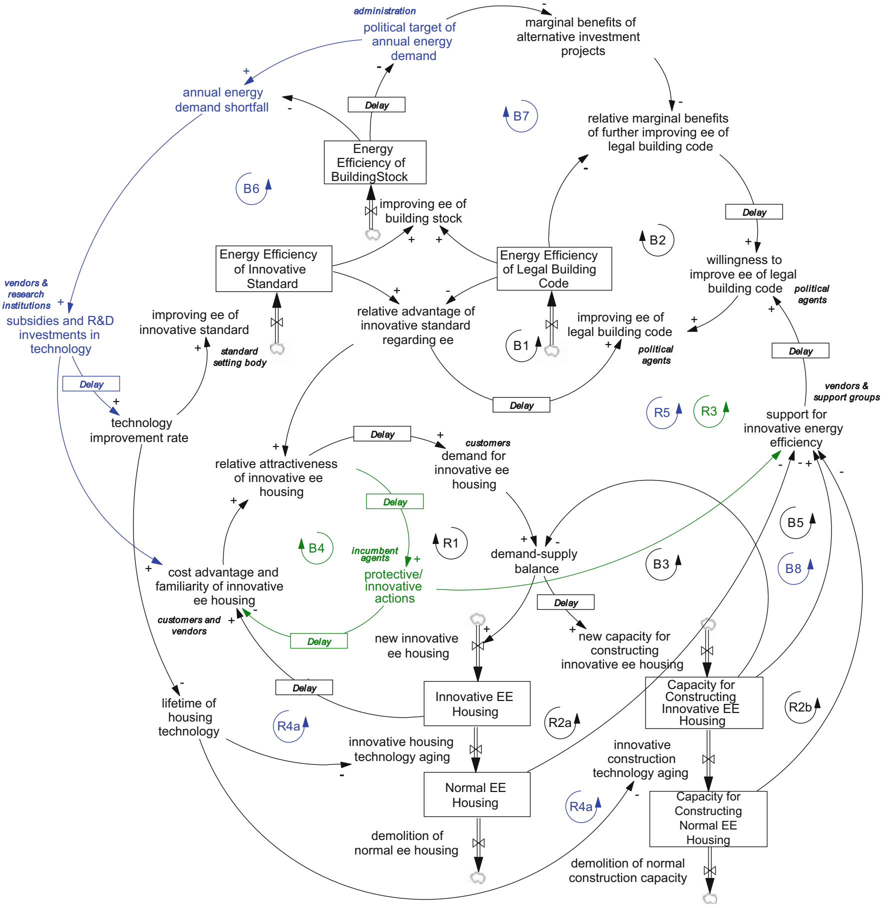

Fig. 3.5 Main causal circularities controlling ee housing (Groesser 2012) Note on the mapping syntax in the displayed causal loop diagram: A *rectangle* represents accumulations; this is a slow-changing variable. The *double arrow* with the valve depicts the rate of an accumulation (*inflow*) or degradation (*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.

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

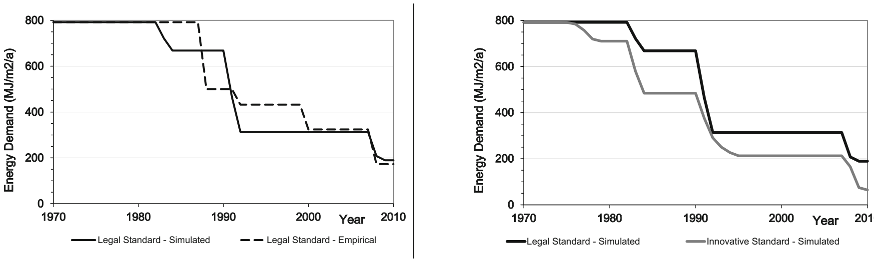

Fig. 3.6 Comparison of empirical standard intensification with simulated legal and innovative standard (Groesser 2012)

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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Chapter 4
How Do We Know Who to Include in Collaborative Research? Toward a Method for the Identification of Experts

Matthias Otto Müller, Stefan N. Groesser, and Silvia Ulli-Beer

Abstract Collaborative research, defined as research involving actors participating in the problem situation under study, has an important role in operational research, strategic management and systems thinking. In a recent study, we found that a strong organizational focus incorporated into many soft operational research (OR) approaches is inadequate for studying societal problem situations, which are fragmented and have no clear boundary. Specifically, we failed to find a process of identifying individuals that is capable of representing the perspectives of actors and sufficient for research into societal problem situations. We found no clear terminology accounting for ontological differences between actors, individuals representing them and conceptual representations of acting entities. In response to this gap in the literature, we propose terminology that differentiates among actors (individuals or collective entities in the real world), experts (individuals capable of representing the perspective of an actor) and agents (ideal-typical representations of

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M.O. Müller (✉)
Interdisciplinary Centre for General Ecology (IKAÖ), University of Bern, Schanzeneckstr. 1, Postfach 8573, 3001 Bern, Switzerland
e-mail: matthias.mueller@ikaoe.unibe.ch; matthiasottomueller@gmail.com

S.N. Groesser
Interdisciplinary Centre for General Ecology (IKAÖ), University of Bern, Schanzeneckstr. 1, Postfach 8573, 3001 Bern, Switzerland

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

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

S. Ulli-Beer (ed.), *Dynamic Governance of Energy Technology Change*, Sustainability and Innovation, DOI 10.1007/978-3-642-39753-0_4,

actors). Based on this terminology, we propose an iterative method to guide the assembly of an expert group to undertake collaborative research into societal problem situations. To demonstrate the application of our method, we present selected insights from our study in an electronic supplement.

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4.1 Introduction

Practitioners and scholars in strategic management and public policy frequently deal with pluralistic problem situations characterized by high degrees of uncertainty and complexity (Schwaninger 2009). Spanning a range of paradigms, the intersecting fields of strategic management, operational research and systems thinking have developed an array of approaches that are helpful in such situations (Rosenhead and Mingers 2001; Hermans and Thissen 2009). By involving the participants of a problem situation in a collaborative process, better insights can be gained for determining policy and strategy because knowledge beyond the boundaries of an organization or a policy-making circle becomes available. Hence, a broader and more systematic understanding of the problem situation can be achieved, which, in turn, allows the development of more effective strategies and policies. Collaborative research refers to research involving participants of the situation under study as partners in a process of mutual learning. The emphasis is on initiating and participating in the collective co-production of knowledge (Pohl 2008: 52). This is in contrast to research that treats participants as objects of inquiry, such as conventional interviews and survey research or experiments. Collaborative research shares basic assumptions with research approaches that are participatory, transdisciplinary and interactive (Scholz et al. 2000; Thompson Klein et al. 2001; Robinson and Tansey 2006; Wiek 2007; Wiek and Walter 2008), and in terms of practice, it resembles action research as described by (Reason and Bradbury 2001). In a recent study, we applied collaborative methods and concepts from strategic management, operational research and systems thinking to investigate how the diffusion of energy-efficient construction practices across different categories of actors could be accelerated to contribute to making Switzerland's stock of new buildings more sustainable. We initially relied on stakeholder theory (Freeman 1984; Mitchell et al. 1997; Eden and Ackermann 1998), cognitive mapping (Ackermann and Eden 2001) and System Dynamics group model building (Vennix 1996; Andersen and Richardson 1997; Andersen et al. 1997) as our set of methods. In the wake of our study, we realized that the context in which we applied our set of methods differed problematically from the context where these methods emerged and are generally applied. In particular, studies often lack a clear distinction between organizational perspectives (e.g., What constitutes a problem situation for organization X?) and inter-organizational (societal) perspectives (e.g., How is a societal problem situation brought about by the interactions of several actors?). We had investigated a situation involving several organizations and their environment rather then applying our set of methods from within an organization. We characterize this setting as a societal problem situation rather than an organizational problem situation (see Sect. 4.3.1). Collaborative research is highly appropriate in societal problem situations because the initial uncertainties are generally larger when compared to an organizational context and, hence, must be compensated by accessing the knowledge of the situation's participants. However, the question of who to collaborate with is also more difficult when compared to research from a predominantly organizational perspective, as it is much less clear what kind of actors are important to understand the situation and who can adequately represent the perspective of important actors. For guidance on how to identify individuals capable of adequately representing the carriers of agency in the societal problem situation under study, we turned to the literature on strategic management, operational research and systems thinking. We found that there does not appear to be a clear distinction between real, acting entities and abstract categories referring to such entities. Individual persons and collectives of individual persons, such as organizations, are real entities. Abstract categories, such as "consumers," "regulators" or "architects" can neither directly act nor collaborate in research projects. For stakeholder analysis from an organizational perspective, it may be unproblematic to ignore this difference; however, in the context of collaborative research into societal problem situations, this difference is crucial, as the purpose of collaboration is to enlarge the epistemic base by using real persons (experts) to represent the perspectives of abstract categories of actors. In response to this gap in the literature, we propose terminology that differentiates between actors (individuals or collective entities in the real world), experts (individuals capable of representing the perspective of an actor) and agents (ideal-typical representations of actors). In line with the lack of clear distinction between real, acting entities and their abstract categories, we found that the contributions in the literature addressing the identification of acting entities in problem situations did not satisfy our specific requirements (see Sect. 4.2). We address this gap by proposing an iterative process that develops the understanding of the societal problem situation and its important actors so that individuals capable of representing them can be identified. In collaboration with these experts, models or conceptualizations of agency in the societal problem situation can be developed, which, in turn, contribute to an enhanced understanding of the societal problem situation.

Summarizing the discussion above, this article addresses the following three research questions:

1. How should inter-organizational and fragmented research settings, in contrast to organizational settings, be conceptualized in view of collaborative approaches in strategic management, operational research and systems thinking?
2. How should differences in the ontological status of carriers of agency in problem situations be conceptualized in a consistent terminology?
3. How can individuals capable of representing the perspective of important actors in societal problem situations be identified methodologically?

By addressing these questions, we contribute to collaborative research methodology in strategic management, (soft) OR and System Dynamics. In addition, we hope to stimulate further research and initiate a broader discussion. The article is organized as follows. In Sect. 4.2, we review the literature and substantiate the research gap we address. Section 4.3 outlines the theoretical foundations, particularly our terminology of acting entities and our conceptualization of societal problem situations. Section 4.4 presents the method we built based on these theoretical foundations. In Sect. 4.5, we summarize our insights, reflect on the merits of our method as a plug-in for collaborative research and point out the need for further research. In addition, we describe the application of our method in an electronic supplement, by providing an illustrative case study based on our research project. Within that supplement, we derive a small set of propositions regarding what we expect other researchers to gain from applying the method.

4.2 Literature Review

In the following, we review the literature on stakeholder theory, System Dynamics and problem structuring methods.

4.2.1 Stakeholder Theory

Freeman (1984) popularized the stakeholder approach in strategic management. He defined stakeholders as “any group or individual who can affect or is affected by the achievement of the organization’s objectives” (Freeman 1984: 46). Since the introduction of the concept, a broad, extensive and heterogeneous body of literature has emerged. Following the popularity of the concept and its use in various contexts, several different definitions of stakeholders have been used (Friedman and Miles 2006: 3, 5–8). Some definitions have moved far away from Freeman’s original definition.

For example, in systems thinking, the term "stakeholders in a system" (Ackoff 1999: 103) is sometimes used to refer to what we would define as actors in the system. In recent years, collaborative strategy-making approaches with a strong focus on collaborating with stakeholders have emerged (see, for example, Eden and Ackermann 1998).

Stakeholder theory has developed a wide range of classifications and criteria to determine which actors should be considered stakeholders of a specific organization (e.g. Savage et al. 1991; Donaldson and Preston 1995; Eden 1996; Mitchell et al. 1997). However, these only provide guidance regarding what class, category or type of stakeholder should be considered important. Achterkamp and Vos (2007) found that the problem of who the stakeholders are and which stakeholders ought to be addressed remains unresolved. In particular, they hold that the "categorization schemes as such are insufficient for actually identifying stakeholders in a specific case" (2007: 6).

Bryson (2004) presents 15 stakeholder identification and analysis techniques grouped around four basic categories. These are (1) organizing participation; (2) creating ideas for strategic interventions; (3) building a winning coalition around proposal development, review and adoption; and (4) implementing, monitoring and evaluating strategic interventions. Our method is as a contribution to the first phase, namely, organizing participation. Here, Bryson (2004) provides a detailed process regarding how to choose participants in stakeholder analysis. His process consists of the following five major steps. To prepare the process, a small group first conducts preliminary stakeholder analysis. Based on these insights, a larger group of stakeholders is assembled in the second step to carry out further analysis, such as the identification of stakeholders to be involved in the change effort. In the third step, the stakeholder group is asked who should be included in further meetings. Then, the full group of involved stakeholders is complete, and stakeholder analysis techniques can be used with the full group as the fourth step. In the fifth step, the different roles (e.g., sponsors, champions, coordinating group, planning team and advisory group) in the change effort are distributed to stakeholders. In addition to this process, Bryson (2004) provides a participation planning matrix, which allows the planning of different degrees of stakeholder involvement, ranging from informing to empowering.

Other than an approach limited to stakeholder identification for projects in organizations (Achterkamp and Vos 2007), we know of only one further contribution from stakeholder theory dealing with the identification of experts beyond the provision of classification schemes. Eden (1996) describes an approach to conceptualize and identify stakeholders in a project with the Northern Ireland Prison Service. In this project, societal actors are considered according to the degree to which they influence the organization. Based on the power-interest diagram, stakeholders are classified into the following groups: players, crowd and leaders/context setters. Eden (1996: 48) uses the term "actors" to refer to "those who have the power to act in a way which has an impact on the future of the strategy-making organization" (players and leaders/context setters). However, he goes beyond classification schemes. In his approach, collaborator workshops with stakeholders are employed to enrich the strategy-making process with insights from outside the organization.

We find that our research question 1 cannot be answered based on the literature on stakeholder theory. Regarding research question 3, we find that some contributions have addressed the issue of how to identify individuals capable of representing important stakeholders in collaborative research. However, the literature does not provide a rigorous method for selecting such individuals in societal problem situations.

4.2.2 System Dynamics

In a strand of research in the field of System Dynamics called group model building (Vennix 1996; Andersen and Richardson 1997; Andersen et al. 1997), the benefit of working with representatives of the system under study is well recognized. Vennix (1996), for example, outlines several guidelines for selecting who to involve in the model-building sessions. Including "those present who have the power to act, i.e., those who can implement a decision" (111) is an important point if the goal of the project is to bring about particular decisions. Regarding the size of the expert group, Vennix (1996: 111) finds that there are trade-offs between small and large and between homogenous and heterogeneous groups: in a large group, the organizational platform for change and the commitment to a decision is often rather large, but the satisfaction and participation of group members may be low. In diverse groups, the quality of the model may be high, but diversity may result in tensions that undermine the group's performance. Although research question 1 is not explicitly answered in the System Dynamics literature, modeling dynamic complexity over large societal settings is standard practice in System Dynamics.

Regarding research question 2, we did not encounter any terminology that clearly considers the different ontological status of experts, actors and agents. Regarding research question 3, we did not find a rigorous method to guide the identification of "those (. . .) who have the power to act" or "who can implement a decision" in the System Dynamics group model building literature. We conclude that the System Dynamics group model building literature treats the process of identifying representative actors in the system under study rather superficially, particularly when compared to our method.

4.2.3 Problem Structuring Methods

Mingers and Rosenhead (2004: 531) argue that unstructured problems are characterized by multiple actors, multiple perspectives, incommensurable and/or conflicting interests, important intangibles and key uncertainties. In response, problem structuring methods have become widely accepted as a "significant new direction for operational research and the systems movement"(Rosenhead and Mingers 2001: xiii). These methods structure issues, problems and decision situations rather than solve them. In practice, a large number of methods are applied to address such problems, and, quite frequently, methodologies are pragmatically combined (Mingers and Rosenhead 2004).

However, in a contribution reflecting the use of problem structuring methods in multi-organizational teams, Franco (2009: 194) argues that "most of what has been reported about PSMs [Problem Structuring Methods, the authors] in the OR literature has focused on management teams operating within single organizations". This statement complies with our finding regarding research question 1 that problem structuring methods generally do not account for the inter-organizational settings we call societal problem situations. The notable exception in the context of problem structuring methods is Soft Systems Methodology (SSM) (Checkland and Scholes 1990; Checkland 1993, 2001), which aspires to "guide action in trying to 'manage' (in a broad sense) real-world problem situations"(Checkland and Scholes 1990: 5). Here, tools such as rich pictures naturally promote a systemic perspective on problem situations that goes beyond a focus on single organizations.

Regarding research question 2, we find that several problem structuring methods provide terminologies to address different actors yet fail to clearly account for the difference between abstract entities, individuals representing them and models employed to represent agency. SSM has a terminology for categorizing different actors, namely clients, problem-owners and problem-solvers (Checkland and Scholes 1990: 47). Strategic options development and analysis (SODA) (Ackermann and Eden 2001) aims to identify supporters or saboteurs of organizations' strategic intentions. The strategic choice approach (Friend 1990) encompasses the team-like group, the partnership group, the inclusive group and, finally, the multi-organizational groups. We find that collaborating with a "multi-organizational team" is a variant of collaborative research, which is compatible with our conceptualization of collaborative research in societal problem situations. By including non-organizational actors, such as consumers or voters, our notion of collaborative research into societal problem situations carries this further.

Regarding research question 3, we find that no other contributions in the literature provide a method with a similar rigor to what we propose in Sect. 4. Neither robustness analysis (Rosenhead 2001b), the strategic choice approach, drama theory and confrontation analysis (Bennet et al. 2001) nor the viable system methodology (Beer 1984) profoundly address the issue of identifying individuals willing to represent actors in societal problem situations. SSM also does not include a method for doing so. Even Hermans and Thissen (2009), who provide an extensive evaluation of actor analysis methods from soft OR methods in the public policy context, do not address this practical topic.

4.2.4 *Conclusions from the Literature Review*

Summarizing the results of our literature review, we find that the notion of the societal problem situation is not alien to stakeholder theory, System Dynamics and problem structuring methods. Rather, the term “societal problem situation” is an extension of the literature, and it promises to facilitate the application of collaborative research methods in inter-organizational settings.

Although several terminologies dealing with acting entities can be found in the literature, there is generally no clear distinction between actors, individuals representing them and models of agency. Our terminology provides clarity in this respect. Finally, the question of how to identify individuals capable of representing actors in collaborative research has been partially addressed. To meet the requirements of research into societal problem situations, the approaches found in the literature are somewhat unsatisfactory, as they seem to rely, to a substantial degree, on knowledge available from an organization. For research into societal problem situations, however, it might be initially unclear where the boundary of the situation lies, and it might not be evident where preliminary work should begin. The fragmented nature of societal problem situations makes it unlikely that there is one person who oversees all relevant actors.

These presented findings do not necessarily mean that the identification and selection of participants in collaborative research projects has, thus far, been systematically flawed. We merely maintain that no discussion of this initial phase of collaborative research has occurred in the literature. We can, however, speculate that the selection of experts in collaborative research projects addressing societal problem situations has often been ad hoc. Moreover, in most cases reported in the literature, the selection of participants in workshops is treated rather briefly. For example, White and Lee (2009: 689) mention “invited people” as the persons invited to workshops for a project to make Bristol a sustainable city.

4.3 Theoretical Foundations

In this section, we introduce the general actor terminology used in our method, and specify the characteristics of societal problem situations.

4.3.1 *Conceptualizing Acting Entities*

To conceptualize acting entities, we propose the following distinctions between the terms *actor*, *expert* and *agent*. Actors are entities in the real word who carry out activities. They can either be individual persons or collectives of real persons, such as an organization or a social movement. Experts are always real, individuals capable of representing the perspective of actors or categories of actors in addition to their individual perspectives. For example, the manager of a trust fund may be able to serve as an expert representing the trust fund's role in a problem situation. Finally, agents are ideal-typical representations of actors or categories of actors. Categories of actors are generally used to merge several actors sharing common characteristics. For example, "consumers" or "suppliers" are groups of actors who share particular characteristics. Agents, on the other hand, are the result of methodological efforts directed at developing scientifically sound and useful models of agency. In the terminology of SSM, agents are a feature of systems thinking about the real world. By methodologically manipulating and debating agents, researchers can derive insights to better understand the real world. By developing a typology of agents, actors in the problem situation can be represented in models. Moreover, by giving the agents behavioral rules, it is possible to model the behavior of actors. This holds regardless of the methodology used or the specifics of the situation under study. Implementing a typology of agents, however, depends strongly on the theoretical framework used to approach the issue and the methodology used for modeling.

4.3.2 Characteristics of Societal Problem Situations

Collaborative research is particularly useful when researchers or practitioners are confronted with situations in which the actions of several actors, each situated in his or her specific context, give rise to an issue that is identified as important and unpleasant by more than just a single actor. The notion conveyed by the term "problem situation" is well established in the literature. For example, in the management literature, Ackoff (1979) sees problems as analytical abstractions from messes. Messes are "dynamic situations that consist of complex systems of changing problems that interact with each other". Ackoff regards problems as being open to solutions based on optimization, while messes require a more thoughtful management approach. Similarly, Checkland (1993: 154) describes structured problems as problems that "can be explicitly stated in a language which implies that a theory concerning their solution is available".

Unstructured problems are problems that are "manifest in a feeling of unease but which cannot be explicitly stated without this appearing to oversimplify the situation". Furthermore, Rittel and Webber (1973) differentiate between "wicked" and "tame" problems, and Schön (1987) uses the image of a swampy lowland rife with messy, confusing problems that defy technical solutions to address an idea similar to the term "problem situation".

Research on the sociology of social problems highlights the fact that the definition of a problem situation strongly depends on subjective interpretation. For example, Blumer (1971) rejects the view that social problems are primarily based on an objective condition with an objective makeup. Instead, social problems exist primarily in terms of how they are defined and conceived by society. Social problems are always a "focal point for the operation of divergent and conflicting interests, intentions and objectives" (Blumer 1971: 300). Focusing more closely on the process of constructing social problems, Kitsuse and Spector (1973: 415) conceived of social problems as "the activities of groups making assertions of grievances and claims with respect to some putative condition". They argue that analysts of social problems should focus on the explanation of the "subjective elements" of social problems (418). To find a middle way, Weinberg (2009) cautions against focusing purely on the subjective element. Rather, he calls for a more balanced approach that considers the meaning and the causes of the claim-making process.

Synthesizing this discussion, we can characterize societal problem situations as highly fragmented situations, where it may not be clear what exactly the problem is, what kind of actors are involved in it, and who is responsible for addressing the problem. In particular, fragmentation means that actors in the problem situation may not be aware that they are participants in a societal problem situation. For example, consumers may have no awareness that they are part of the societal problem situation of "pesticide use and loss of biodiversity". In our opinion, collaborative research based on systems-thinking methodologies is best suited to address such situations. This is because collaborative research allows participants' to drawn upon their knowledge of the problem situation and because systems thinking methodologies integrate "objective" and "subjective" aspects of societal problem situations (Schwaninger 2004). Due to the fragmented nature of societal problem situations, the research methodology cannot rely on one single perspective to identify the important actors. Instead, identifying important actors and the experts representing them must be grounded in empirical research into the problem situation itself. The next section proposes a method for doing this.

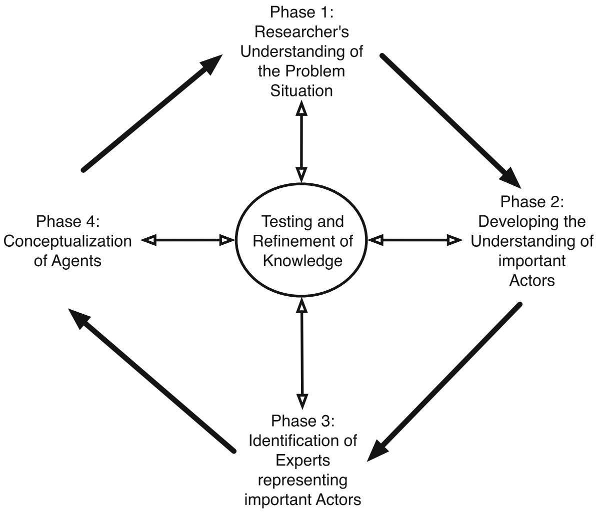
4.4 Description of the Method

In this section, we describe how individuals who are capable of representing the perspective of important actors in societal problem situations can be identified methodologically.

4.4.1 General Description

We divide the process of identifying experts into four phases, as shown in Fig. 4.1. First, an understanding of the problem situation must be developed (phase 1) to understand the important actors of the problem situation (phase 2). Then, for all actors preliminarily considered important, experts who represent the perspectives of important actors must be identified (phase 3). By working together with the experts, the actors and their behavioral rules are conceptualized as agents (phase 4).

Fig. 4.1 Overview of the method



This knowledge and the model used to structure it further develop the understanding of the problem situation (again phase 1) and may prompt researchers to either include further actors or reconsider the value of actors previously seen as important (again phase 2).

Our approach is iterative and evolutionary and seems well suited to guide the initial phases of collaborative research into societal problem situations. It is evolutionary because, after each phase, we undertake empirical testing and, if needed, update the insights gained. The method is iterative because the individual steps should be undertaken several times. The two types of arrows in Fig. 4.1 visualize this process. Bold arrows signify increasing knowledge and confidence as a result of iterations, while the thin arrows stand for testing processes and updating this knowledge. By circling several times through the four stages, an understanding of the problem situation and its actors develops until researchers deem that their understanding is saturated. The practice of repeated checking and adapting until a saturated understanding is reached is similar to the hermeneutic circle (Gadamer 1975; Schön 1983) and qualitative research methods, such as grounded theory (Glaser and Strauss 1967; Strübing 2004; Flick 2005). Once researchers reach the conclusion that the important actors of the problem situation have been identified, experts representing them can be invited to serve as the epistemic base for further research.

4.4.2 *Explication of the Four Phases*

4.4.2.1 Developing the Understanding of the Problem Situation

Developing the researcher's understanding of the problem situation is a prerequisite for identifying important actors. Unfortunately, research into problem situations often begins with little knowledge of the issue under study. Moreover, in many cases, there is no scientific literature available that adequately addresses the specifics of the problem situation, or else the literature provides only partial insights. In societal problem situations, there may be no written information available, and it is unlikely that a single person could guide the researchers because, in fragmented situations, no single person has a sufficiently broad perspective on the important actors. This contrasts with research conducted in an organizational context. In such a context, an experienced practitioner can often serve as a gatekeeper who provides researchers with a list of potential experts and written information that can inform the researchers in the initial phases of the project. Researchers in the initial phase of a project rely on everyday knowledge or must make assumptions concerning the problem situation. In some cases, the initial understanding of the problem situation may seem so trivial that it is not even recognized as a distinct phase, and phase 2 or even phase 3 may appear to be the starting point of the research process.

To overcome the initial lack of knowledge, any available source of information, from the researcher's everyday knowledge and information found on the Internet to information derived from participants, can be used to develop the understanding of the problem situation. A lack of confidence in accuracy poses no problem at this early stage of the research process because testing and subsequent adaptation are constitutive elements of the method. The distortions and weaknesses of the researchers' early understanding of the problem situation will be overcome during the subsequent research process.

Depending on the requirements of the research project and the working style of the researchers, the insights gained in the first phase can principally remain in the researcher's "mental data base" (Forrester 1987), be expressed as written text, be put into a computer database, or structured in any way, such as using one of the problem structuring methods reported in Rosenhead and Mingers (2001) or by developing formal models.

4.4.2.2 Developing the Understanding of Important Actors

Informed guesses regarding which actors might drive the societal problem situation are only the starting point. Investigating the empirical manifestations of the problem situation through activities such as searching the Internet, reviewing literature, talking to or interviewing people participating in the situation, or analyzing numerical data increases the overall understanding of the situation and its actors. Repeated questioning, testing, verifying, cross-referencing and adapting the knowledge gained leads to the emergence of an increasingly valid and accurate understanding of the important actors.

At this point, the question emerges of how to distinguish between important and unimportant actors. However, this question must be answered in the specific context of projects. We refer to the literature on stakeholder management (see for example Mitchell et al. 1997; Eden and Ackermann 1998; Bryson 2004; Bryson et al. 2004; Achterkamp and Vos 2007; Ackermann and Eden 2011) rather than proposing substantive criteria according to which actors might be identified as important.

4.4.2.3 Identification of Experts That Represent Important Actors

The main task to be accomplished in this step is to identify and contact persons who are able and willing to represent the perspectives of important actors in the research. Representatives are required because collaborative research relies on working with real persons and it is generally not possible to collaborate with collective actors or categories of actors such as "consumers" or a whole corporation. Finding representatives may be straightforward or nearly impossible, depending on the specifics of the situation under study.

It may prove helpful to ask the experts already contacted who they would include and to then contact the persons suggested by the experts. By going from one expert to another, a list of potentially relevant actors and individuals, who might be considered as experts, can be compiled. While this approach promises to be effective, it runs the risk of identifying experts within a specific network and not representing important actors from other, possibly competing networks. Therefore, great care must be taken to access other, possibly competing networks to obtain a variety of represented perspectives. Additionally, it may prove important to ensure that experts are drawn from a variety of backgrounds, as the social background of an expert may intersect with his or her perception of the actor's perspective on the problem situation. This can help reduce bias stemming from background variables, such as gender, ethnicity, age, and hierarchical position.

4.4.2.4 Conceptualizing Actors as Agents

Agents are ideal-typical representations of actors that condense the relevant aspects of the real world as a result of a process of methodical inquiry. Depending on the specifics of the research project, it may suffice to simply define agents according to their relevant functions. In many cases, however, an elaboration of the behavior patterns and decision functions of agents is required.

The conceptualization of agents involves endeavors such as cross-referencing, merging and testing the insights derived from collaborating with experts. Ideally, several experts familiar with the perspective of an actor would be interviewed or consulted. However, the variety of perspectives considered is more important than the actual number of experts consulted. Subsequently, researchers can develop a 'dense description' or a more formal model capturing the central interests, values and actions carried out by each actor or category of actors identified as important. Based on these empirically well-founded "dense descriptions" of important actors, the research team can return to phase 1 to refine and update its understanding of the system. To ensure that the researchers' understanding of the problem situation is represented in an inter-subjectively valid model, group-oriented methods such as workshops, focus groups or group model building can be employed. Together with the expert group, the researchers can test and refine their understanding of the societal problem situation, identify missing actors and refine the conceptualization of agents.

4.5 Conclusions

Finding experts who represent important actors is not an end in itself. Rather, it is a necessary precondition to conduct collaborative research, regardless of the specific methodology used. In the context of a research project, we combined methods from strategic management, operational research and systems thinking to analyze the diffusion of energy-efficient buildings. However, we failed to find a terminology that deals in general with acting entities in societal problem situations and transcends the specifics of the different methods we used. In addition, we failed to find an approach in the literature that would provide us with specific guidance on how to identify and select representatives of important actors in societal problem situations. In the sections above, we proposed terminology and a process to identify and select experts representing important actors or categories of actors in societal problem situations.

In addition, we provided the theoretical foundations underlying our approach, and, by way of example, we evaluated the potential benefits of our approach. The research questions we stated in the introduction were answered as follows. We addressed research question 1 by elaborating on the characteristics of societal problem situations in Sect. 4.3.2. We addressed research question 2 by providing a conceptualization of acting entities in Sect. 4.3.1. We addressed research question 3 by proposing a method to identify capable individuals in Sect. 4.4 and provide a case study of its application in an electronic supplement to this article.

The added value of applying our approach in collaborative research is that the selection of individuals to represent important actors becomes a distinct, reflective and important phase of the research process rather than a preliminary administrative task. In organizational contexts, it may be the case that gatekeepers do a good job of selecting experts who represent important actors or categories of actors. In the context of collaborative research into societal problem situations, however, gatekeepers might be hard pressed to provide a valid account of important actors or categories of actors and experts representing them. In such situations, we expect our method to yield a group of experts who represent the important actors of a societal problem situation, and we expect our method to be more advantageous in comparison to ad hoc approaches that rely on the perspective of an individual gatekeeper. Consequently, we expect collaborative research projects to produce better insights.

We propose our method and the terminology that grounds it as a plug-in for collaborative research approaches in stakeholder theory, System Dynamics and problem structuring methods. In the context of (collaborative) problem structuring methods, we find that our method can be easily integrated by applying it as a first step. Systematically researching which actors or categories of actors need to be considered in the societal problem situation is already a step toward structuring a societal problem situation and, in our opinion, should be treated as such. The identification of individuals capable of representing actors or categories of actors is then a prerequisite for applying further techniques from soft OR.

We do not think that our contribution is directly applicable to stakeholder theory; however, our distinction between actors, experts and agents may yield some ontological clarity in that context. A stakeholder can be defined as an individual or collective actor or a category of actors who can affect, or is affected by, the achievement of an organization's objectives. Experts are individuals capable of representing the perspective of stakeholders. In collaboration with experts, agents representing stakeholders can be conceptualized and used to methodologically investigate stakeholder management strategies. By offering the possibility to refer to agency in inter-organizational contexts, we contribute to keeping the stakeholder term focused on its original organizational perspective. To identify the stakeholders of a specific organization, our approach is probably of limited value. In such a situation, classification schemes and techniques, such as those discussed by Bryson (2004), are probably more adequate. In System Dynamics, however, our method and terminology should be useful; we provide a terminology to deal with agency in social systems and a method to assemble a group of system experts who represent the important actors in such systems.

While we hope to have contributed clear terminology and a useful method, we must emphasize that the method we have presented is conceptual rather than strictly prescriptive, as each collaborative research project faces unique challenges that may require adaptations. Therefore, we see our contribution as being in line with the spirit of multi-method approaches (Mingers and Brocklesby 1997). Hence, it seems probable that the proposed method will need to be adapted to the specifics of different research projects.

While we are confident that we did not miss out any substantial contributions elaborating on the identification and selection of experts in the reviewed literature, we were unable to conduct a broad and systematic analysis of the literature reporting cases of collaborative research. The task of systematically analyzing such contributions remains an object for further research. Such an enterprise could provide a typology of approaches taken regarding the identification and selection of actors and highlight the specific benefits of the identified approaches.

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Appendix

An Illustrative Case Study: Identifying the Actors Driving the Diffusion of Energy-Efficient Buildings

Application

To illustrate our method, we present its application in a study that we conducted on the diffusion dynamics of energy-efficient buildings in Switzerland. The study was carried out between 2005 and 2009 by an interdisciplinary team of researchers collaborating with an expert group representing the important actors. Methodologically, the study combined soft OR methods, such as causal mapping (Bryson et al. 2004), with System Dynamics (Forrester 1961; Sterman 2000) and survey methods. The collaborative research approach was chosen to overcome the difficulties associated with fragmentation and because we wanted to synthesize objective and subjective elements. The study implemented a case study design in a medium sized city in Switzerland.

At the beginning of the study, our understanding of the housing and construction sector was not very elaborate. However, before empirical investigations could begin, a theoretical framework needed to be defined. After some deliberation, we chose to combine Porter's (1998) value chain approach with the agent-in-environment framework (Kaufmann et al. 2001; Kaufmann-Hayoz 2006; Ulli-Beer 2006). The agent-in-environment framework conceptualizes action as a co-evolution of acting entities and their environment by means of perception-action cycles. We relied on this, as it was compatible with the systemic perspective that the study wanted to achieve and because it focuses attention on the way actors shape societal structures and how societal structures feed back and influence action. The value chain approach seemed appropriate, as the construction of buildings can be represented as a sequence of different steps. Figure 4.2 shows the theoretical framework, including the actors we positioned within it after several iterations. Guided by this theoretical framework, we began to look at websites, searched and read scientific and non-scientific literature, and undertook discussions with other researchers. In addition, we conducted face-to-face interviews with persons

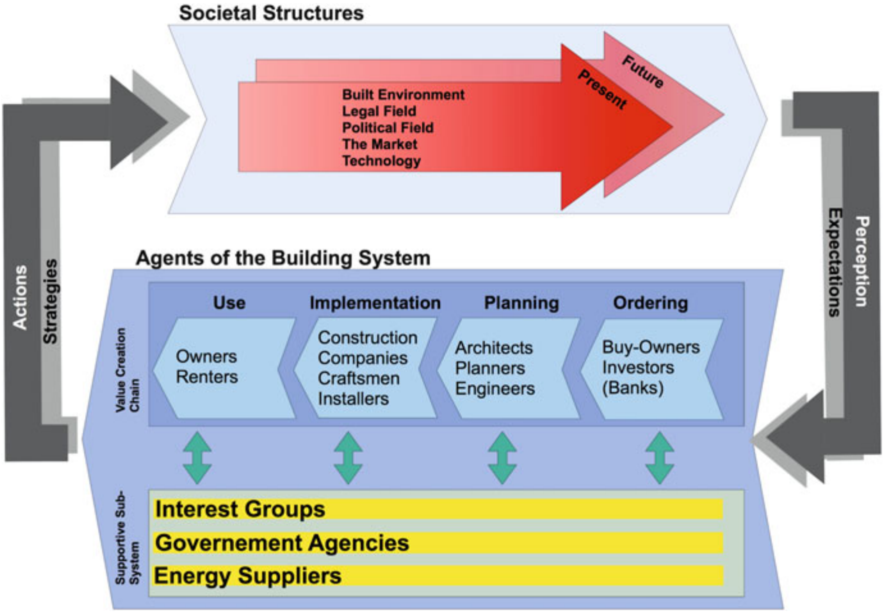

Fig. 4.2 A representation of main actors in the societal problem situation

involved in the administration of the city where we carried out our case study. As a result, our understanding of the societal problem situation began to evolve from a layperson's piecemeal understanding of the construction sector toward a theoretically saturated and empirically grounded perspective (phase 1). We expect that any collaborative research project profits from consciously undergoing an exploratory stage because exploratory research allows an understanding of the issue under study to develop quickly. As our study progressed and we deemed our understanding of the societal problem situation to be sufficient, we moved on to phase 2. We began to evaluate potential actors by asking the following questions adapted from stakeholder theory: Who holds the power to significantly influence the societal problem situation? Who can claim to have a legitimate interest in the state or the evolution of the situation, and what reasons or justifications are used? For whom does the present or any potential state of the situation suggest urgent consequences? (adapted from Mitchell et al. 1997) Inspired by the power-interest grid approach (Eden and Ackermann 1998: 122), we first developed hypotheses about the power actors have to accelerate or block the diffusion of energy-efficient buildings and what interest such actors might have in favor of or against energy efficiency in buildings. We think that asking these kinds of questions would be helpful in any research project to develop the understanding of important actors. The next task we needed to tackle was the identification of individuals capable of and willing to represent an actor's perspective by participating in our expert group (phase 3). We approached this task by relying on reference buildings and investigating individuals involved with the construction of these buildings. By researching recent building permits, we learned about recent construction projects. This information and the data obtained from phone books and the Yellow Pages allowed us to contact the persons applying for the building permits, who were mostly architects. In addition to inviting the architects, we asked them to provide contact details of other important actors involved in the project, whom we subsequently contacted. When contacting the persons involved with the reference buildings, we asked them to evaluate who has an interest in energy-efficient buildings or the power to affect the diffusion process. To achieve a broad sample of reference buildings, we asked architects to contribute recent projects that met specific criteria. On several occasions, we went to look at construction sites and obtained listings of the construction companies involved with that particular construction site from signs. To identify actors outside the value chain, we contacted government agencies dealing with energy in buildings on the federal, cantonal and communal levels. We asked them to participate and provide us with the names of private or semi-private organizations that they thought should be included. These were subsequently contacted and asked to help us identify further actors and individuals capable of representing them. The procedure of selecting,"a reference cases" as a starting point to identify experts capable of representing important actors is expected to be of value for other researchers investigating societal problem situations.

When no new actor emerged as important and phase 3 was completed for the time being, we conducted the first workshop with our experts to discuss our typology of important system agents (phase 4). During the first part of the workshop, we evaluated whether the important actors of the societal problem situation were represented. As it turned out, we had missed producers and importers of advanced technology. Consequently, after the workshop, we briefly moved back to phase 2 to adapt our understanding of important actors. Then, we moved to phase 3 again and identified and contacted individuals who would be willing to serve as experts representing advanced technology producers and importers. After this iteration, we were fairly certain that in the future workshops, we would be collaborating with individuals representing all the important perspectives. We found that although we had asked the experts to tell us which actors had an interest in or power to affect the diffusion process of energy-efficient buildings, the workshop setting triggered further actors. Hence, we think that fellow researchers performing collaborative research would profit from holding a workshop in addition to interviews. The second part of the first workshop was reserved for investigating behavioral aspects of actors. To reduce the complexity associated with actors' behavior in the real world, we approached this task by representing actors as agents in a modified version of the power-interest grid. Researchers and the members of the expert group jointly debated and developed hypotheses concerning the power that actors have to accelerate or block the diffusion of energy-efficient buildings and what interest such actors might have in favor of or against energy efficiency in buildings. Figure 4.3 depicts a refined version of the power-interest diagram developed during the first workshop. Developing this power-interest diagram with the expert group allowed us to gain deeper insights

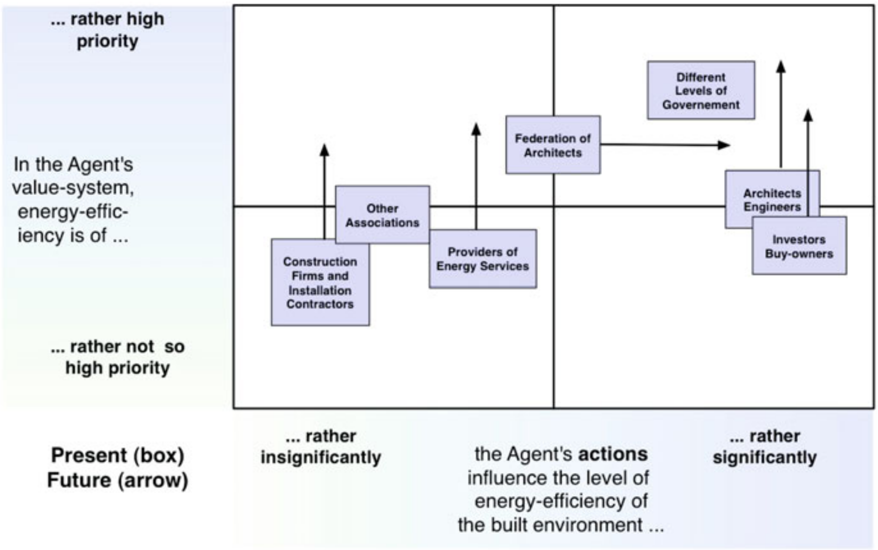

Fig. 4.3 Agents of the societal problem situation

into the behavior and rationales of actors. This illustrates how the use of problem structuring methods with an expert group representing the important actors can be applied to model actors of the societal problem situation as agents (phase 4), and this work increased our understanding of the societal problem situation (phase 1).

In the weeks following the first workshop, we conducted individual interviews with the experts using cognitive mapping techniques described by Bryson et al. (2004) to research the experts' cognitive map of the feedback structure of the societal problem situation. A second workshop was used to discuss causal-loop diagrams representing the merged cognitive maps. Subsequent workshops discussed the System Dynamics simulation model representing the experts' and researchers' joint perspectives. This work can be interpreted as a series of iterations between phase 4 and phase 1. These iterations contribute to testing because members of the expert group would sometimes reject the researchers' perspectives, leading to further refinement of the System Dynamics model.

Evaluation

In retrospect, we found that applying our method in the context of our research project had several benefits. First, by applying the method, we were quickly immersed in the problem situation and were able to make the transition from a layperson's perspective to a deeper understanding of the problem situation rather quickly. Second, our method led to the formation of a dedicated group of experts. Consequently, we gained a solid epistemic source from within the problem situation. In particular, we learned a great deal about the specific situation of each actor or category of actors by collaborating with the experts. This, in turn, provided important guidance for the subsequent development of a formal System Dynamics model. A possible limitation to our approach is the fact that it is comparatively resource intensive and may take several weeks to implement. Depending on the specifics of the situation, a determined effort may be necessary to find experts willing to participate. In our research project, it took several weeks to complete the process and prepare the first workshop. Therefore, we think our method will primarily be useful for researchers conducting larger investigations into societal problem situations characterized by high degrees of fragmentation and that lack a gatekeeper who can guarantee a balanced selection of experts. Secondarily, however, we think that our approach also provides terminological precision and theoretical grounding for practitioners who work under more constrained time frames.

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Part II

Fields of Analysis: Clean Personal Road Transportation and Energy-Efficient Housing

Chapter 5
The Role of Social Norms for the Diffusion of Eco-Innovations: Tipping Point, and Lock-in Effects

Mathias Bosshardt, Silvia Ulli-Beer, and Alexander Wokaun

Abstract In the innovation literature, paradigm changes in supply have been elaborated during the last three decades, while interdependencies between technology competition and social norm changes on the demand-side have received less attention. This paper investigates the concept of the social norm to model green product diffusion. It offers a social perspective on the systemic phenomena of tipping point and lock-in effects in relation to green product diffusion; this is our first contribution. Social interaction effects of distinct technology adoption patterns are conceptualized as social norm competition. We apply the method of simulation based theory building, to test the system behavioral implications of the postulated nonlinear socio-technical norm effect. We show that this conception provides an endogenous explanation of tipping behavior in s-shaped diffusion models. This complements pure probabilistic technology diffusion models that neglect both endogenous and social influences on adoption decisions. We perform simulations for two and three competing technologies, using the example of vehicle fleet penetration with alternative drivetrain technologies. We show that the critical mass and the transition pathway is path dependent. Our second contribution is the specification of the critical mass within distinct socio-technical norm regimes. We apply a mathematical analysis of the technological landscape potential to visualize the characteristics of the tipping point. The tipping point is explained by the built up of a critical mass of users that signal a new socio-technical norm fostering transition to irreversible substitution. The offered approach and perspective is intended to be useful for effective long term policy making and to enhance the intuition about feedback rich sustainability transitions.

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

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5.1 Introduction

Understanding processes that link societal needs, and institutional changes (e.g. social norm building) with green product diffusion becomes increasingly important for mastering socio-technical sustainability transitions (Geels and Schot 2007). The innovation literature reflects a long history of innovation diffusion research and modeling. The pioneering work on diffusion of innovations is credited to Rogers (1962) and Bass (1969). Their models mapped positive effects of advertising and imitation. Robinson and Lakhani (1975) introduced negative influence on adoption within their model. Subsequent work by Christensen (1997) and Rogers (2003) directed attention towards the notion of tipping points in the diffusion process. The notion of a tipping point refers to critical mass, bifurcation, or threshold values in a nonlinear system and is related to systemic phenomena such as lock-in and path-dependencies. These phenomena have attracted the interest of social scientists in multiple fields including economics (David 1986; Arthur 1989; Arrow 2000; Unruh 2000; Arrow 2004; Stonemann 2004), politics (Pierson 2004), managerial and organizational schools of thought (Sydow et al. 2009; Thrane et al. 2010) and sustainability science (Rotmans et al. 2001; Geels 2004; Geels and Schot 2007). They refer to models, which explain lock-in and break-out effects as interactions between sub-system and different selection environments. However, they explain the causes of a bifurcation or of a tipping point in product markets at rather abstract levels. In addition the definition of a tipping point has not been formalized, and therefore remains a vague concept (Phillips 2007). Phillips' analysis of different probabilistic models (2007) has begun to shape the mathematical characterization of a tipping point. He compared 1-, 2- and 3-parameter probabilistic models and showed that a 3-parameter formulation is needed to describe a tipping point exogenously, as it is understood in today's managerial science: a transition to irreversible growth. But, this analytical understanding does not yet explain what real world counterpart creates the resistance that must be incorporated into the model, as demanded by Philipps (2007) and still provides 'a snap shot' understanding of an intrinsic dynamic process. Positive feedback that creates increasing returns may be one important economic dynamic aspect. Diffusion theory (Rogers 2003) and social psychology (Ajzen and Fishbein 1970; Schelling 1971; Latané 1981; Schwartz and Howard 1981; Rohlfs 2003) for example give evidence that more careful attention to the social context should be paid to understand the determinants, mechanisms of adoption or not-adoption. However, social norms often have been considered as stable parameters in path dependency analysis and product diffusion models. While these assumptions may be valid in economies with stable environments, they are limited in economies with changing environments. Today, increasing energy security threads and climate change are such global changes that affect whole societies. Such societal threads induce paradigm changes in industries, and norm or preference changes in markets fostering eco-innovations and diffusion. Therefore, understanding processes that link green product diffusion with social norm research becomes increasingly important. However, it is difficult because the different research fields often refer to different situations, and apply different perspectives and methods. In this paper we address this challenge. Our first contribution is to clarify the link between green product diffusion and social norm effects. We offer an *endogenous perspective* on socio-technical norm effects and link them to the systemic phenomena of tipping point and lock-in effects. We analyze the effect of social norm changes in a market with multiple competing technologies. How should the tipping point be explained? How should it be specified? What is the effect of multiple competing eco-technologies on path dependency and diffusion pathways? By answering these questions, we aim to establish a dynamical understanding of the concept of critical mass; this is our second contribution. Therefore, we apply simulation based theory building (Davis et al. 2007). For illustrative purpose we present the case of green passenger car diffusion with different drive drain technologies.

The paper has been organized as follows. The first section has provided the general overview and the objectives of the study (Sect. 5.1). Section 5.2 provides the theoretical background on the main concepts. These include social norm in adoption decisions, and the systemic phenomena critical mass, tipping point, lock-in and path dependency. An explanation frame based on social norm dynamics is introduced. Sect. 5.3 summarizes the simulation model that is based on the explanation frame introduced in the previous section. Section 5.4 provides a mathematical analysis of the model in order to provide an intuitive understanding of the critical mass and the acting driving forces in the model. Section 5.5 discusses the insights and provides a systematic and more abstract picture on socio-technical norm regimes, tipping points and the critical mass in a force field. Section 5.6 summarizes our findings and assesses the implication of the study for policymaking and further research. Limitations are pointed out.

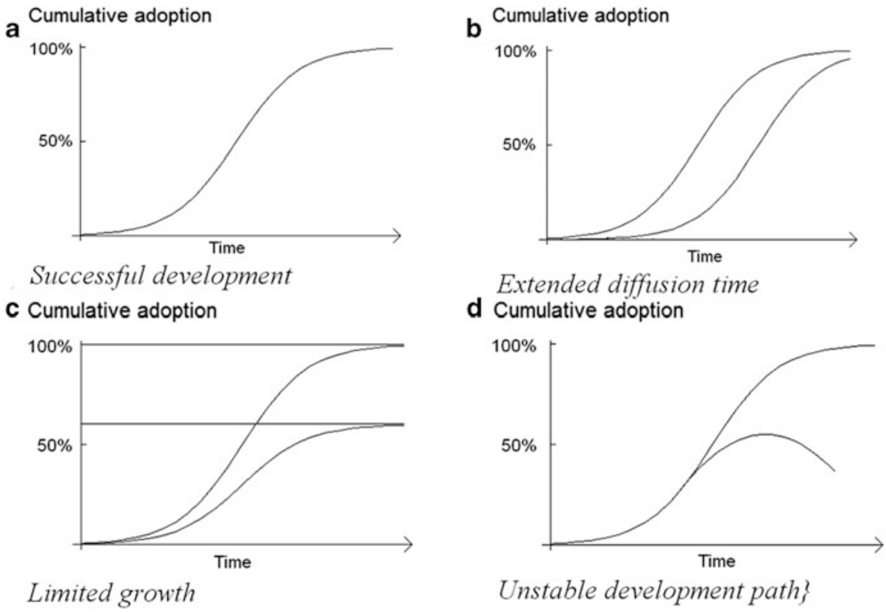

Fig. 5.1 Fundamental qualitative behavior patterns of s-shaped growth. Complete adoption goes from 0 % to 100 %, time in arbitrary units

5.2 Tipping Points and Social Norm Effects in Green Product Diffusion

5.2.1 Innovation Diffusion Pathways

Most diffusion models are able to reproduce s-shaped diffusion patterns as described by the theory of Rogers, but the concepts critical mass and tipping point are often not addressed or only vaguely circumscribed (Phillips 2007; Ulli-Beer et al. 2010). Rogers identifies a ‘point of no return’ in a diffusion process. It becomes manifest in the number of adopters of a technology, the critical mass (Rogers 2003) that is needed for the further rate of adoption to become self-sustaining. At this point stimulating measures are no longer needed for the diffusion process to proceed to saturation. Due to different initial conditions and tipping point characteristics of innovation diffusion fundamental qualitative patterns of s-shaped growth or decline can be observed. A simplified, idealized innovation diffusion that follows an s-shaped cumulative adoption curve (Rogers 2003) is shown in Fig. 5.1a. The graph shows the percentage of adoption for one technology (y-axis) plotted against time (x-axis). We refer to a successful development, if the curve follows an s-shaped form that reaches a desired level within an acceptable time frame, i.e. the level and the timeframe of a reference technology in a reference market. Possible failures would be an extended diffusion time (diffusion takes more time than acceptable, Fig. 5.1b), a limited growth (diffusion does not reach a desired level, Fig. 5.1c) or rejection (start-up of diffusion with subsequent decline, Fig. 5.1d).

An appropriate diffusion model and the explanatory theoretical framework upon which it is built must be able to reproduce and explain the different types of behavior described above. Ulli-Beer et al. (2010) have shown that growth in the Bass model (Bass 1969) is basically self-catalytic, and lacks a tipping point in terms of a transition to irreversibility. A model that does not map acceptance and rejection (behavior patterns shown in Fig. 5.1d) is limited to describe only successful growth. Ulli-Beer et al. (2010) identify the tipping point with the critical mass of adoption that shift the dominance of two competing social norms, and present an exact analysis of acceptance and rejection dynamics. Building on their analysis, we argue that the critical mass in markets should also be theoretically founded in the concept of the social norm. We investigate the case of two and three competing technologies in a substitution process and address the following three *Research Questions:*

1. How should tipping point dynamics in green product diffusion be explained?
2. Under what conditions does one eco-technology become dominant in a substitution process?
3. What is the effect of the number of competitors?

In order to address the first leading research, we give a short summary on the concepts of critical mass and social norms, as well as lock-in and path dependencies, which are traditionally treated in separate bodies of research.

5.2.2 Conceptual Links Between Social Norm Building, Critical Mass and Path Dependency

According to Rogers (2003) *critical mass* is a fundamental concept that expresses the social nature of technology diffusion. Rogers characterizes ‘reaching the critical mass’ as the ‘moment when the adoption rate experiences an acceleration’. The critical mass is described as the cumulative adopter share, which a technology must reach in order to succeed in a market. From a micro-economic perspective, a threshold of utility has to be exceeded for a customer to adopt a certain technology, that depends on the number of previous adopters of a technology (Arthur 1989; Dolfsma and Leydesdorff 2009). On a more aggregate level, it corresponds to a tipping point in technology substitution, after which social pressure becomes strong enough to induce a self-sustaining bandwagon effect (Rohlfs 2003). The social pressure concept can be directly linked to social norms of a group of people (Schwartz and Howard 1981), and to individuals’ personal norms (Ajzen and

Fishbein 1970). Both are decisive concepts for the explanation of human behavior in (social) psychology. The psychological focus theory of normative conduct describes the perception of prevalent behavior as a driving force of individual behavior and is commonly referred to as the descriptive (social) norm (Cialdini et al. 1991). Such social norms are seen as social behavior rules telling a group of people, how they should behave in a given situation. In socially complex behavior contexts they have an important coordination function. They are internalized and lead to un-reflected behavior patterns that are hard to change (Cialdini and Trost 1998; Kahan 2000). Establishing a new norm (for example, to mitigate a collective action problem such as global warming) is therefore often costly for individuals due to the old norm itself, which stigmatizes any deviation from it (Akerlof 1980; Kübler 2001). Although the empirical evidence of the relation between social norm and consumer acting has been established in the literature (Latané 1981; Cialdini and Trost 1998; Vatter et al. 2001; Ulli-Beer 2006), Nolan et al. (2008) showed that "descriptive norms" have a powerful but under-detected effect on the important social behavior of "energy conservation".

According to Fisher and Pry (1971), advancing technology allows the user to perform an existing function or satisfy a need in a different way. Fisher argues that change is rarely radical, and once competitive substitution has progressed to a few percent, it would proceed towards completion. This assumption seems to be overly optimistic for eco-innovations. Disconfirming examples may be found regarding penetration of the passenger car fleet by cleaner drivetrain vehicles. In New Zealand (Janssen 2004) and the Netherlands (Liu et al. 1997), the fleet penetration reached 10 % for natural gas vehicles in the mid-1980s and 8.6 % for liquefied petroleum gas vehicles in 1995. Both fleet shares decreased again, showing that this assumption does not hold in general.

Economic application and operationalization provide the most developed discussion of lock-in and breakout of a path-dependency. Positive feedback is the crucial feature of a historical process that generates path-dependence (Arthur 1994; David 2001). David (2001) provides a broad definition of a path dependent stochastic process. It "is one whose asymptotic distribution evolves as a consequence (function of) the process's own history" (19). That means that a historical event or strategic decision can lead to irreversible branching processes of product diffusion and the development of industries or markets. In economics, positive feedback process are operationalized by increasing returns that may be the result of large set-up costs, learning effects, coordination effects, and adaptive expectations (Arthur 1994). Building on this line of research, Dolfsma and Leydesdorff (2009) show how lock-in results from two selection environments that involve positive feedback processes, and how break-out from a lock-in can be generated if a third selection environment with a further positive feedback begins to interact with the two locked-in ones. These models explain lock-in and breakout effects as interactions between sub-systems and different selection environments, but only vaguely address the causes of a bifurcation or of a tipping point in product markets.

5.2.3 The Dynamics of Green Product Diffusion: Linking Technology Competition and Social Norm Building

Based on these grounds, we suggest that the concept of social norm needs to be considered as an important determinant of diffusion patterns of eco-innovations in markets. The primary advantage of eco-innovations is their superior ecological performance compared to relevant alternatives. Hence eco-innovations help to reduce the risk of harmful or undesired environmental change, which is a societal value, but only an indirect value added for the users. Therefore, eco-innovation adoption is based on values and beliefs concerning what are the right things to choose rather than mere private utility calculations. Particularly, the choice of eco-innovations becomes a function of the perceived prevalent choice of relevant adopters (Schwartz and Howard 1981). Therefore social norms also stabilize behavior patterns in complex decision situations (including the choice between different competing drivetrain technologies that provide uncertain direct and indirect transport utility). The perception of prevalence is often nonlinearly correlated with the number of adopters; only a recognizable new minority may induce a shift in the social norm that leads to a tipping point in the diffusion process (Schelling 1971). Consequently, social norm building processes may also lead to a lock-in in the dominant technological design, similar to processes as described by Arthur (1989). An example for a demand lock-in would be the case in the passenger vehicle market. In the past, the US and European automobile industries have pursued a development strategy with a low *emphasis on reduced fuel consumption*, increasing power and weight of new vehicles, triggered by the prevalent consumer demand (Bandivadekar et al. 2008). This led to the technological paradigm of typically high-powered, large vehicles supplied by the industry, and established a strong social norm based on the high number of adopters. This social norm influenced the purchase decision of potential buyers towards the same type of vehicle increasing consumer demand. This type of behavior illustrates how a dominant technological design is stabilized by social norm dynamics in the market. However, today we can observe a shift towards a stronger *emphasis on reduced fuel consumption* (Ulli-Beer et al. 2011)*;* this may be attributed to technology paradigm change (Dosi 1982), or a double loop learning process in organizations (Argyris and Schoen 1996; Dosi et al. 1999), or to social norm changes in the market, as discussed in this paper. Probably, it may be best described as a co-evolutionary process involving different rule shifts in the linked subsystems.

The examples give evidence that a discontinuous change may be necessary for inducing a self-sustaining diffusion path that is not only based on a critical share of adopters but also on the strength of the social norm. In order to erode the social norm of the prevalent petrol and diesel vehicles, a respected group of opinion leaders needs to attach a new social value to a unique feature of the new technology, for example, the high eco-friendliness. They need to establish the recognizable new minority (Schelling 1971). The motivation for innovators and early adopters to adopt a eco-innovations may be to mitigate the collective action problem of climate change (Kübler 2001). These are often a niche population of users that have developed more distinct product preferences than the mainstream (Levinthal 1998). In other words, eco-innovation uptakes may result when opinion leaders realize a need and opportunity for alternative actions. Ulli-Beer et al. (2010) have developed a double-loop acceptance framework that explains how social norm dynamics are overriding utility evaluations (see also Kopainsky et al. 2012). The social norm is initiated by new distinct behavior patterns of a recognizable new minority of early adopters that respond to undesired long-term consequences of the dominant technology design. Eventually, these early adopters may provide a new social norm to successive adopters that cumulate in the stock of the recognizable new minority increasing the strength of their social norm.

While innovators launch the new technology, deliberate adoption decisions of opinion leaders trigger a new social norm within a social-technical system. That is the reason why innovators and opinion leaders are critical to solve the start-up problem of a new technology. Succeeding adopters reinforce the prevalence of the new purchase pattern, and subsequently the social norm effect on the adoption decision. These social interaction effects of distinct purchase patterns can be understood as social norm competition. As soon as the new social norm dominates and guides an increasing number of adoption decisions, the diffusion process reaches the critical mass of adopters and crosses the tipping point, where the process becomes self-sustaining. With this description, we complement Roger's statistically derived adopter categories by an explanation framework based on *social norm dynamics*. It offers a better understanding on how self-enforcing social norm building and the concept of eco-innovativeness may be used to explain and simulate the diffusion of green products, in general, and the related tipping point or lock-in phenomena, in particular.

To conclude our theoretical discussion, we argue that in the context of green product diffusion, the critical mass should be anchored in the concept of *nonlinear social norm dynamics*, because societal issues are the main triggers of eco-innovations and their wide spread use. In the following, we will illustrate the macro effects of social norm dynamics, creating tipping behavior and path dependency. For this purpose, we introduce a system dynamics model for the case of eco-innovations in the passenger car fleet.

5.3 The System Dynamics Model for the Market Penetration of Alternative Drivetrain Technologies

We have developed a SD model to endogenously simulate the market penetration of alternative drivetrain technologies (Bosshardt 2009; Ulli-Beer et al. 2011). It is based on the above introduced explanation frame of social norm dynamics in green product diffusion. In this paper, we describe the simplified structure that operationalizes the structure of social norm dynamics and allows analyzing the behavioral impact on the diffusion path. We aim at increasing the understanding about the potential effect of social norm dynamics on the emergence of a tipping point, and the required critical mass considering an increasing variety of technology options. Therefore, the model is applied to two and later three competing drivetrain technologies in the passenger car market. Our focus is on the adopter potential, a variable describing the consumer choice, moderating the sales rates of the vehicle technologies and thus the substitution rate. The adopter potential depends on three arguments for the consumers' purchase decision:

Comparative attractiveness summarizes the factors influencing the monetary utility of a drivetrain technology, such as purchase and fuel prices, as well as the drivers' satisfaction of infrastructure needs and vehicle type spectrum. The approach of discrete choice modeling with logit functions can be applied to calculate the probability of purchase when accounting for cost criteria.

Social norm is the internal social pressure. The force is positively related with the technology-specific adopter potential and rate of adoption. Its value is given by a nonlinear, s-shaped function of the number of the technology-specific installed vehicle stock (Schelling 1971; Ulli-Beer 2006). It operationalizes the cumulative, normative influence of the increasing prevalence of a new vehicle technology. The normative social influence is the impulse to imitate observed behavior. Observed behavior, in this sense, refers to the recognizable new minority who has already adopted the new vehicle technology.

Inherent attractiveness comprises technological attributes, which are not covered by monetary, infrastructural or normative social considerations. It represents the evaluation of a technology due to its attributed potential to address new or existing needs, values and beliefs of potential adopters and the broader society. In terms of Rogers' categories of 'perceived attributes of innovation', it fits best with the compatibility concept. However, the notion *inherent attractiveness* also captures the aspect of a promise and potential a technology portends. It is an attributed compatibility with a newly debated norm for solving a collective action problem. Compared to the social norm, the inherent attractiveness is the impulse on innovation that a new drivetrain technology gives. The corresponding technological attributes also trigger the motivation of innovators and early adopters. The inherent attractiveness input data is used as an exogenous parameter in order to analyze the impact of a parameter value change on the overall model behavior as illustrated in Figs. 5.4 and 5.5.

Each drivetrain technology is represented by its vehicle stock. Discards gradually decrease the vehicle stocks, depending on the lifetime of a vehicle. When a vehicle is replaced by a new one, the total of all vehicles is not affected. Fleet growth or decrease is a result of positive or negative new sales, not replacements. Technology substitution means that a discarded vehicle of technology A is replaced by a vehicle of technology B, depending on the drivetrain technologies' attributes. Then the technology specific vehicle stock changes, while the overall fleet stock remains constant. The attributes comparative and inherent attractiveness, as well as

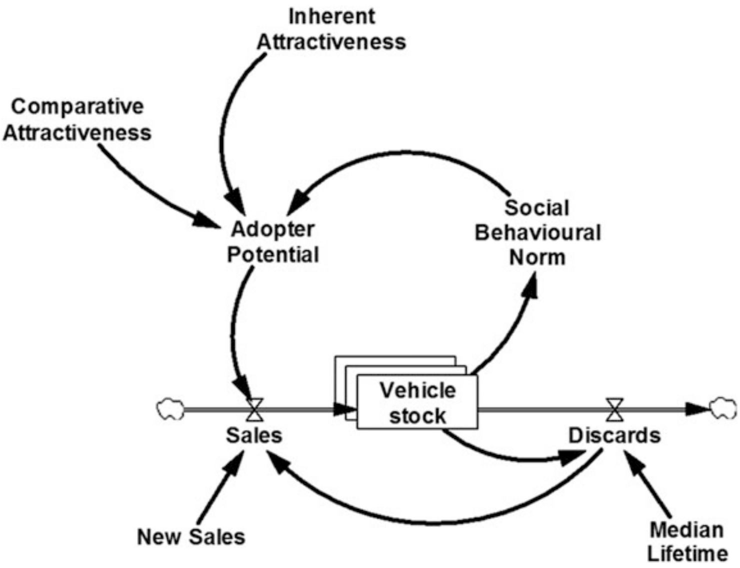

Fig. 5.2 Main structure of the model as applied to multiple technologies (i.e., different vehicle stocks)

the social behavioral norm control the technology-specific adopter potential, a percentage which is assigned to each technology in terms of a market share. The translation into sales rates is achieved by multiplication of the adopter potential with vehicle sales, including both replacement sales and new sales. The structure displayed in Fig. 5.2 shows the interrelationship between the model variables for each technology. It further indicates that this structure is applied to all technology specific vehicle stocks. The adopter potential combines these sub-model structures. The attractiveness and norm values are normalized and used to allocate the market shares to each drivetrain technology. The heart of the model and the most important aspect for the analysis in this paper is the feedback loop featuring the social norm building process. Each drivetrain technology produces a social norm by the presence of its vehicles. This influences the adopter potential (i.e., the consumer's purchase decision), and via sales affects the vehicle stocks again. In our further analysis we will give evidence that this reinforcing feedback loop of the *socio-technical norm effect* has severe consequences on green product diffusion pathways, i.e. the emergence of path dependencies and tipping points, as well as the identification of a critical mass.

For illustrative reasons the mathematical formulation of the model variable "Sales" will be introduced (see also Appendix. It is the rate equation of the technology specific vehicle stock X_i.

$$\frac{dX_i}{dt} = S_i - D. \tag{5.1}$$

The sales of technology i (S_i) can be expressed by the adopter potential (relative market share) AP_i multiplied with the total sales. The total sales, however, are given by the discards of every drivetrain technology D_k as required by technology substitution, plus new sales (NS):

$$S_i = AP_i\left(\sum_k D_k + NS\right)$$

The discards are obtained by dividing the vehicle stock by the vehicle median lifetime τ.

$$S_i = AP_i\left(\sum_k \frac{X_k}{\tau_k} + NS\right)$$

The adopter potential of drivetrain technology i (AP_i) represents the probability that a consumer buys a vehicle of this platform. It is obtained by normalization of the total perceived attractiveness PA_i over all technologies, that is

$$AP_i = \frac{PA_i}{\sum_k PA_k}$$

where PA_i combines the three consumer choice attributes: behavioral norm SN_i, inherent attractiveness IA_i and comparative attractiveness CA_i. In our model it is given as (Bosshardt 2009)

$$PA_i = CA_i * (SN_i + IA_i - SN_i IA_i)$$

Substitution of the above into Eq. 5.1 yields

$$\frac{dX_i}{dt} = \frac{CA_i * (SN_i + IA_i - SN_i IA_i)}{\sum_k CA_i * (SN_k + IA_k - SN_k IA_k)}\left(\sum_j \frac{X_j}{\tau_j} + NS\right) - \frac{X_i}{\tau_i}. \tag{5.2}$$

We have operationalized and quantified the socio-technical norm effect as a lookup function (cf. Fig. 5.3), using the number of vehicles for each drivetrain technology as input. This input value is normalized to the total of vehicles in the fleet to map perception, or people's everyday life experience. The lookup function outputs a fraction of people willing to adopt the corresponding technology by social pressure.

A fleet share of 0 % will certainly not produce any adopter paradigm. The other extreme case is a complete fleet penetration, where the socio-technical norm effect is limited. We assume that about 5 % of potential adopters do not follow the norm

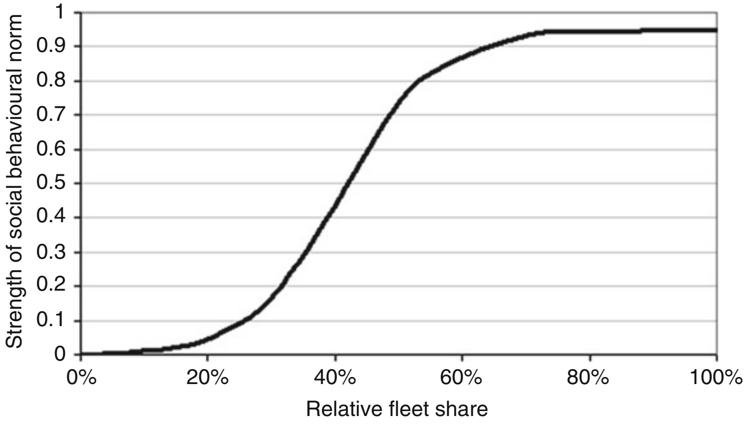

Fig. 5.3 The socio-technical norm effect corresponds with people's perception of the diffusion of a drivetrain technology in the vehicle fleet. It is modeled by an s-shaped lookup function. Saturation reaches 0.95 for a 100 % fleet share

and must be convinced to adopt by one of the other two factors, inherent or comparative attractiveness. This fraction corresponds to people such as innovators, who adopt new technologies without considering trends, but rather setting trends and enabling diffusion or substitution processes to start (Rogers 2003).

5.4 Model Behavior

We now investigate the behavior of this model with two and three competing technologies. The model is applied to the passenger car market, starting with the competition of internal combustion engine vehicles (ICEs) operated on petrol and diesel. In a second step, an eco-technology, natural gas vehicles (NGVs), is introduced into the market to compete with the conventional ICEs.

5.4.1 Two Competing Technologies

The following model output presented in Fig. 5.4 is based on a scenario for Germany, focusing on competing petrol and diesel ICEs. The observed dominance of petrol ICEs is attacked by an upcoming diesel fraction. The graphs below show the model results for two scenarios, (a) *Persistent ICE Petrol Dominance* and (b) *Establishing ICE Diesel Dominance*. The difference between the two scenarios (a) and (b) is the duration of an increase of the parameter inherent attractiveness of the diesel vehicles as displayed by (i) the inherent attractiveness settings.

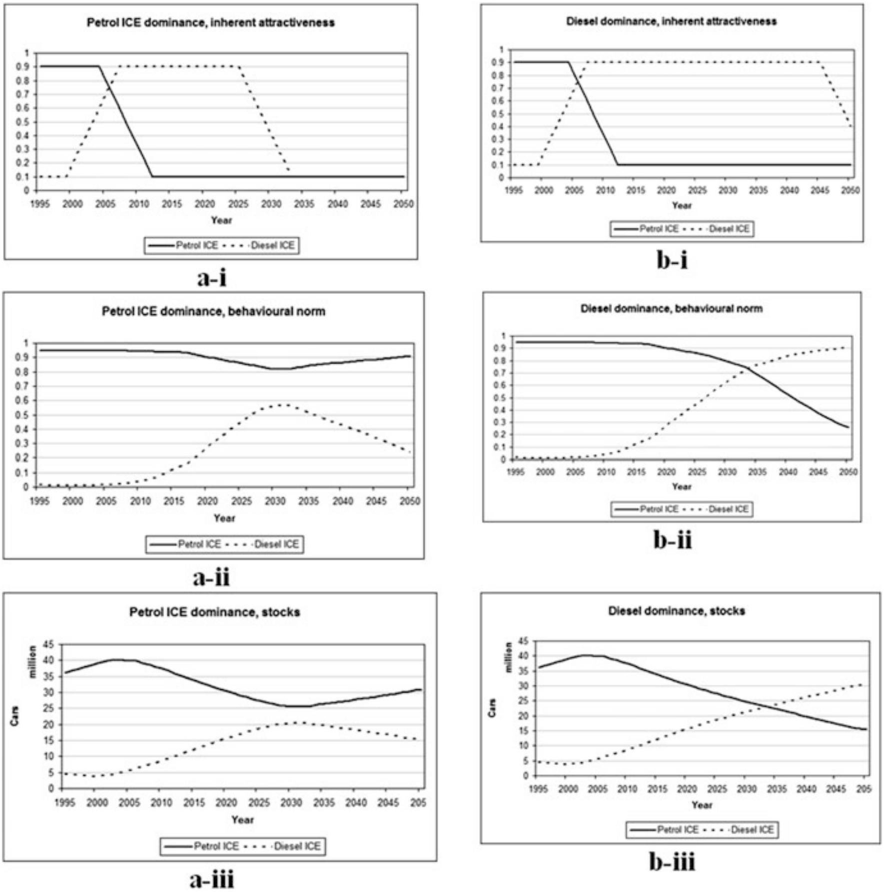

Fig. 5.4 Effect of the established socio-technical norm on the vehicle stocks of competing petrol and diesel ICEs, based on different inherent attractiveness scenarios

The comparative attractiveness is assumed to be similar for both technologies and is kept constant. The consequences for the social behavioral norm (ii) and the corresponding impact on the vehicle stock development (iii) are displayed in the subsequent graphs.

The simulation results highlight typical behavioral characteristics. First, the fleet behavior strongly depends on the development of the social behavioral norm, which is in line with Bass' diffusion by imitation. The strong represented petrol ICE fleet is supported by its highly influential socio-technical norm. Diesels do not have a high installed base, and consequently an ineffective socio-technical norm loop; therefore they need a change in their inherent attractiveness to enlarge their fleet share. Although the inherent attractiveness of petrol vehicles drops, while the inherent attractiveness of the diesels increases (e.g. due to an improved end-of-pipe technology), they remain the dominant drivetrain technology. Second, if the inherent attractiveness of the diesels ceases before its norm effect has exceeded the norm effect of petrol vehicles, the original states are re-established, as shown in scenario (a). In scenario (b), the inherent attractiveness remains longer on the high level, long enough to build up a dominating social behavioral norm. And finally, even though the inherent attractiveness ceases, the norm loop is strong enough to keep its dominating influence; this is a counterintuitive result according Bass' diffusion by imitation.

However, it establishes evidence that the socio-technical norm loop and its nonlinearity explain tipping point behavior in green product diffusion: the strength of the socio-technical norm effect as a function of the fleet share of diesel ICEs has exceeded a critical *relative* threshold value. Beyond that point, the technology diffusion is successful and stable. According this understanding the *critical mass* can be identified as the required *relative* fleet share that generates a shift in the dominance of competing socio-technical norm processes. The example describes typical behavior patterns of the *class of* green product diffusion challenges involving technology substitution.

5.4.2 Three Competing Technologies

We now describe the socio-technical norm effect on the critical mass that occurs in our model, as soon as at least three drivetrain technologies compete. We apply the model to the same settings as in the case for two competing technologies and introduce a third technology, natural gas vehicles (NGVs). The graphs in Fig. 5.5 show the model results again for two scenarios (a) *Persistent ICE Petrol Dominance* and (b) *Establishing NGV Dominance*: the inherent attractiveness settings (i), their consequences for the social behavioral norm (ii) and the corresponding impact on the vehicle stock development (iii). The difference between the two scenarios (a) and (b) is again the period of increased inherent attractiveness for diesel ICEs, but now in the context of NGVs simultaneously entering the vehicle fleet. In scenario (a), the introduction is a long-term stagnation, in scenario (b), it is successful. The comparative attractiveness is assumed to be similar for all technologies and is kept constant again.

The breakthrough of NGVs does not happen in scenario (a), and of course, similar to our example before, it could be forced with a high inherent attractiveness of NGVs for a longer period. However, this example reveals a second possibility. The stronger presence of diesel ICEs in the vehicle fleet of scenario (b) by an extended high level of the inherent attractiveness, additionally weakens the norm of petrol ICEs. The new NGVs benefit from this, and achieve a long-term successful fleet penetration.

The example illustrates that the critical fleet share is higher on a direct transition path without any other competing drivetrain technologies. Additional alternative technologies with significant fleet penetration reduce the norm of the dominating technology, lowering the threshold value for the tipping point for each technology. This means that the critical mass and thus the transition process is path dependent;

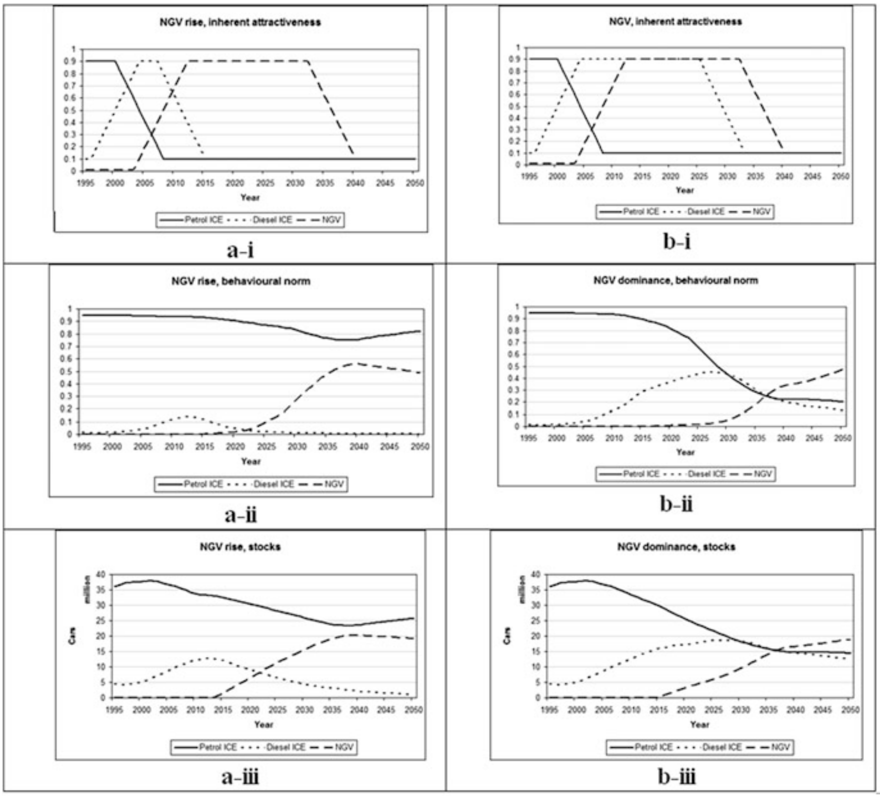

Fig. 5.5 A stronger diesel presence additionally weakens the dominating norm of petrol ICEs and enables NGVs to break through

it depends on historical technology substitution processes that have weakened the social behavioral norm of the dominant technology.

5.5 Model Analysis

A mathematical analysis of the System Dynamics (SD) model is helpful to enhance the understanding of the behavior patterns presented above and the nature of the critical mass (critical relative fleet shares). The analysis of the dynamics corresponding to the situation with two competing technologies was performed by Ulli-Beer et al. (2010). We build on this analysis and directly examine the case with three competing technologies. This analysis enables us to illustrate the model behavior with the intuitive analogy of a lightweight-ball rolling downhill (Ulli-Beer et al. 2010).

We introduce the short notation x_1, x_2, and x_3 for the normalized[1] vehicle stocks of the three drivetrain technologies, i.e., petrol ICEs, diesel ICEs and NGVs. In the absence of the third vehicle type x_3, where we have the two groups of vehicles x_1 and $1 - x_1 = x_2$, Ulli-Beer et al. (2010) have shown that the underlying dynamics can be formulated on the basis of a double well potential function $V(x_1)$:

$$\frac{dx_1}{dt} = -\frac{dV}{dx_1}$$

The mathematical analysis (see Appendix) shows that with three drivetrain technologies, we get the vehicle groups x_1, x_2 and $1 - x_1 - x_2 = x_3$, and two equations determining the potential function $V(x_1, x_2)$:

$$\frac{dx_1}{dt} = -\frac{\partial V(x_1, x_2)}{\partial x_1}$$

$$\frac{dx_2}{dt} = -\frac{\partial V(x_1, x_2)}{\partial x_2}$$

Although there is no general global solution $V(x_1, x_2)$ for these two equations, we can find an approximated potential $U(x_1, x_2)$ *for* $(x_1, x_2) \in \mathbb{R}^2$ where $x_1 \geq 0, x_2 \geq 0$ and $x_1 + x_2 \leq 1$. As Ulli-Beer et al. (2010) point out, the nonlinearity of the social norm influence creates the acceptance and rejection dynamics. Although, in reality the norm influences may correspond best with a s-shaped curve, the mathematical analysis is done with the simplest nonlinear example, a quadratic function. However, the qualitative results will not change when using an s-shaped social norm effect. If we further choose a very symmetric case of all parameters (i.e. the parameter value of the inherent and comparative attractiveness of each technology are the same), we get the following potential (see Appendix):

$$\begin{aligned} U(x_1, x_2) = {} & 0.4x_1 - 11.9x_1^2 + 23.6x_1^3 - 12.1x_1^4 + 0.4x_2 + x_1x_2 - 1.9x_1^2x_2 \\ & - 11.9x_2^2 - 1.9x_1x_2^2 + 23.9x_1^2x_2^2 + 23.6x_2^3 - 12.1x_2^4 \end{aligned}$$

A plot of this approximated potential U is shown in Fig. 5.6. The dynamics of the model correspond to a lightweight-ball moving in the landscape defined by U. Its coordinates refer to the fleet shares (normalized stock values) of technologies 1 and 2. The fleet share of technology 3 is not directly accessible in a 3D-picture (a third dimension is needed to show the potential), but can easily be calculated as $1 - x_1 - x_2 = x_3$. The fleet shares change when the ball is moving. It is not possible to move into the plateau region, because the highest fleet share possible is 100 %.

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[1] Normalized to the total fleet stock $x_i = \frac{x_i}{x_1 + x_2 + x_3}$.

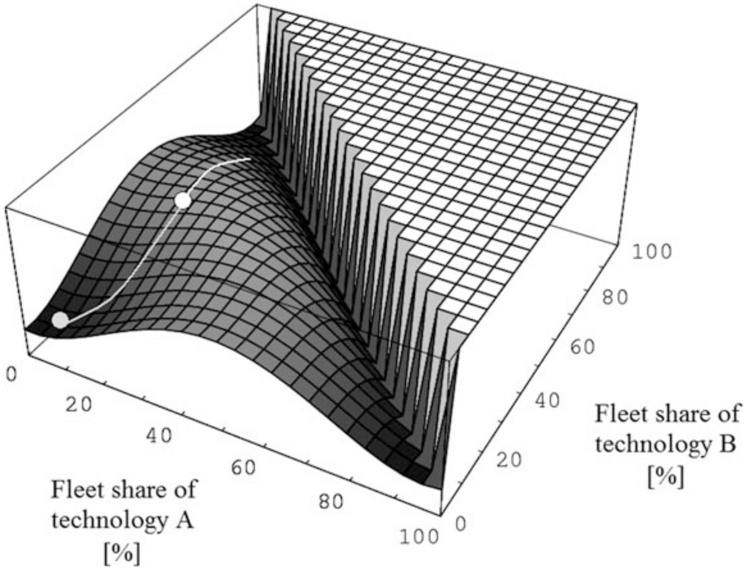

Fig. 5.6 Approximated potential in the case of three competing technologies with a quadratic socio-technical norm effect. A possible initial state of the system is symbolized by a *white ball*, rolling downhill along the *grey line* to the *grey ball's* position. This corresponds to the development of the system without any incentives or additional external influences. Another stable state other than the *grey* one can be reached when the system is lifted above one of the potential walls, for example, following the *white line* in the opposite direction

The local minima in the picture indicate stable states of the system. These are attracting points and the ball will move to one of those minima, depending upon where it is released. The minima correspond to preferred fleet share combinations, and the vehicle fleet will develop towards one of these combinations when it is not forced by external influences. The existence of local minima divides the area into different regions that are dominated by one of these stable states. All trajectories of the system starting in the same region end up in the same equilibrium. In Fig. 5.6, the initial state of the system is symbolized by a white ball. If the ball is released while the system parameters are kept constant (i.e., without external influence), it will move downhill along the grey line to the grey ball's position. Another stable state other than the grey one can only be reached when the system is lifted above one of the potential walls, for example, following the white line, entering the regime of another minimum. In other words, there are barriers separating these regions from each other. Crossing such a wall does always cause a complete change of the trajectory towards a new equilibrium. These walls represent the critical mass in the model. The minima emerge from the social norm mapping imitation effects.

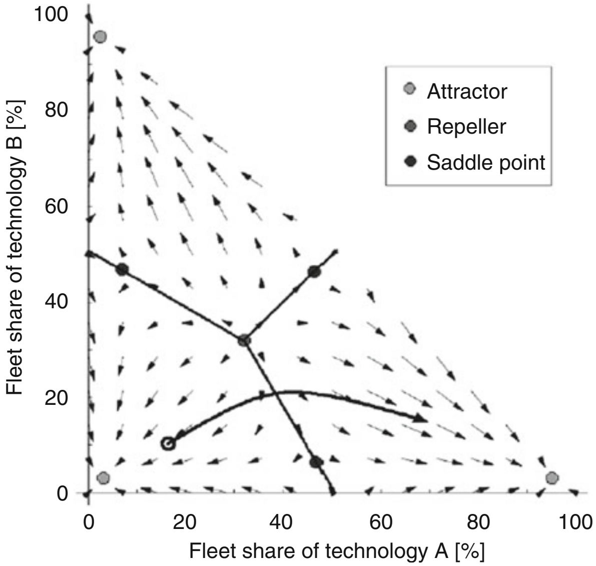

Fig. 5.7 Visualization of the driving 'force field' of the system without external influence. *Arrows* indicate the direction and velocity of movement. Coordinates are given as fleet shares. Connecting the central repeller with the saddle points reveals areas that are dominated by different drivetrain technologies. These connections represent the *critical mass* in the adoption process, i.e. a shift in the dominance of the socio-technical norm due to the nonlinear norm building process. If external influences force the system to move along the indicated pathway (*long arrow*), the critical mass is reached when crossing one of the straight lines

5.6 Discussion

The insights gained from model behavior and analyses are discussed in the following. To abstract the specifics of the case, we replace the names of the three competing drivetrain technologies with A, B and C. The system behavior can be described in the same way as in the mechanical lightweight-ball analogy. To visualize the driving forces of the socio-technical norm regime, Fig. 5.7 shows the top view of the area containing all possible system states where coordinates are given as fleet shares of technologies A and B, again with fleet shares C $= 100\ \% - \mathrm{A} - \mathrm{B}$. The small arrows indicate the direction and strength of the driving force if there are no external influences, revealing three local minima or stable states (attractors), three saddle points and one completely unstable point, a local maximum (repeller) in the center. The repeller corresponds to a fleet composition of one-third for each drivetrain technology, a very sensitive, unstable equilibrium.

Deviations from the central equilibrium lead into one of the three areas separated by straight lines. In our highly symmetric example (all technologies share the same general parameter settings), they are found by connecting the repeller to the three

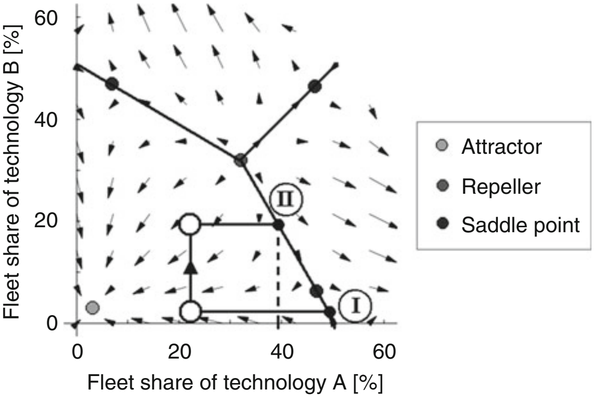

Fig. 5.8 A transition to technology A's regime on two different paths, both starting in the lower *white* spot: Direct transition with 50 % critical adopter share for A, or a precedent increase in technology B's share from 2 % to 20 % (*arrow*), reducing the critical share for A to 40 %

saddle points. Each area comprises an attracting equilibrium point or local minimum. The local minimum near (0/0) is dominated by the third technology which cannot be shown in this graph but has the fleet share C = 100 % − A − B.

Policy-based consumer incentives, for example, may influence the purchase decision and move the system away from its equilibrium state. Crossing the boundaries means entering another technological *norm regime* and ending up with that dominant technology. If we look at an example trajectory (long arrow), the system must be forced by external influence to move against the intrinsic driving force. It reaches a tipping point when crossing the boundary line. Entering the *norm regime* of technology A determines the final state of the system, even if external influence is stopped. The coordinate of the point where the boundary is crossed corresponds to a critical adopter share for A. Obviously this coordinate may be varied depending on the systems trajectory. However, if the external influence is ceased *before* the boundary is crossed, the system moves back to the old equilibrium.

Most interesting is the case of three competing technologies, since it causes path dependency. As soon as there are three or more competing technologies, the critical mass depends on the path of the development. Figure 5.8 illustrates two path examples for the transition into a new regime. The Fig. 5.8 shows a picture detail of the driving force field. Moving the system from the lower white spot to the regime of technology A would require a fleet share of A of about 50 % (mark (I)). After that point the transition is self-sustaining and any incentive can be ceased. Technology B's fleet share is constant at some 2 %. However, if B's share is increased to 20 %, i.e. the system is first moved along the arrow, conditions change. The fleet share of technology B attacks technology C's dominance too, making it 'easier' for technology A to gain a critical share. The transition in horizontal direction only needs an adopter share of 40 % to become self-sustaining (mark (II)). If the transition to A on the lower path fails because the external influence is ceased early, the transition on the upper path could still be successful. We conclude that the cost and external influence needed is path-dependent. The development may become irreversible.

5.7 Conclusions

The purpose of the study is to clarify the link between green product diffusion and social norm building and to analyze resulting system behavioral effects. We establish an endogenous understanding on socio-technical norm effects on green product diffusion. We link the systemic phenomena of tipping point and path-dependency with the concept of social norm building and technology competition in markets. This provides a more detailed understanding of the dynamic processes behind green product diffusion. We argue that competition in the market is also a competition between socio-technical norms, specifically in cases of green product substitution.

We show that green product diffusion models should also include social norm effects to analyze the pathways of technology substitution. We propose a model that uses the social behavioral norm to map imitation effects. Social norm effects depend nonlinearly on the customers' perception of the corresponding drivetrain technology's stock. This nonlinear relationship makes the difference between an autocatalytic model, such as the Bass model which "is limited to describing only successful market diffusion into one stable state" (Ulli-Beer et al. 2010), and a model that maps adoption and rejection as well. The social norm dynamics of competing technologies provide the endogenous mechanisms of tipping behavior in s-shape diffusion models. This is in line with the understanding of the tipping point as a point of no return between rejection and adoption. It also substantiates the proposition that a diffusion model must incorporate a resistance to produce tipping behavior, as suggested by Phillips (2007).

In order to enhance the dynamic understanding of the observed behavior patterns we use the intuitive analogy of a lightweight-ball moving in a landscape (Ulli-Beer et al. 2010). A quadratic socio-technical norm effect generates a fourth degree potential function. Based on this mathematical representation, we can identify socio-technical norm regimes, which are interpreted as technological lock-in situations. These equilibrium states represent fleet shares of different drivetrain technologies that do not change over time without modifying the parameters. Since the system is always in the domain of one technology, i.e., in a technological lock-in, the other technologies are locked out. Breaking the lock-in situation is possible but, to change the norm regime, external influence is needed. These can also be co-evolutionary changes in the technological innovation systems, but those are excluded from our analysis. External influences by policy incentives force the system to move from its equilibrium state against the intrinsic driving force. The incentives can only be ceased if the new socio-technical norm becomes dominant and sustains the substitution process. The *relative* cumulative adopter share of the corresponding technology, which is needed for that is identified as the critical mass. The tipping point is understood as the moment where the critical mass is reached. Since policy incentives usually involve high costs, it is useful to know that the process has become self-sustaining and that incentives can be ceased. However, an early stop would lead to a transition failure and give rise to costs that do not have any long-term effect. The system would move back to its original equilibrium. In the long run, a new lock-in is inevitable. This analysis also confirms our argument, that the circular causalities of socio-technical norm effects explain tipping behavior in green product diffusion (see *Research Question 1*).

Coming back to the *Research Question 2* we draw the following conclusions: A critical relative adopter share is needed to establish a new dominant social behavioral norm. The norm causes the existence of norm regimes (lock-in areas), and therefore the critical mass of adopters, as well as the tipping point. The tipping point marks the transition into a new norm regime, determining the final state of the system, if any external influence is stopped and no further changes are effective. In this situation, moving between norm regimes always requires external influence to reach the critical mass.

Concerning *Research Question 3* we conclude that the number of competing technologies causes path dependence. As soon as there are three or more competing technologies, the critical mass depends on the path of the development.

Finally we point out, that the model has a generic structure and can be used to describe technology substitution processes in a general context, where societal needs trigger social norm building. It also helps to identify the critical mass under different parameter setting, or boundary conditions, respectively. Understanding the effect of competing normative influences has important implications for entrepreneurs and policy makers that have to take long term investment decisions concerning green technologies. Social marketing policy measures may become cost-effective levers. Also, preference changes based on social norm influences may offer a new research perspective to traditional theories on the hazard of disruption in industries (Tellis 2008; Sood and Tellis 2011).

However, while the socio-technical norm dynamics may describe the diffusion pathway, other co-evolutionary (feedback) processes may be effective in further subsystem (e.g. learning-by-doing, standardization), that influence the shape of the socio-technical landscape and subsequently the diffusion pathway. These kinds of processes are not considered in our analysis. Nonetheless, they can be addressed as well with the illustrated simulation based theory building approach. Eventually, with increasing feedback complexity, the mathematical analysis may fall short – but the analogy may still remain helpful to build intuition.

Acknowledgments Our special thanks go to Fritz Gassmann who provided important input to the model analysis approach. We are grateful for financial support to the project by novatlantis, a sustainability initiative of the Board of ETH Zürich.

Appendix

Derivation of the Potential for the Three Competing Technologies

In Fig. 5.9, the stock and flow structure for drivetrain technology i is shown twice: the picture to the right introduces short names for the model variables which are used in the equations below. The index i represents one of the drivetrain technologies considered in the model.

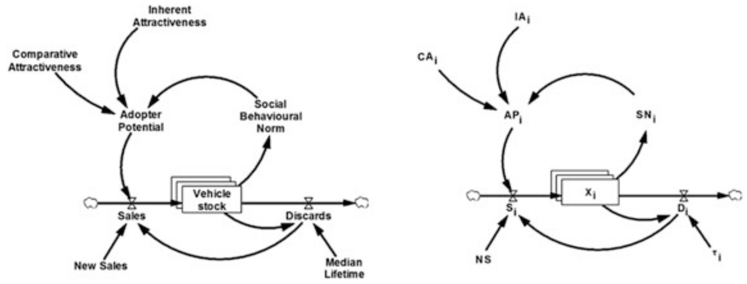

Fig. 5.9 Stock and flow structure as it is applied to every technology platform with abbreviated variable names.

In Subsection 2, we have introduced Eq. 5.2 of the rate for X_i, which reads

$$\frac{dX_i}{dt} = \frac{CA_i * (SN_i + IA_i - SN_i IA_i)}{\sum_k CA_i * (SN_k + IA_k - SN_k IA_k)} \Big(\sum_j \frac{X_j}{\tau_j} + NS\Big) - \frac{X_i}{\tau_i} \tag{5.3}$$

For simplification we

- Set the net new sales *ns* equal to 0, keeping the total number of vehicles in the fleet constant.
- Normalize Eq. 5.3 to the total number of vehicles *N* in the whole fleet: $x_i = \frac{X_i}{N} . x_i$ represents the fleet share of technology *i*.
- Use the same lifetime τ for all drivetrain technologies.
- Assume that all involved technologies have the same comparative attractiveness. Therefore the term CA_i is cancelled out.

These simplifications yield

$$\frac{dx_i}{dt} = \frac{SN_i(1 - an_i) + IA_i}{\sum_k \big(SN_k(1 - IA_k) + IA_k\big)} \sum_j \frac{x_j}{\tau} - \frac{x_i}{\tau}. \tag{5.4}$$

The social norm SN_i is given as a function of the fleet share x_i. As Ulli-Beer et al. (2010) point out, that the behavioral norm should be represented by a nonlinear function. The easiest nonlinear case is a pure quadratic function (see the **Results** section and Appendix):

$$SN_i = f(x_i) = x_i^2$$

This yields

$$\frac{dx_i}{dt} = \frac{x_i^2(1 - an_i) + IA_i}{\sum_k \big(x_k^2(1 - IA_k) + IA_k\big)} \sum_j \frac{x_j}{\tau} - \frac{x_i}{\tau}.$$

In our 3-drivetrain system with constant fleet we have $x_3 = 1 - x_1 - x_2$ and therefore $\frac{dx_3}{dt} = -\frac{dx_1}{dt} - \frac{dx_2}{dt}$, leading to two independent rate equations:

$$\frac{dx_1}{dt} = \frac{1}{\tau}\Big(- x_1 + \ldots$$

$$\ldots + \frac{x_1^2(1 - an_1) + an_1}{x_1^2(1 - an_1) + x_2^2(1 - an_2) + (1 - x_1 - x_2)^2(1 - an_3) + an_1 + an_2 + an_3}$$

$$\frac{dx_2}{dt} = \frac{1}{\tau}\Big(- x_2 + \ldots$$

$$\ldots + \frac{x_2^2(1 - an_2) + an_{21}}{x_1^2(1 - an_1) + x_2^2(1 - an_2) + (1 - x_1 - x_2)^2(1 - an_3) + an_1 + an_2 + an_3}$$

Following the lightweight-ball metaphor introduced by Ulli-Beer et al. (2010) and extending it to three competing technologies leads to the elegant form including a potential $V(x_1,x_2)$:

$$\begin{pmatrix} \dfrac{dx_1}{dt} \\ \dfrac{dx_2}{dt} \end{pmatrix} = -\nabla V(x_1, x_2) = \begin{pmatrix} -\dfrac{\partial V(x_1, x_2)}{\partial x_1} \\ -\dfrac{\partial V(x_1, x_2)}{\partial x_2} \end{pmatrix} \tag{5.5}$$

However, it is not possible to define a global potential $V(x_1,x_2)$, satisfying Eq. 5.5. This can easily be shown by calculating the rotation of the left-hand side.

Although no global potential $V(x_1,x_2)$ exists, we can find an approximated potential $U(x_1,x_2)$. For this purpose we use a general fourth order function of x_1 and x_2 of the following form:

$$\begin{aligned} U(x_1, x_2) = a_1x_1 - a_2x_1^2 + a_3x_1^3 - a_4x_1^4 + b_1x_2 + fx_1x_2 - cx_1^2x_2 \\ - b_2x_2^2 - dx_1x_2^2 + ex_1^2x_2^2 + b_3x_2^3 - b_4x_2^4 \end{aligned}$$

There is no constant term because this would just cause a translation of the potential function, and can be omitted. We now insert $\tau = 15$ and $IA_i = 0.02$, *for all i*, and set up a homogeneous system of equations using the roots of the dynamic equations. Solving for the parameters a_1, a_2, a_3, a_4, b_1, b_2, b_3, b_4, c, d, e, f leads to the approximated potential

$$\begin{aligned} U(x_1, x_2) = 0.4x_1 - 11.9x_1^2 + 23.6x_1^3 - 12.1x_1^4 + 0.4x_2 + x_1x_2 - 1.9x_1^2x_2 \\ - 11.9x_2^2 - 1.9x_1x_2^2 + 23.9x_1^2x_2^2 + 23.6x_2^3 - 12.1x_2^4 \end{aligned}$$

Quadratic Versus S-Shaped Norm Function

To keep the mathematical analysis simple we used a quadratic function for the social behavioral norm. With a logistic function for SN_i, Eq. 5.4 would read

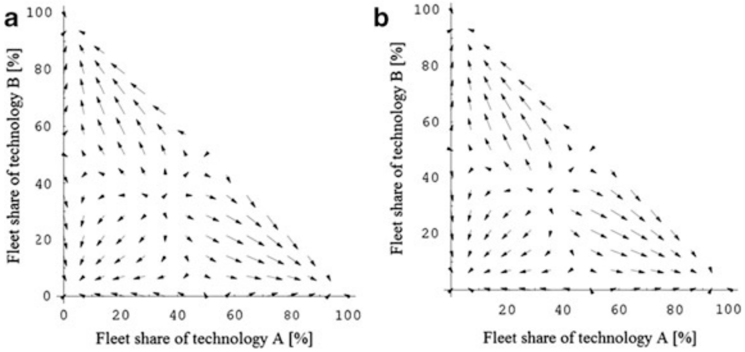

Fig. 5.10 Driving force field plot with a quadratic social norm function (**a**) and its equivalent with an s-shaped social norm function (**b**), here a logistic function

$$\frac{dx_i}{dt} = \frac{\frac{1-IA_i}{1+e^{-10(-0.5+x_i)}} + IA_i}{\sum_{k=1}^{3}\left(\frac{1-IA_k}{1+e^{-10(-0.5+x_k)}} + IA_k\right)} \sum_{j=1}^{3} \frac{x_j}{\tau} - \frac{x_i}{\tau}.$$

Without giving a profound analysis, we illustrate the similarity of the resulting potentials and behavior using the underlying force field as in Fig. 5.7. These are plotted in Fig. 5.10b for the s-shaped and in Fig. 5.10a for the quadratic norm function respectively. Qualitatively the two yield the same results in the area of interest.

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Chapter 6

Industrial ECO-Transformation: Impacts of Climate Policy and Advanced Vehicle Technologies on the Carmaker Industry

Benjamin Boksberger, Silvia Ulli-Beer, Manuel Bouza, and Alexander Wokaun

Abstract This paper introduces an industrial transformation model applied to the carmaker industry. We analyze the interaction between supply and demand as well as policy regulations supporting the diffusion of advanced vehicle technologies. The simulation experiments highlight the dynamic interaction of industrial viability, and public policy for mitigating diffusion barriers, as well as CO2 emission reduction targets in the EU. Data analysis and simulations show that high capital stocks in the automobile industry form decisive market barriers for newcomers. Also automakers' capacity to strongly invest in R&D becomes an important competitive advantage specifically for market leaders throughout an induced transition towards a greener industry. Policy analysis highlights the critical role of early investment into the infrastructure build-up and its effect on cost reduction paths of alternative vehicles. In addition, model analyses give evidence that anticipation of policy regulations and early responses of the supply side induce economically and environmentally advantageous transition paths. Specifically the deployment of natural gas vehicles turns out to be a robust short term strategy for improved CO2 emission reductions. Electric range extended vehicles help to overcome infrastructure barriers. The pace of infrastructure build-up and production capital adjustment are critical determinants of the transitions paths towards near zero emission vehicles.

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B. Boksberger • S. Ulli-Beer (✉) • M. Bouza • A. Wokaun
General Energy Dynamics of Innovative Systems, Paul Scherrer Institut, PSI Ost, 5232 Villigen, Switzerland
e-mail: silvia.ulli-beer@bluewin.ch

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6.1 Introduction

The transportation sector is the second largest contributor to world CO_2 emissions by sector, and road transportation is with 75 % the leading emitter within this sector (IEA 2011). But, advanced vehicle technologies may contribute significantly to CO_2 emission reduction in road transportation in the future. A cost effective CO_2 emission reduction path of −54 to −67 % till 2050 (with base year 1990) has been set for the transportation sector by the European Union (EU) (Edenhofer et al. 2006; EC 2011).

However, history and the research on technology change have shown that successive incremental improvement patterns that are punctuated by radical innovation may have dramatic impacts on the competitive advantage of companies and the profitability of the whole industry (Abernathy and Clark 1985; Tushman and Anderson 1986; Freeman and Perez 1988; Henderson and Clark 1990; Dolata 2009). While these research avenues point to threats and opportunities of technology change and inform technology and innovation management, recent literature highlight typical alignment processes in the broader socio-technical system at the niche, regime and landscape level that may influence socio-technical transition to more sustainable (low carbon) economies (Geels 2005; Geels et al. 2008). Furthermore, the literature suggests that such alignment processes and transitions need to be managed in distinctive ways (Rotmans et al. 2001). In particular, systemic failures such as infrastructure barriers and (institutional) lock-in effects need specific policy considerations (OECD 2011). However, the findings of these studies are only rarely used to coherently analyze different governance approaches supporting socio-technical transition. Neither their impact on technology diffusion, nor the profitability of the industry, nor the industry specific CO_2 emissions have been analyzed in a coherent manner (Foxon and Pearson 2008). This constitutes an important research gap. Closing this gap is important, specifically if we take into account that scenario building approaches have been identified as important tools for informing the actors involved with socio-technical transitions (Vergragt and Brown 2007).

With our study we make one step in elaborating scenario analysis tools that help to fill the research gap. Concretely, this study aims at identifying robust and economic feasible strategy and policy approaches for supporting the socio-technological transition towards near zero emission road transportation. Therefore, we have developed an industrial transformation model (ITM) for the carmaker industry founded in evolutionary economics and industrial dynamics including recent theorizing on socio-technical transition, as well as micro level innovation and adoption behavior. It has been validated and calibrated against data of the European carmaker industry. The purpose of this modeling exercise is to better understand the structure and dynamical interaction between the succession of eco-innovation, supply side and demand responses as well as policy regulation in the automotive industry. Our specific research focus is three-dimensional and geographical bounded. We analyze the dynamic effect of different governance approaches on, first the diffusion path of multiple competing drive train technologies, second the economic viability of market leaders, and third the prospective CO_2 emission pathways of the light duty vehicle fleet (LDV) in the EU.

Consequently, we include different aspects from different levels such as finance, production, R&D at the firm level and adoption and diffusion at the market level as well as policy pressure from the landscape level. While most aspects of this model have been dealt with in other papers (Zachariadis 2005; Collantes 2007; Schwoon 2008; Dougherty et al. 2009; Köhler et al. 2009; Kloess and Müller 2011) none of them study the dynamical implications of the interacting domains at once, which may lead to biased or over optimistic findings. With our holistic modeling approach and multidimensional analysis, we consider the dynamical interaction between the different sub-systems and variables at different levels in order to provide a coherent assessment of combined policy and strategy making. However the scope of the analysis is focused only on induced technology change, i.e. technological change triggered and supported by dynamical policy and strategy making and does not include behavioral and preference changes in the LDV market (i.e. we assume fixed mobility demand).

Our modeling exercise will show the decisive role of the capital stocks in the automobile industry as well as automakers' capacity to strongly invest in R&D. Policy analyses address the critical role of early investment into the infrastructure build-up and its effect on cost reductions of alternative vehicles and their diffusion pathways. In addition, the paper will investigate if anticipation of policy regulation and early responses of the supply side induce economically and environmentally advantageous transition paths. We specifically look into technology specific performance criteria, the time frame and context conditions under which internal combustion engine vehicles (ICEV), natural gas vehicles (NGV), electric range extended vehicles (EREV) and battery electric vehicles (BEV), as well as fuel cell electric vehicles (FCEV) may contribute to improved CO_2 emission reductions.

After this brief overview of the motivation, the purpose and the comments on the specific focus of the chosen modeling approach, the remainder of the paper is structured as follows. A synopsis of the relevant characteristics of the carmaker industry and the theoretical background of the modeling exercise is provided in the second section. In the third section the model structure and its basic behavior is summarized. The fourth section presents illustrative findings of combined strategy and policy simulation. Also, the main determinants and typical behavior patterns of the simulation results are discussed. In Sect. 6.5, we derive practical policy and

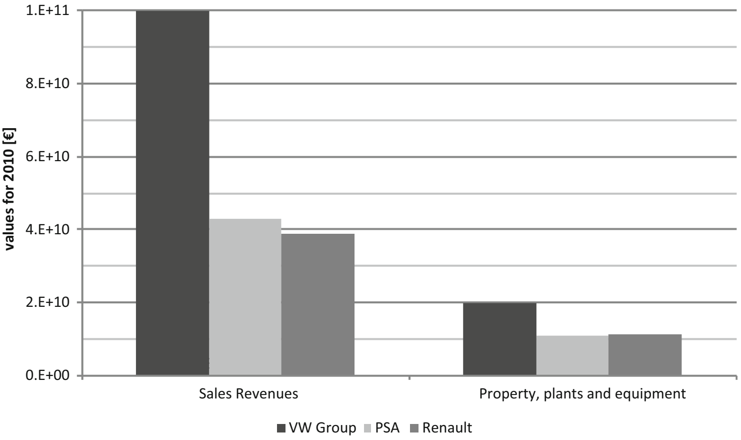

Fig. 6.1 **Financial comparison:** The comparison of financial key data of the European market leader VW Group with the second PSA and third Renault shows remarkable differences (Source: Based on Annual Reports of the carmakers)

strategy implications. We conclude in Sect. 6.6 with reflections on the modeling exercise and on the main implications of our findings with respect to the impact of socio-technical transition on the carmaker industry and its CO_2 reduction potential. Limitations and avenues of further research are pointed out.

6.2 Model Context

This section provides a short summary on the relevant operating figures of the European carmaker industry. Also a short outline of the theoretical background of the model and simulation experiments is given.

6.2.1 The Industrial Context

The carmaker industry is a capital intensive industry. The production of vehicles requires a large amount of capital in properties, plants, and equipment and binds it over a long time period. Figure 6.1 shows the revenues and invested capital of the three leading European carmakers for the year 2010. VW Group had a 20 % market share, PSA and Renault 14 % and 11 %, respectively (ACEA 2010a, b).

The LDV technologies require extremely large capital investments (Zapata and Nieuwenhuis 2010). One the one hand the large investments allow to increase scale and cut costs, yet on the other result in huge sunk costs (Christensen 2011). To recover the sunk costs a high sales volume is needed. Due to such large capital costs

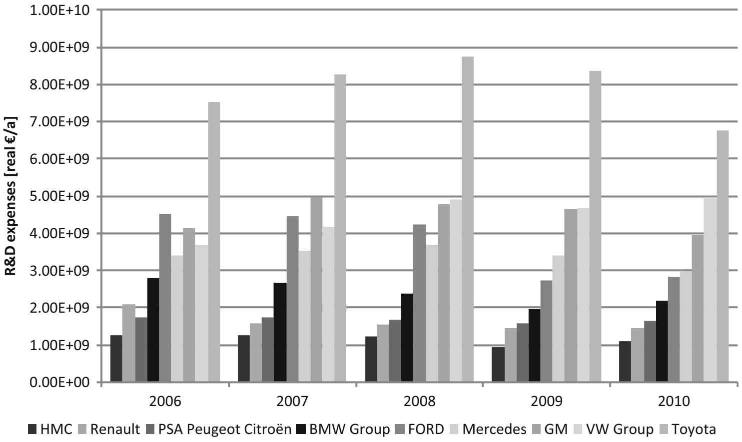

Fig. 6.2 R&D expenditures: The R&D expenditures of different carmakers show vast differences. Toyota is leading by multiple scales followed by VW Group (Source: Based on Annual Reports of the carmakers)

new technologies that are not easily integrated into mass-production are faced with high entry barriers (Andrews et al. 2006; Sovacool and Hirsh 2009). Toyota for example spent almost one billion Euros on the development of Prius (Taylor 2006), the first commercial hybrid. Nissan faced development cost of four billion Euros for the Leaf (The Economic Times 2011). It would be even harder for a newcomer starting from scratch to introduce a new technology to the market. Carmakers rather start R&D partnerships with promising entrepreneurs in order to build up competitive advantages based on advanced technologies (van den Hoed 2007).

The absolute money invested in R&D and thus the capacity to foster new technologies varies considerably across the industry. Figure 6.2 illustrates the high R&D expenditures within the carmaker industry. The budget of Toyota for example is in 2010 more than six times higher than that of Hyundai Motor Corporation (HMC). Noticeable is that VW Group is the only carmaker shown in the graph that has in real terms constantly increased its R&D expenses over the last years. A logical consequence of the large differences in R&D budgets, thus, can be seen in an increasing technology transfer between carmakers. A quick open access internet research revealed that today almost all carmakers are directly involved in R&D partnerships with at least one of the other carmakers. VW Group seems to be one exception.

Many industrial characteristics such as complex operations, low margins, and high financial risks favor rather incremental technology improvements than radical change (Orsato and Wells 2007). However, there are also signs that radical changes by the incumbent carmakers are possible. Strong environmental regulations do provide the urgency to elaborate the possibilities of rather radical alternative technologies while also providing a competitive space for new technologies (van den Hoed 2007). However, a more recent study on patents reveals the continued strong dominance of the internal combustion engine also addressing environmental aspects. Further on, patents indicate that hybrid electric vehicles appear to be currently the most promising alternative (Oltra and Saint Jean 2009). Finally, from the consumer demand side stems little incentives for radical changes in the automobile industry. The environmental aspect of a car is only one attribute considered in the vehicle purchase process (de Haan 2007) and there, it tends to be included only indirectly via the focus on consumption which itself is an expression for kilometer costs.

6.2.2 The Theoretical Context

The literature on technical change has early on emphasized the strong impact of technological innovation on industries and economics (Freeman and Perez 1988; Grübler 1998). Therefore, the industry focused literature provided a rich basis for the model design. A detailed account of concept development and the formulation of the (dynamic) hypothesis for the industrial transformation model is given in working papers (Bouza 2009a, b). Here, we will give a short summary of this work and the theoretical context on the governance of socio-technical transitions that is relevant for the strategy and policy experiments, as reported in the Sects. 6.4, 6.5 and 6.6.

6.2.2.1 Technological Transformation Processes in Industries

Technological advancement can have different effects on the industry structure (characterized by number of firms, leading companies and firm size). The literature identifies the following determinants as decisive for influencing industrials responses: organizational inertia (Nelson and Winter 1982; Henderson and Clark 1990; Sastry 1997), maturity of the new technology (Abernathy and Clark 1985; Tushman and Anderson 1986; Christensen and Rosenbloom 1995; Adner 2002), knowledge trading and spillovers (Cohen and Levinthal 1990; Furman et al. 2002; Dolata 2009), as well as the pressures on/within the current socio-technical regime (Smith et al. 2005; Geels and Schot 2007).

An industrial transformation framework relates their influence on the industry to four transformation modes, see Fig 6.3 (Bouza 2009a, b). The four different modes are separated by the dimension of availability or marketability of a new technology and the dimension valued product characteristics. These are the most important technological product attributes for the users.

Incremental maturation can be observed if the commercialized technological improvement follows the same uncontested technological trajectory with fixed preferences in the value network. *Disruptive transformation*, (i.e. a transformation where newcomers may considerably change the industrial structure) may evolve if an available and marketable new technology in a secondary value network with

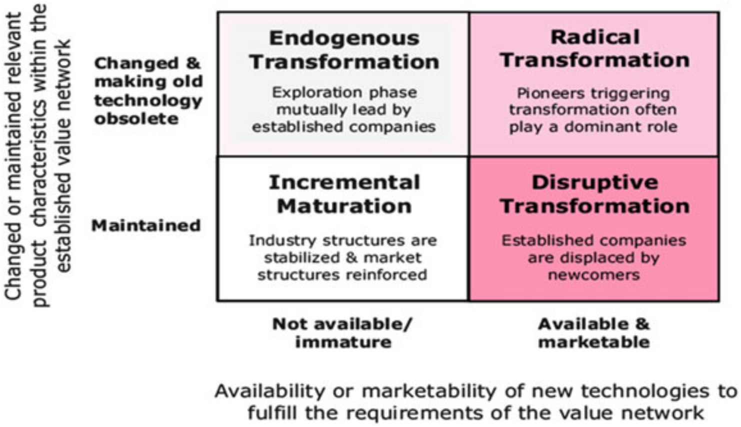

Fig. 6.3 Industrial transformation framework: Four industrial transformation patterns are distinguished depending on the two dimensions availability of new technology and the forming of the relevant product characteristics within an industry (Source: Bouza 2009a, b)

slightly different preferences (e.g. niche market) starts to compete with the primary value network along its established primarily valued product characteristics. *Radical transformation* is likely to be observed, if commercial technology advancement leads to newly preferred product characteristics. In this case, pioneers of the incumbent industry but also newcomers are likely to gain a distinctive competitive advantage in the industry. *Endogenous transformation* may be observed if new product characteristics become relevant due to selection pressure while the corresponding technology is not yet available or marketable in the established industry. In this situation, where the whole industry needs to respond to changed selection pressure, joint efforts of the incumbents will result in a stable industrial evolution where the technological transformation may not change the established industry structure.

While the former transformation pathways have been described and discussed before in the literature (Nelson and Winter 1982; Abernathy and Clark 1985; Henderson and Clark 1990; Christensen and Rosenbloom 1995), the endogenous transformation mode has been recently suggested by Bouza (2009a, b) as it correspondence better to today's situation in the automobile industry. Based on this classification system and the above highlighted determinants of technology change, this paper argues that strong collaborative efforts and relaxed organizational inertia within carmaker's firms will result in an endogenous transformation within a consolidated industry structure.

6.2.2.2 Governance of Socio-Technical Transitions

According to the framework outlined above, endogenous transformation in industries depends primarily on selection pressure and not on short term competition deliberations and autonomous market driven innovation. Complementary, the modern literature on (eco-)innovation system approaches (OECD 1998) point to lock-in effects and path dependencies that generate systemic barriers at different levels (Foxon and Pearson 2008; del Río et al. 2010; OECD 2011). These systemic barriers may hinder socio-technological transition to greener industries – valuing near zero emission product characteristics. Foxon and Pearson (2008) argue that "the richer picture of innovation processes provided by innovation system theory should provide a useful basis for reconciling innovation policy and environmental/sustainability policy to overcome the difficulties . . ." (Foxon and Pearson 2008). Further on, they argue that this systemic view requires strong consideration of systemic failures as an addition rational for public policy design, complementing the market failure approach. Also, the identification of strategic windows of opportunities (i.e. 'techno-economic' and 'policy' windows of opportunities), and variety generation, in respect to technological and institutional options, increasingly demand the attention of policy makers. But, the systems failure concept as a rational for public policy design requires the identification of barriers and the availability of effective policy options to overcome them.

Our modeling approach and the combined strategy and policy analysis will respond to some of these guiding principles. First, our rich systemic model of the carmaker industry is seen as a strategic framework that allows for testing of combined innovation and environmental policy packages. It helps to translate the long term policy goal in effective policy and strategy designs, supporting high policy compliance. Second, the anticipated fueling infrastructure barrier for different alternative vehicles is specifically assessed (Köhler et al. 2009; Stephens-Romero and Samuelsen 2009). Finally, our approach helps to identify strategic windows of opportunities in order to effectively implement strategy and policy choices.

6.3 The Model

As stated in the introduction, the purpose of this modeling exercise is to better understand the structural determinants and their dynamical implications of a succession of eco-innovation, supply side and demand responses as well as policy regulations in the automotive industry. Specifically, we are interested in the dynamic interaction of industrial viability, and public policy for mitigating diffusion barriers, as well as achievable CO_2 emission reductions in the EU for the time horizon from 2000 to 2100.

From an extensive literature study no model so far has been found that dynamically combines finances, R&D, production, and the market as well as the fueling infrastructures at the same time. While most aspects have been dealt with in other papers (Zachariadis 2005; Collantes 2007; Schwoon 2008; Dougherty et al. 2009; Köhler et al. 2009; Kloess and Müller 2011) none of them study the dynamical implications of the interacting domains at once. Three factor mistakes tend to be made when analyzing the potential of new technologies: factor time, factor price, and factor man. The diffusion tends to happen rather fast (Schwoon 2006; Köhler et al. 2009), and in that short period the price for new technologies will approach those of incumbent technologies (Schwoon 2006), and customers will accept the changes without reservation (Schwoon 2006; Collantes 2007).

The system dynamics model presented here fills the identified synthesis gap and considers the dynamical complexity between subsystems and components within the firm and its environment. The basic assumptions underlying the model are based on evolutionary economics (Nelson and Winter 1982), industrial dynamics as highlighted above, interconnected by reinforcing structures (Sterman 2000), spillovers and acceptance dynamics (Brownstone et al. 2000; de Haan 2007; Ulli-Beer et al. 2010). Penalty taxes or the infrastructure availability does not only influence the adopter potential of alternative vehicles directly, but it has self-enforcing indirect impact on companies' revenue, company cash and the magnitude and allocation of R&D investments, as well as production capital adjustment. The challenge has been to come up with a coherent white box model with a logical structure that maps such circular causalities consistently with the real world structure. Therefore, theory and empirical data, as well as calibration and validation techniques have been used that help to build up sufficient confidence in the model structure and behavior for the formulation of robust strategy and policy implications (Bouza 2010).

The model has been designed to simulate five carmakers, five different drivetrain technologies and the corresponding fuels, within five different markets. The markets can be defined as sub markets in order to represent niches with alternative preferences or policy regulations. We are using averaged technologies as reference; hence, market segmentation cannot be analyzed in detail. The introduction of bio or synthetic hydrocarbon fuels is also disregarded. Furthermore, the model allows no firm acquisition. When a firm goes bankrupt, the invested capital thus cannot be integrated by one of the other companies. A crowding out of a firm thus lead to a shock as other companies need to build up production capital in order to take up the free market share.

The model concept mapped in Fig. 6.4 provides a high level overview of the ITM that highlights model boundary, the main model inputs and the interconnected modules with its main variables. The modules are interconnected with variable specific information flows.[1] The landscape level comprises of the environmental policies, consumer preferences and the existing fuel infrastructure, but also income trends and population dynamics. The three modules FINANCES, R&D, and PRODUCTION capture the processes internal to the firm. The MARKET module presents the near environment. It is influenced by landscape specific inputs.

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[1] A detailed description of the System Dynamics model implemented with the software Vensim® would be beyond the scope of this paper, but can be provided by demand based on the system dynamics model documentation tool developed by the Argonne National Laboratory, Lemon IL, USA. Please contact the corresponding author of this paper.

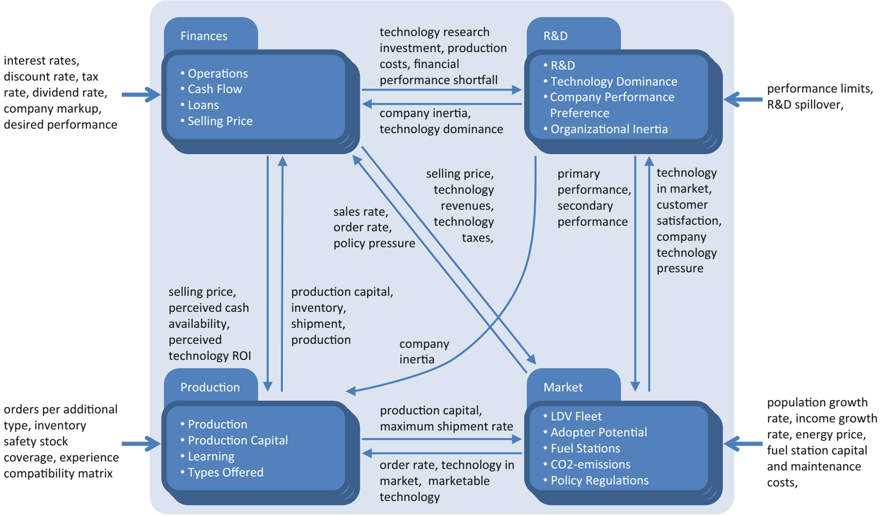

Fig. 6.4 **Model concept:** The model consists of four modules. Each module involves a set of subsystems. In addition, different classes of firms, technologies, fuels and markets are specified by subscripts

6.3.1 The Feedback Loop Structure

The main feedback loops that control the transition towards near zero emission vehicles in the ITM are highlighted in the causal loop diagram shown in Fig. 6.5. The diagram nicely distinguishes the loops that control the incremental maturation and the endogenous transformation modes (cp. Fig. 6.3). On the one hand the incremental maturation is explained by the four reinforcing loops r1 to r4. The research paradigm in this mode guides the enhancement of vehicles primary performance attributes (i.e. acceleration, driving range, the refueling or recharging time, and weight as a measure for safety). On the other hand the endogenous transformation process is mainly governed by the three balancing loops b1 to b3. They balance a perceived performance gap concerning energy consumption and are related to the emergence of a new research paradigm. It guides the establishment of the technological improvement trajectory emphasizing energy consumption and CO_2 emissions per technology (Bandivadekar et al. 2008). These attributes characterize the ‘Secondary Performance’ variable. ‘Energy Cost’ or ‘Policy Pressure’ from CO_2 emission regulations force the carmakers to intensify their R&D expenses on ‘Secondary Performance’. A prolonged induced pressure causes in a first step a research *paradigm* change (Bandivadekar et al. 2008; Meyer and Wessely 2009; Hankey and Marshall 2010). Due to system inertia, once the external pressures have been reduced, carmakers would keep their new ratio between primary and secondary performance R&D constant. Where a research paradigm change is not sufficient to reduce the external pressures, carmakers will in a second

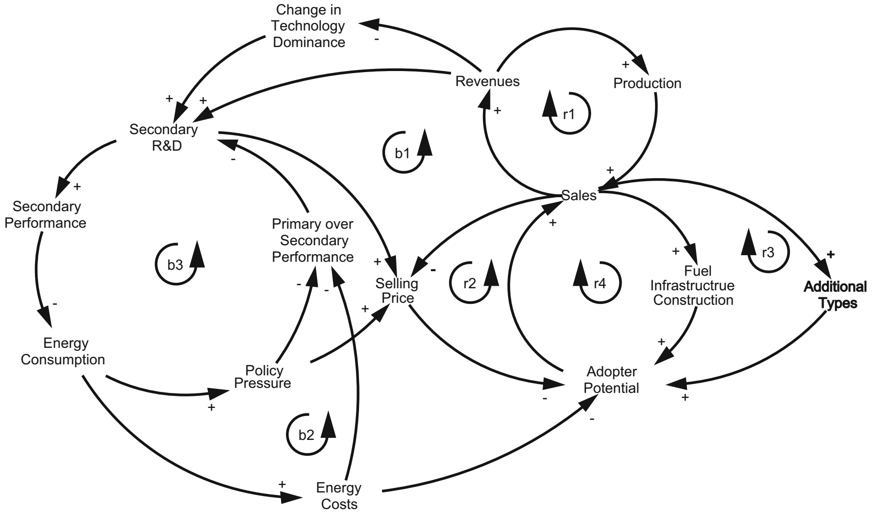

Fig. 6.5 Causal-loop diagram: The causal loop diagram highlights the main causal circularities of the industrial transformation towards near zero emission technologies in the carmaker industry. Positive correlations are marked with a (+) sign, negative with a (−) sign. There are four reinforcing loops (r1-r4) and three balancing loops (b1-b3)

step undergo a technology *dominance* change (Utterback 1994). Their long term focus will move away from incumbent technologies towards a single or a portfolio of new technologies that are better suited for the changed regime. However, while the reinforcing loops r1-r4 have supported the incremental transformation path, they may act as barriers for the endogenous transformation path. This may occur when ever either ‘Revenues’, ‘Selling Price’, ‘Fuel Infrastructure Construction’ or/and ‘Additional Types’ of the alternative technologies are not competitive with the established technology.

In addition, the causal loop diagram also indicates how too ambitious standards may bring the system to a collapse. R&D is linked directly with revenues that define the magnitude of R&D (b1). In order to invest in R&D, a revenue generating technology is needed. Switching to fast from one technology to another without maintaining the same revenues would result in a reduction of R&D, thus slowing down the enhancement of the performance level. Subsequently, strict policies would undermine the technological development. Without a “cash cow” the means for technology development can be vigorously limited.

6.3.2 The Reference Behavior

The reference behavior of the model describes the BASE scenario that is based on business as usual assumptions. The base year for simulation is 2000 and the time

Table 6.1 Primary and secondary performance assumptions: The technology specific performance levels for the primary performance attributes and the second performance attributes are provided. The technology potentials stem from expert interviews with researchers of the Swiss Federal Institute of Technology (Boksberger and Ulli-Beer 2011)

	ICEV		NGV		EREV		BEV		FCEV	
Performance	2,000	Max	2,000	Max	2,000	Max	2,000	Max	2,000	Max
Primary										
Acceleration (s)	10	8	10.5	8	10	7	8	7	10	7
Range (km)	1,100	1,100	400	800	500	800	200	400	400	800
Refueling (min)	3	3	3	3	3	3	30	15	4	3
Secondary										
Consumption (Whkm^{-1})	665	300	680	260	255	200	170	130	270	200
Emissions (gCO$_2$km^{-1})	175	80	130	50	30	25	10	7	20	15

horizon is 100 years. This long time horizon helps to identify long term behavior patterns such as of over- and under-shoots or oscillation. The European market serves as reference point. We focus on the four leading carmakers. For the simulation carmakers' financial values have been adjusted for their European market shares. We use the approximation of a 20 % share of the market leader and a 10 % share for all three contenders (ACEA 2010a, b). Relevant thus are the magnitude and the relative difference between the market leader and its contenders. The relative size difference has been directly transferred to their invested production capital and their R&D investments. All companies show similar innovation rates per invested Euro, but the contenders need to collaborate in order to keep up with the market leader's R&D investments. While the market leader does not engage in knowledge trading, all others do. The assumption is in line with what can be observed in the current carmaker industry Resent activities: Renault-Nissan (source), BMW and Toyota (source), BMW and PSA (source), but also failed attempt between BMW and Mercedes (source).

All companies start with a research paradigm focusing on primary performance, and ICEV is the dominant technology. Energy efficiency improvements of the hybrid electric technology are included in the assumed energy efficiency assumptions of ICEV. The mapped alternative technologies are NGV, EREV also including plug-in hybrids, BEV, and FCEV. The primary performance and the initial CO$_2$ emissions of the market leader's fleet are higher than those of the contenders. The average vehicle price of the leader is also set the highest. No price difference has been assumed for the remaining three.

Table 6.1 gives an overview of the assumed performance levels of firm 1. Table 6.2 shows the CO$_2$ emissions per fuel. The average lifetime for a vehicle, independent from technology, is set to be 17 years (ACEA 2010a, b).

In a comparison of all alternatives, BEV face the biggest challenge compared to the incumbent technology, as their secondary performance cannot offset the large primary performance deficits mainly resulting from the range and refueling performance deficit. The other three alternatives have secondary performance advantages and rather minor deficits in primary performance (Boksberger and Ulli-Beer 2011).

Table 6.2 CO2 concentration of fuels

	Petrol	CNG[a]	EREV-Mix	Electricity[b]	H2 (electrolysis)
Emissions (gCO_2MJ^{-1})	73.2	52	30	15	20

[a]CNG is mixed with biogas
[b]We assume that a low-carbon energy production has replaced the current system in the long run

Without additional policy regulations, ICEV and NGV will remain the cheapest technologies in the future, directly followed by BEV. Forth in line are EREV. FCEV are assumed to remain the most expensive alternative in the long run (Bandivadekar et al. 2008; McKinsey and Company 2010; Thiel et al. 2010; Douglas and Stewart 2011; Kloess and Müller 2011; Streimikiene and Sliogeriene 2011). Figure 6.6 displays the price development for the considered vehicle technologies. The decrease in price depends on learning by search (in the first phase) as well as on learning by doing and using (mainly from 2017 to 2030). Exhibit (a) illustrates the effect of an infrastructure barrier for FCEV, where exhibit (b) illustrates a scenario, where the barrier has been alleviated. It results in a further price decline down to competitive levels around 2030 since learning effects could be deployed successfully.

CO_2 emission targets follow the European regulation No. 443/2009 introducing a mandatory CO_2 emission limits for new LDV of 130 gkm^{-1} until 2015, and 95 gkm^{-1} until 2020, respectively. For the post 2020 situation, we assume a further reduction to as low as 20 gkm^{-1} until 2050. This value is low enough for purely electric alternative drivetrain technologies to become essential – under the premise that electric power is produced with as low as 15 gCO_2MJ^{-1} and synthetic fuels cannot be produced on a large scale. Validation and calibration analysis has shown that without a reasonable price reduction of alternative technologies reaching the ICEV-level, CO_2 emission standards below 60–80 g per kilometer will be disruptive for the car industry, given customers keep their income to vehicle ratio. They can even be counterproductive, as increasing vehicle prices will motivate customers to hold on to their vehicle longer, with an undesired effect on fleet emission.

The population development is based on the UN medium scenario (United Nations 2004). It will peak in 2050 and from there start to slightly decrease Due to model design constraints only half are relevant for the simulations.. Real income will rise by 50 % until mid century. The assumptions are based on an extrapolation of EUROSTAT values. For the utility calculation the purchase price is stronger weighted than kilometer costs. Only kilometer costs of the first 4 years are taken into account. The kilometers traveled per vehicle and year is kept constant. A fueling station infrastructure is no longer seen as a restraint, when 10 % of the gasoline stations are in operation For the whole European fleet this value would be at 8,000. This is at the lower end of what is suggested in the literature (Sperling and Kitamura 1986; Yeh 2007). We assume a fuel price scenario, where fossil fuel prices increase by 150 %, natural gas by 100 %, and electricity by 50 % until 2050. The values are higher than forecasted in other studies (Capros et al. 2008). We assume that electric or hydrogen driven vehicles can be used as a buffer thus profit

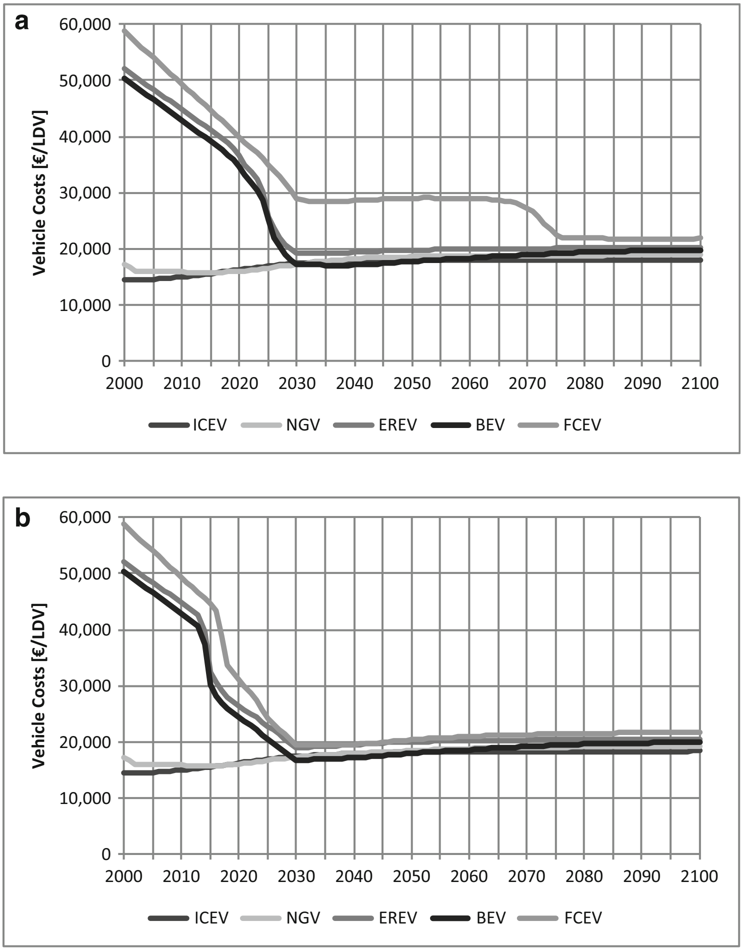

Fig. 6.6 Price development: The price development of the advanced vehicle technologies depends on the deployment of learning effects (**a**) illustrates a price curve with limited learning effects due to infrastructure barriers (**b**) illustrates price curve with fully deployed learning effects

from lower energy prices. But it is assumed that hydrogen will be produced by electrolyses, and thus remain more expensive than electricity. Hence, hydrogen faces a tradeoff between fuel costs and CO_2 emissions (Offer et al. 2010).

The resulting model behavior with these BASE run settings are displayed in Fig. 6.7 (a–d) for the model variables 'Total LDV', 'Total CO_2 Emissions', 'Sales Share by Technology', and 'Firm Cash'. We see that within the BASE scenario, NGV, EREV and ICEV may dominate nearly equally the market around 2050, while BEV and FCEV only enter the market in the second half of this century. CO_2 emissions can be reduced substantially but will not reach the ambitious EU target of nearly 70 % till 2050. Firm cash may decline till 2050 but will recover afterwards.

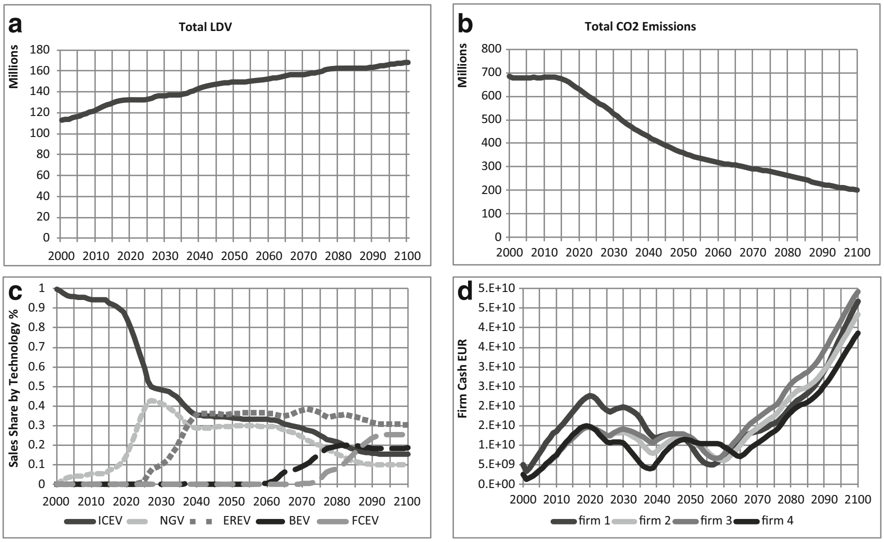

Fig. 6.7 BASE behavior: The BASE behavior of the model is demonstrated with the four reference variables: (**a**) Total LDV; (**b**) Total CO_2 Emissions; (**c**) Sales Share by Technology; (**d**) Company Cash. The term in the bracket indicates the relevant constituent of the four classes: company, technology, fuel, market

This BASE simulation will be compared with simulation results of combined strategy and policy experiments.

6.4 Policy and Strategy Simulation Experiments

The purpose of the simulation experiments is to better understand the interaction of industrial viability, and public policy for mitigating diffusion barriers, as well as CO_2 emission targets. To this aim we have analyzed two critical policy approaches (mitigating infrastructure barriers and enforcing policy compliance) in combination with a firm internal market introduction strategy (i.e. a firm internal cross-subvention strategy of alternative vehicles for their market introduction).

Table 6.3 gives an overview of the different infrastructure and non-compliance penalty policy scenario. Each policy has a low, medium, and high scenario. The infrastructure policy is additionally differentiated by fuels. This policy establishes a protected early fueling station infrastructure. For NGV 500 additional fueling station are built in 2012 yielding a level of 2000 fueling stations, the built up of electric charging stations starts in 2013 and hydrogen fuel stations in 2015. For the CO_2 emission policies, the penalty tax is either kept constant or a progression of varying magnitude is applied between 2040 and 2100 as indicated in Table 6.3.

Table 6.3 Settings of the policy and strategy experiments

Emission policy	A: constant	B: doubling	C: highly progressive
Noncompliance penalty[a]	×	2 ×[b]	10 ×[b]
Fuel stations policy	1: low	2: medium	3: high
CNG (additional FS)	500	1,000	2,500
Electricity[c]	1,200	2,400	4,000
Hydrogen[c]	1,200	2,400	4,000

[a] 100 Euro per gCO2 above emission target

[b] Value in 2100

[c] Initial niche market value of fueling stations in 2013 for electricity and in 2015 for hydrogen

The public policy analysis has been combined with a firm internal cross-subvention strategy for the market introduction of alternative vehicles. We have furthermore compared different firm strategies. In the BASE scenario, no cross-subvention of the firms applies. In F1, the market leader cross-subvention scenario, only firm 1 applies cross-subvention that reduces the purchase price of alternative vehicles towards 150 % of the ICEV option, during the early market introduction while alternative vehicle costs still are prohibitiv high. We have also analyzed the impact of an active cross-subvention strategy of the competing firm 2. The simulations show similar patterns as in F1, but its effects on the market has been less pronounced.

6.4.1 Simulation Results

In the following some combined policy and strategy simulation results are shown that illustrate typical behavior patterns observed in many experiments. The effects of the chosen policy and strategy settings are discussed regarding the resulting technology specific diffusion pattern (with the rate variable ‘Sales Share by Technology’), regarding economic viability (with the stock variable ‘Cash’) and CO_2 emission mitigation (with the rate variable ‘Emissions’).

6.4.1.1 Technology Specific Diffusion Patterns

Figure 6.8 compares the technology specific diffusion patterns of the combined policies ‘low infrastructure availability policy’ and ‘low constant penalty tax’ A1 (left side) with ‘high infrastructure availability’ and ‘highly progressive penalty tax’ C3 (right side) both for the proactive market leader case (F1). In the rather conservative policy environment F1A1 (that correlates strongly with the BASE scenario shown in Fig. 6.7) BEV and FCEV enter the mass market only in the second half of the time horizon, where as in the thightened policy environment F1C3, EREV, BEV and FCEV enter the mass market in the first quarter of the time horizon. The early market introduction is due to the improved infrastructure

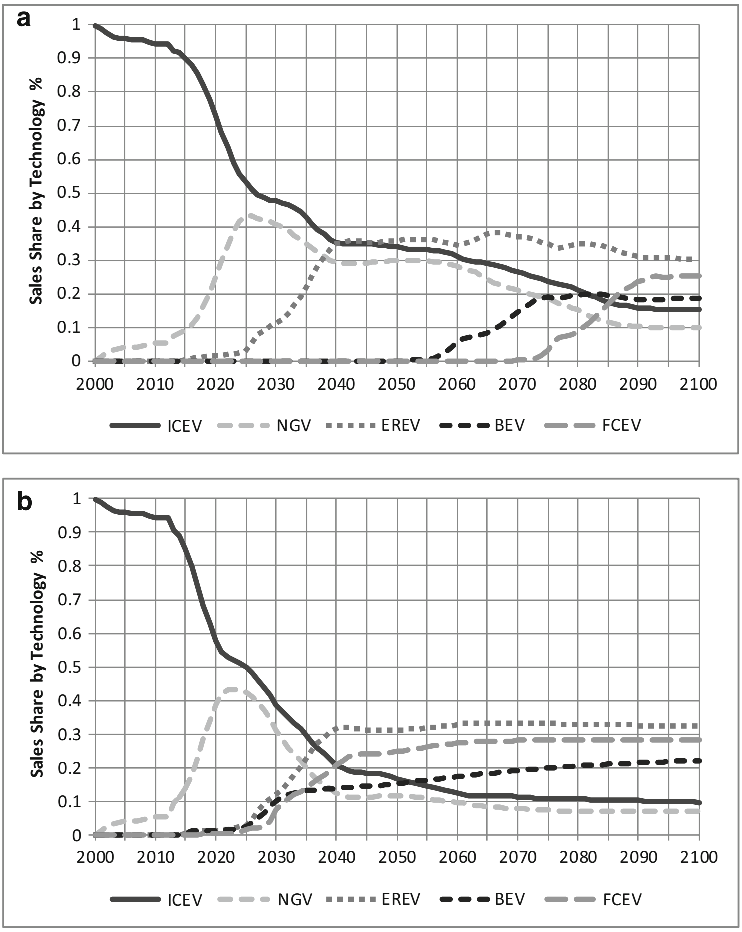

Fig. 6.8 Comparison of technology specific diffusion patterns: The technology specific diffusion patterns are influenced by different policy environments: (**a**) with the rather conservative policy setting F1A1 and (**b**) with the tightened policy environment F1C3. The run acronyms (e.g. F1C3) reads as follows: The first two characters indicate the applied strategy of the firm and the third and forth character indicate the applied strength of the non-compliancy penalty and the infrastructure policy as explained in Table 6.3

conditions, while the stronger replacement of the ICEV and NGV is triggered by the highly progessive penalty scheme in the second half of the time horizon. Both results show that after the transition from ICEV towards alternative technologies, no single dominant technology can be identified and that EREV, BEV, and FCEV tend to co-exist. Furthermore, in both scenarios we see no full crowding out of the ICEV and NGV.

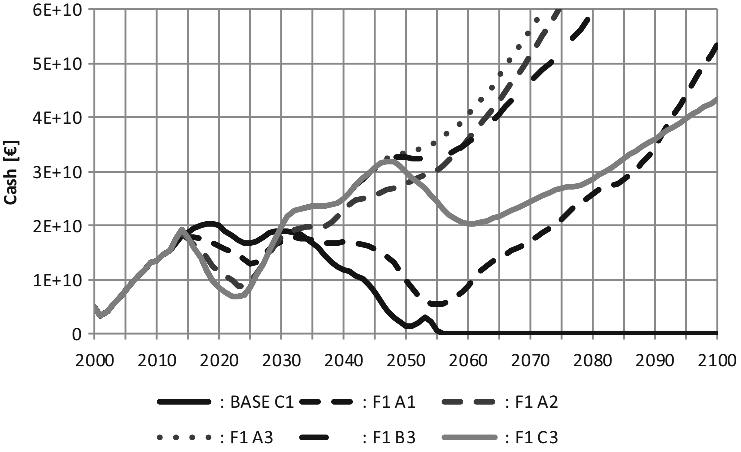

Fig. 6.9 Trends in economic viability: The trends in economic viability are influenced by the varying combination of strategies and policies

6.4.1.2 Trends in Economic Viability

The typical trends of different policy and strategy packages on the economic viability are illustrated in Fig. 6.9. The BASE C1 approach with passive cross-subvention strategies of all companies, and low infrastructure availability as well as a high penalty tax, results in an industrial breakdown. In the first half of the time horizon, NGV and EREV help to achieve sufficient policy compliance. However, in the second half, when stronger standards and a higher penalty tax apply, the companies have not enough time and cash to ramp up the market introduction of the near zero emission BEV and FCEV. But the most striking finding of this analysis is the behavior patterns of the best perfoming policy and strategy packages F1A2, F1A3 and F1B3. It shows that active cross-subsidizing of the market leader is a rewarding strategy in the long run, even with a low infrastructure availability (F1A1). However, we can observe 'a first worse before better' behavior pattern, because investment into the production capital for alternative vehicles around 2020 helps to avoid high penalty payments after 2040.

The F1A1 package illustrates the long term outcome of an underinvestment behavior due to a modest fueling infrastructure in the early phase, resulting in an inferior cash performance after 2030. F1C3 on the other extrem shows how tough regulations and high penalty tax have an imense effect on the firm performance level.

6.4.1.3 Industrial's CO_2 Emission Pathways

Figure 6.10 reveals typical trends of CO_2 emission mitigation paths induced by the different policy and strategy packages. The most interesting finding is that policy

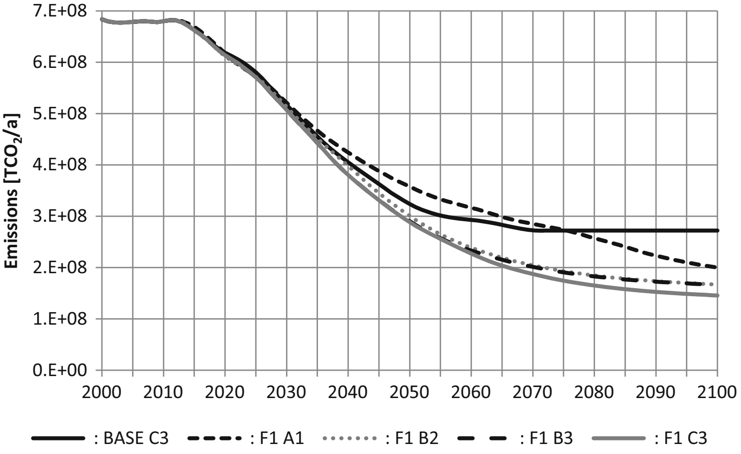

Fig. 6.10 Industrial's CO_2 emission pathways: The CO_2 emission pathways are influenced by the varying combination of strategies and policies

packages which are most rewarding for a proactive market leader also results in most promising CO_2 emission reduction paths. This can be seen with the F1B3 package that nearly achieves a comparable CO_2 mitigation performance as the most strict package F1C3 that yields inferior economic results for the proactive market leader, due to the high penalty tax.

We see that the best performing mitigation pathway results in a CO_2 emission reduction of around 56 % by 2050 and in 79 % by 2100 (base year 2000), meaning that the sectoral EU reduction target for transportation of 54–67 % by 2050 remains a challenge.

6.5 Discussion of Simulation Results

In the following the main determinants causing typical behavior patterns of the simulation experiments are discussed.

6.5.1 Determinants and Their Effect on Technology Specific Diffusion Patterns

The simulation experiment with the conservative policy environment F1A1 (Fig. 6.8, left side) shows that ICEV remain the most prefered option until 2020 with the CO_2-emission limit of 95 gkm^{-1}. Stronger limits will foster the diffusion of the alternatives NGV and EREV. While NGV are cost competitive and a minimal

CNG fueling station infrastructure has been in place since the year 2000, additional policy support for the infrastructure build-up would help to increase the attractiveness of NGV.

EREV do not face a public infrastructure barrier, but will become cost competitive only around 2030. That explains their strong take off at that time. For BEV and FCEV the low infrastructure availability policy seems not to be sufficient to foster their take off before 2050. The comparison with the high infrastructure availability policy shows that this policy does not primarily accelerate their diffusion rate, but enables an earlier market entry. This finding suggests that due to system inertia it may be harder to accelerate the diffusion of alternative vehicles directly than to mitigate infrastructure barriers. But the right timing of infrastructure support is important. It becomes most effective when technology enhancement depends primarily on ‘learning by doing & and using’ and helps to decrease technology cost. In such strategic moments, not only a lack of demand affects the development of the technology itself, but also an insufficient infrastructure is hindering the technology from reaching an attractiveness level acceptable by a large interest group. This pronounces the well-known chicken-and-egg problem of network externalities.

System inertia arises due to production capital build-up and time lags. This also explains the flat diffusion curve of alternative drivetrain technologies in an early phase. Carmakers are cautious not to ramp up their production line for alternatives too fast, as they would have to bear the risk of technology failure (Mortsiefer 2012; Spendelow and Marcinkoski 2011).

The vehicle price assumptions applied in the model are comparable with those in the literature (McKinsey and Company 2010; Thiel et al. 2010; Douglas and Stewart 2011; Kloess and Müller 2011). The price decline and technological improvements result in the co-existence of different alternatives. No one technology out performs the others significantly, thus rather leading to a technology mix than a technology takeover. This finding corroborate a most recent conjoint analysis (Friedl and Götz 2011) that shows how a share of up to 40 % of the customers would still buy an ICEV in 2035, even if prices would be the same for all technologies and all would show similar primary performance levels. Further on, the dominance of petrol driven vehicles is challenged by NGV and EREV and later on by FCEV and BEV, whiteout strict policy regulations, ICEV will still be on the roads in 2100, according to our findings. Also, ICEV are to be expected to remain at the low end of vehicle costs and thus stay a viable option also for suppliers.

However, NGV can be expected to play a major role over the next decades, if the current fueling infrastructure is further developed and ambitious CO_2 emission regulations for LDV become effective. Whereas the performances of NGV, EREV and FCEV can compete with those of ICEV, BEV have a hard stand. Their advantage lies with low consumption and thus low emissions. But BEV may remain a segment specific technology due to their driving range deficit unless consumers will renounce it.

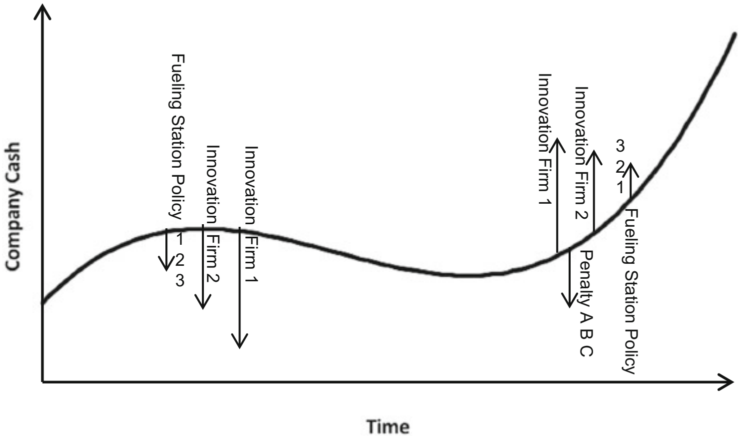

Fig. 6.11 Distinctive effects on economic viability: the long term view: The long term view highlights the transition decades of the first half of this century which are followed by a sectoral boom phase. The effects of the different strategy and policy settings are indicated

6.5.1.1 Distinctive Effects on Trends in Economic Viability

An in depth analysis of the simulation runs in Fig. 6.9 shows the influence of different policy and strategy measures on the economic viability of a firm in the carmaker industry in distinctive ways. They control the strength of the 'first worse before better behavior' trend. Figure 6.11 schematically points out their distinctive effects on the company cash trends.

A firm's proactive innovation behavior (i.e. cross-subvention strategy of alternative vehicles) in general decreases the company cash in the first two quartiles, while it helps to strengthen the strategic position of the company in the third quartile. However, the resulting competitive advantage depends on the policy environment.

The provision of an early fueling station infrastructure propels further investments in technology development and production capacity adjustments. Subsequently it decreases company cash in the second quartile. Likewise tightening standards and high penalties decrease company cash primarily after 2040. But such a policy environment rewards innovative companies with a higher competitive edge, i.e. they can capitalize on their earlier investments.

The overall cycle pattern seems to play out over a time period of 50 years. It is strongly influenced by the climate policy regime and the innovation investment behavior of firms. It results in a sectoral boom phase once the transition towards near zero emission vehicles has been mastered. The policy induced technology change pattern is comparable to the long wave theory in terms of its duration and the argument, that deep structural causes are innovation processes in whole technological systems (Freeman and Perez 1988). According to Freemann and Perez (1988)

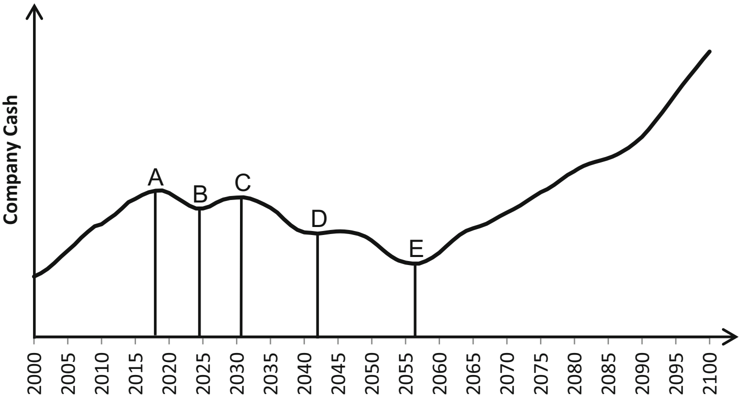

Fig. 6.12 Distinctive effects on economic viability: the short term view: The short term view differentiates short term fluctuations during the transition decades

favorable conditions for such transitions are “complementarities between innovations and the emergence of an appropriate infrastructure as well as some degree of political stability and institutions which do not hinder too much the diffusion of new technologies” (Freeman and Perez 1988). Freeman and Perez (1988) agrees with Schumpeter (1961) that such techno-economic paradigms changes induce profound adjustments in social and institutional framework that may cause periods of deeper depressions (Schumpeter 1961; Freeman and Perez 1988). According to this theory and based on our findings, we should take into consideration that carmakers’ second quarter of the twenty-first century may fall short with the first in its achieved financial progress. But an up-turn may be expected in the third quarter. However, the endogenous transformation framework (section 6.2.2.1) suggests that collaborative knowledge development and sharing between carmakers may rather result in a creative transition process than a creative destruction of the existing carmaker industry. However, this does not exclude the danger of a takeover of smaller carmakers by leading carmakers.

Examining further the simulation results in Fig. 6.9, we can identify shorter distinct fluctuations within decades in the first half of the time horizon. These patterns are schematically highlighted in Fig. 6.12. Based on model inspection, the drivers of the single short term cash cycles can be discussed. Differences between cash inflow and outflow over time that are triggered by strategy and policy changes explain the fluctuations (A to E) in the stock variable ‘Company Cash’.

- Downturn in A: Investments into the production of NGV and cross-subsidizing strategies increases cash outflow. Alternative drive train technologies are subsidized for 10 years until 2023 for EREV and BEV as well as until 2025 for FCEV.
- Upturn in B: The subsidizing and investment for NGV production capital has stopped. Therefore cash outflow is reduced below the level of cash inflow which results in a cash increase.

- Downturn in C: The vehicles sold per year of the companies do not comply with the CO_2 emission targets, which results in growing penalty taxes that increases the cash outflow. At the same time, capital is invested for the production of EREV, BEV, and FCEV rising cash outflow further.
- Downturn D: The progressive penalty tax is introduced in 2040. Its effects start to show, specifically when the near zero emission limit of 20 gkm^{-1} becomes effective until 2050.
- Upturn E: The transition phase towards near zero emission technologies has ended. Companies are able to capitalize on their investments and to reap scale economies resulting from the mass market penetration of advanced vehicle technologies.

In sum, the financial fluctuation of the induced technology change can be explained by the arising policy pressure and successive technology investments as well as their successive capitalization, offering a slightly different perspective to Schumpeterian business cycles.

6.5.1.2 Directional Effects on the CO_2 Emission Pathways of the LDV Fleet

Finally, the directional effect of the different policy and strategy measures on the fleet's CO_2 emission reduction path is systematically discussed as highlighted in Fig. 6.13. The build-up of the fueling infrastructure leads to earlier CO_2 emission reductions resulting from the earlier uptake of the alternative vehicles. Innovative firms improve the mid-term CO_2 emission reduction effect, too. Strong standards actually determine the overall magnitude of the CO_2 emission reduction in 2100. On the one hand strong standards with a higher penalty tax support the achievement of CO_2 reduction targets under supporting infrastructure conditions. On the other hand an insufficient infrastructure with a high penalty tax scheme (C1) may be counterproductive, as the firms loose their innovation capital or may even exit the market. The balance between cost and benefits is strongly shifted (Compare also Figs. 6.9 and 6.10).

6.5.2 Strategy and Policy Implications

Based on our findings four recommendations for carmakers and eight implications for policy makers are elaborated.

6.5.2.1 Strategy Implications

First, collaboration between carmakers is a decisive strategy in order to cope with induced technology change processes and to avoid a strong adjustment crisis

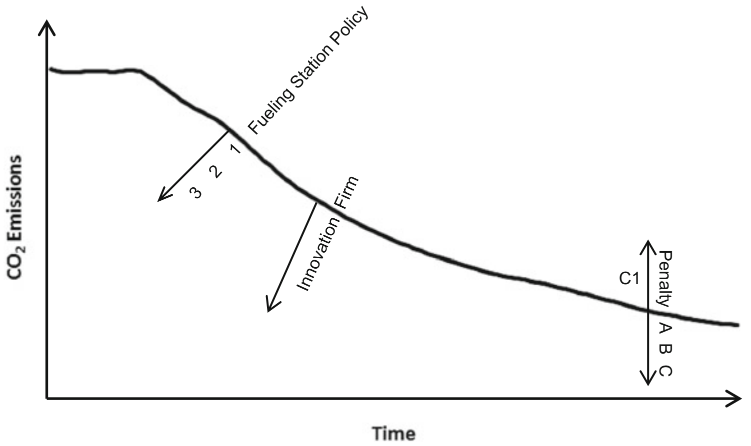

Fig. 6.13 Directional effects on the CO_2 emission pathway: The different strategy and policy settings have distinctive effects on the shape of the CO_2 emission pathway

(i.e. industrial disruption). As a result of increasing policy pressure to reduce vehicle CO_2 emissions, it is to be expected that even more car companies need to engage in some sort of cooperation with competitors.

Second, proactive innovation behavior is rewarding during strategic moments (i.e. when learning by doing and using become crucial) and in a benign policy environment. Therefore, lobbying for a tight CO_2 emission regulation may be an important strategy for carmakers in order to reap the gain of investments into the improvement of the secondary performance, and proactive innovation behavior. Higher CO_2 emission standards and penalties create a geographical market in Europe that is hard to invade by competitors with a production cost advantage.

Third, in order to keep up customer acceptance and to accelerate the diffusion of advanced drivetrain technologies, carmakers may need to serve the highly segmented car market with a wide variety of types offered per technology. Therefore, highly flexible vehicle design platforms that allow producing a fast changing mix of drivetrain technologies and car types may be cost effective. At the same time, new car designs may rapidly become obsolete as the successive technological advancement of the alternatives lead to still better performing vehicles. Subsequently, the broader technology portfolio requires also a very flexible just-in-time production and supply chain, in order to avoid costly over- or under-supply. That being said, European carmakers still need to be sensitive to other geographical markets, with different demand characteristics and policy environments, which have not been considered in this analysis.

Finally, it is worth mentioning that the overall market size for the carmaker industry may shrink if future technology improvements lead to higher vehicle costs. Consequently, R&D efforts, and process optimization, as well as supply chain coordination needs to be directed towards vehicle cost reduction, in order to keep the car market size at least stable.

6.5.2.2 Policy Implication

First, a minimal infrastructure for alternative fuels is essential for the acceptance and diffusion of new technologies. Based on the literature and our analysis, 10 % of the existing fuel infrastructure is needed in order to mitigate the infrastructure barrier sufficiently. Therefore partnerships for the build-up of adequate fueling infrastructures are a high leverage point.

Second, we have learnt that diffusion takes at least 10 years for a fleet large enough to support a self sufficient fueling infrastructure. In the mean time, the infrastructure needs to be subsidized. Whether the subsidies stem from public or private actors or a combination of both, needs to be negotiated. The timing of the infrastructure build-up is important, the strategic right moment depends again on the relevance of learning by using and doing. In order to keep the subsidies to a minimum, the infrastructure should be built up, once the alternative drivetrain vehicles approach mass production.

Third, not each fueling station generate the same turnover, it depends on its location. At the same time, the utility of the fueling station infrastructure increases with its geographical coverage, resulting in so called network externalities. Therefore, suppliers need to balance overall infrastructure coverage criteria with averaged profitability consideration. This characteristic indicates that homogenously composed supplier organizations (e.g. public private partnership) are most adequate.

Forth, the profitability of the fueling station infrastructure tends to decline with efficiency increase of vehicles, in general. This specifically turns out to be very critical for alternative fueling infrastructures. For example, with current construction costs of either H_2-stations or electric public (fast-) charging stations it is difficult to build a business case solely on selling energy. Either the cost of building charging and fueling stations need to drastically decline or new finance mechanisms need to be developed.

Fifth, a long term prospect of tightening standard setting is most important in order to reduce the environmental uncertainty for firm's investment behavior. The emergence of near zero emission technologies till 2050 depends critically on the projected reduction level. Furthermore, tight reduction levels reward firms' proactive search and innovation behavior, as highlighted above.

Sixth, a moderate non-compliance penalty scheme is more conducive for both the carmaker industry and overall CO_2 emission reduction. Although high taxes shift research investments from primary to secondary performance, it may trigger policy resistance further downstream. A penalty tax is added to the vehicle price that affects overall new sales and leads to a longer use of existing vehicles and a postponed scrapping. Hence a price increase extends the vehicle lifetime. Subsequently, the emission reduction potential of new cars is given away.

Seventh, in the long run a radical policy option would be to prohibit the sales of vehicles that do not comply with certain emission standards. Also stimulating earlier scrapping of inefficient vehicles is promising. For one it increases the diffusion rate as old cars are replaced faster with new more fuel efficient vehicles. In addition it prevents undesirable side-effects of price policies.

Finally, a decrease in the LDV fleet's CO_2 emissions that goes beyond 50 % seems feasible until 2050, with the applied technology development assumption, a sufficient infrastructure and stable mobility demand. But higher reduction target requires extended policy packages, focusing directly on travel behavior change. However, in this paper we did address neither consumer demand driven emission reduction nor rebound effects.

6.6 Conclusion

A generic industrial transformation model (ITM) has been applied to the carmaker industry in Europe. The study has highlighted main structures and dynamics influencing a socio-technical transition and has informed the formulation of strategy and policy recommendations for ecological driven innovation strategies in the carmaker industry.

This study has shown that the ITM model allows to assess prospectively threats and opportunities of induced technology changes for industries, as well as to identify promising governance approaches supporting socio-technological transitions. The simulation exercise provides evidence that smart governance approaches involving concerted entrepreneurial and political decision making can avert severe industrial crisis of adjustment during phases of socio-technical transitions. Smart strategy and policy making helps to stabilize the European carmaker industry during the induced technology change phase. Its core determinants are inter-organizational knowledge sharing, proactive innovation strategies of firms aligned with corresponding policy and infrastructure adjustments. This implies on the other hand that companies lacking adaptive and absorptive capacity may be disadvantaged in international competition, if system changes start favoring clean vehicles.

On this base, the ITM framework and model discussed, portrays the notion of 'creative transition' as an alternative to 'creative destruction' as coined by Schumpeter. However, we have also seen that this requires successive investment behavior of the carmaker industry in the next three decades. This depends on confidence in long term policy targets and corresponding financing mechanisms. Alternative drivetrains are necessary to lower the fleets' CO_2 emissions in the long run, yet they will have modest impact on CO_2 emission reductions in the years ahead, due to their slow diffusion uptake. Therefore, it is necessary to drive down the emissions of the incumbent technologies while building up the system necessary for alternative ones. However, this will remain a major challenge since the large social benefits as well the economic attractiveness of a fueling infrastructure build-up becomes effective not until a few decades have passed.

Although we are confident that the findings are robust concerning the policy and strategy implications, we would like to emphasize that the model results should not be seen as forecasts but as scenario explorations. Due to simplification, the model has several limitations. For example, fueling station construction does not take into consideration, that some fueling stations are visited more frequent than others. Also, purchase behavior, operational or driving behavior change is not considered (e.g. rebound effects). Further on, likely impacts from complementary niche markets that apply also alternative propulsion technology are not taken into account. Therefore, explosive surges of interrelated innovations as often observed in techno-economic paradigm change are not considered.

In further research, the model could be applied within stakeholder dialogs in order to inform concerted policy formulation and road mapping, but also to explore further strategy and policy approaches. Not only policy and strategy approaches may be evaluated but also the value added of a simulation based scenario analysis may be assessed.

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Chapter 7
How Should Public Policy Transform the Stock of Buildings Toward Energy Efficiency and Low Emissions? Results from a System Dynamics Modeling Study of Switzerland

Matthias Otto Müller, Ruth Kaufmann-Hayoz, Franz Schultheis, Markus Schwaninger, and Silvia Ulli-Beer

Abstract We report on modeling work that shows how the market, technology, civil society and the state govern the diffusion of energy-efficient renovations in Switzerland's stock of residential, multifamily buildings. The particular focus of this chapter is on the policy implications that we drew from an extensive System Dynamics modeling study. We conclude that energy efficiency is important, yet not sufficient in order to reach ambitious emission reduction goals. In addition to promoting energy efficiency, Switzerland should aim for a widespread decarbonization of heating systems. We discuss what kind of instruments can be used to address various policy levers in order to accelerate the diffusion of energy-efficient renovations. We propose two regulations that could serve as a framework

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This chapter summarizes and further elaborates on research presented in Müller (2012, 2013). Hence, it may include identical wording taken from those publications. Previous versions of this chapter were presented at the 3rd Sustainability Conference in Basel and the 30th System Dynamics conference in St. Gallen.

M.O. Müller (✉)
Greenwood Strategic Advisors AG, Zugerstrasse 40, Unterägeri 6314, Switzerland
e-mail: Matthias.mueller@greenwood-ag.com; matthiasottomueller@gmail.com

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

F. Schultheis
Seminar for Sociology (SfS), University of St. Gallen, Tigerbergstrasse 2, St. Gallen 9000, Switzerland

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

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

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for ambitious long-term decarbonization efforts. Finally, we propose a service innovation that could assist building owners in complying with the ambitious regulations required.

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7.1 Introduction

The building sector accounts for about a quarter of global energy-related greenhouse gas emissions and consequently it is a key lever in climate change mitigation efforts (Levine et al. 2007). Such emission reductions may come at a negative price in a substantial share of cases (Ürge-Vorsatz and Metz 2009). Particularly the renovation of old buildings is seen to be among the most cost-effective ways to reduce CO_2 emissions in industrialized countries (Galvin 2010). In the long run this calls for nothing less than a radical transformation of the built environment (Barrett 2009). Currently, however, sustainability in the construction sector is probably just a minor aspect of the design, use, management and maintenance of the built environment (Lovell 2005).

In a recent study, we analyzed the diffusion dynamics of energy-efficient renovations in Switzerland's stock of residential, multifamily buildings (Müller 2012, 2013; Müller and Ulli-Beer 2010, 2008a, b; Ulli-Beer and Müller 2006). The focus of our study was on space heating and hence we abstained from issues such as warm water, appliances or grey energy. We built a System Dynamics model that explains how the market, technology, civil society and the state govern the diffusion of energy-efficient renovations and the CO_2 emissions of the stock of buildings. This enabled us to analyze the following research question: *How can the diffusion of energy-efficient renovations of buildings be accelerated in order to reduce the CO_2 emissions from the stock of buildings?*

In this chapter, we aim to concisely present the most important results from that study. Specifically, we discuss how public policy should transform the stock of buildings toward energy efficiency and low emissions. Beyond the narrow 'use value' of our research we hope to make several exemplary contributions to research in the spirit of ecological economics and sustainability science. For example, our study might be seen as an illustration as to how different fields of society (e.g. the market, technology, civil society and the state) are interrelated in the creation and governance of environmental issues.

This chapter is structured as follows. In Sect. 7.2, we elaborate on methodological aspects of our study. In Sect. 7.3, we describe the context within which the diffusion of energy-efficient renovations occurs as a societal problem situation. In Sect. 7.4.1, we describe the structure of causality that governs the diffusion of energy-efficient renovations. Then, in Sect. 7.4.2, we carry the analysis further by elaborating our building stock model sector. That sector is crucial for understanding the transformation of the stock of buildings. In Sect. 7.7.5, policy levers are identified (Sect. 7.5.1) and analyzed quantitatively (Sects. 7.5.2, 7.5.3, and 7.5.4) in order to understand the policy implications of the model's behavior (Sect. 7.5.5). In Sect. 7.6, we discuss how public policy should transform the stock of buildings. In Sect. 7.7, we answer our research question.

7.2 Research Design and Methods

Before we indulge in the results, we must briefly describe how we proceeded methodologically. The research design[1] that we followed is best described as theory building with System Dynamics (Schwaninger and Groesser 2008; Schwaninger and Pfister 2007). In order to arrive at an empirically grounded simulation model, we followed a research design that relied on five distinct steps. The first step consisted of orienting ourselves in the field and clarifying the relevant research questions. Second, we conducted exploratory (N = 7), systematic (N = 14) and validating (N = 7) interviews. While the interviewees were from heterogeneous backgrounds, most of them can be described as either academic researchers or practitioners (architects, representatives of building owners, representatives of construction companies). We recorded and transcribed the interviews and analyzed them using the MAXQDA software package. We were mostly interested in the content given by the interviewees and did not focus on deep meaning structures as this is done in more hermeneutic methodologies. Hence, we deemed content analysis (Flick 2005: 280) to be sufficiently rigorous and abstained from any analysis methods that strive for deeper analysis. As a third step, we developed four analytical perspectives. Specifically, we analyzed the context, we built a small

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[1] See Müller (2012, 2013) for the complete documentation of the research design and the methods we used.

simulation model of the stock of buildings (Müller and Ulli-Beer 2010), we analyzed actors and we developed an endogenous theory of the causal drivers of the diffusion of energy-efficient renovations. As a fourth step, we integrated insights obtained from the analytical perspectives into a quantitative System Dynamics simulation model, implemented in the VENSIM simulation software. As a fifth step, we conducted policy analysis with the simulation model.

However, these five steps were not followed in a strictly linear fashion. Instead, we iterated as we deemed fit. Throughout the research process, we conducted desktop research and we routinely tested and verified our results. In particular, model testing entailed evaluating the simulation model against many of the standard tests described in the literature (Barlas 1996; Sterman 2000; Schwaninger and Groesser 2009). Because behavioral data against which the model behavior could be tested against was mostly not available, we strongly relied on model structure tests.

7.3 Context

Analyzing the context within which the diffusion of energy-efficient renovations takes place helped us to determine the adequate boundary in our modeling efforts. Further, it provided us with an important opportunity to learn about the issue under study. On the most general level, we found that climate change and energy security concerns should be considered to be the most important drivers of the diffusion of energy-efficient renovations. The emergence of a distinct energy policy in Switzerland can be traced to the first oil crisis in 1973, when the country's strong dependence on energy imports became evident. Since then, promoting energy efficiency has been a crucial part of Switzerland's energy policy (Linder 1999; Jegen 2003). Scientists recognized anthropogenic climate change as a dangerous possibility as early as in 1977 (Weart 2008). However, only over the last decade has climate change emerged as a publically influential discourse. As this discourse became ubiquitous, it profoundly re-shaped the way energy policy was debated (Reddy and Assenza 2009) and led to an additional problematization of current energy use patterns (Jasanoff 2010). Mitigating greenhouse-gas emissions now is a key aspect of many public policy efforts.

Climate change concerns and energy supply security concerns can be considered to be general drivers that exert pressure on the stock of buildings and the various societal fields associated with it. Eventually, this has created a societal problem situation that involves actors in the market, actors in civil society and the state. In the wake of the emergence of a societal problem situation, established practices are destabilized and change processes are put into motion. Such change processes are typically highly unstructured, uncertain and rife with conflicts of interest among different actors (Geels 2005).

We found that analyzing societal actors was particularly important in understanding the diffusion of energy-efficient renovations. This is because this diffusion process is not primarily driven by markets and prices. Instead, it is a diffusion process that is substantially driven by societal actors who want to influence public policy according to their interests. In particular, it was mostly societal actors (e.g., environmental pressure groups) who began to call for the transformation of the stock of buildings. These claims were generally intended as a contribution to the public good, undertaken with the intention of reducing energy security risks and reducing the risks of global climate change. Eventually, such environmental discourses and the prospects of strong state regulations cause other societal actors (e.g., industrial associations) to voice opposed views and participate in a competition for the publics' endorsement.

In the political science literature, the effect of societal actors on the policy process has been described in the context of the advocacy coalition framework (Sabatier 2007; Weible et al. 2009). That framework has been used to understand the policy process, particularly policy change over long time periods lasting a decade or longer. Several contributions empirically analyzed the effect of advocacy coalitions in various policy domains in Switzerland. For example, in the domain of energy policy (Kriesi and Jegen 2000, 2001; Jegen 2003), climate policy (Lehmann and Rieder 2002; Ingold 2007, 2010) or environmental policy in general (Bornstein 2007). From that literature, we were able to confidently derive the existence of an advocacy coalition that generally demands further public policy interventions into the stock of buildings ("pro ecology") and an advocacy coalition that generally opposes further interventions ("pro growth").

As societal actors influence public policy to initiate and promote energy efficiency technology and low-emission energy systems, actors in the market too play an important role. Based on a series of interviews, we identified building owners, architects and tenants to be the most important actors in the market. In contrast, we found that construction companies hardly influence the decisions-making related to energy efficient renovations. Based on our interviews, we proposed to further categorize building owners according to the amount of professional know-how they have. We found that building owners without professional know-how may be a crucial group, because they own about 70 % of multifamily buildings. Unfortunately, they frequently face greater obstacles in implementing energy-efficient renovations.

We found two barriers to a low-emission stock of buildings to be particularly powerful. First, building owners implement energy-efficient renovations only if and only when they deem fit. There are no regulations forcing them to increase the energy efficiency of their building. Building owners, for example, may choose to do nothing at all or simply paint their façade instead of insulating it. Energetically relevant regulations only become relevant once substantial renovation is actually undertaken. Then, pre-defined levels of energy efficiency have to be achieved in the elements under renovation. The second barrier refers to the "investor-user dilemma". This occurs when a building owner carries the costs of an investment into energy efficiency and the tenants obtain the benefits. In such a situation, the building owner has an incentive to chose the investment with the lowest cost, regardless of cost-benefit considerations (Golubchikov and Deda 2012; Schleich 2009; OECD/IEA, AFD 2008).

It is noteworthy that the state of technology and the economics of energy-efficiency now no longer are substantial barriers in Switzerland. The last decade has brought about spectacular technological and economical progress in energy-efficient construction (Erhorn-Kluttig and Erhorn 2007). In fact, CEPE and HBT (2002: 314) recall that the rapid technological progress achieved over the last decades would have been called a super-efficient development in the early 1980s. In the future, the potential for technological and economical breakthroughs is rather limited. Instead, incremental cost reductions, further improved performance and the integration of various technologies should be expected (IEA 2008: 183).

7.4 Modeling the Diffusion Dynamics of Energy-Efficient Renovations

7.4.1 Governance Structure of the Diffusion Process

Figure 7.1 shows a causal loop diagram (CLD) of the governance structure that controls the transformation of the stock of buildings toward energy efficiency and low emissions.[2] While the actual simulation model consists of variables and equations, we chose to present a causal loop diagram (Sterman 2000). This enables us to focus on the main structure of causality and abstain from technical details. Specifically, the CLD consists of variables that are linked with an arrow according to the direction of causality: A positive causal relationship (marked with a "+") is postulated to exist between the *Number of NEE buildings* and the *Number of renovations implementing EE building designs*. Both variables move in the same direction. An inverse causal relationship (marked with a "–") is postulated to exist between the *Number of renovations implementing EE building designs* and the *Number of NEE buildings*. When the *Number of renovations implementing EE building designs* rises then the *Number of NEE buildings* falls.

As can be seen, several interrelated feedback loops were conceived. Loop A shows how energy-efficient renovations transform the stock of buildings. Loops B and C represent the two sides of the housing market that control the stock of buildings. Specifically, loop B describes the demand for and loop C describes the supply of energy-efficient housing. Loops D and E represent technological and

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[2] Due to limitations in space, the following description is substantially abbreviated. A complete account of the feedback loop perspective is available in Müller (2012, 2013).

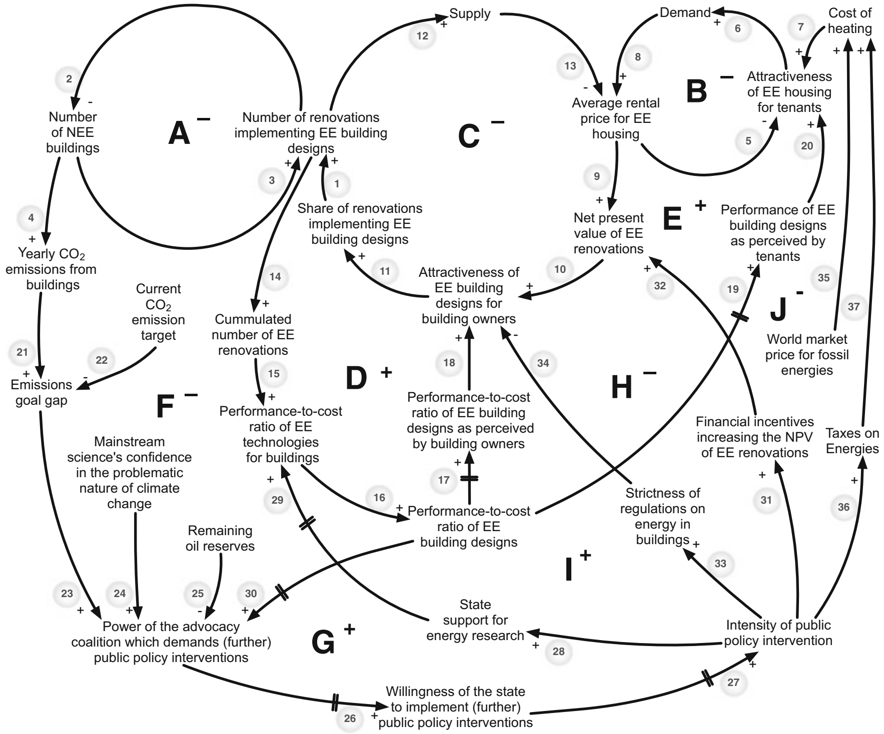

Fig. 7.1 Causal loop diagram of the main structures of causality in the simulation model. Note that loop *A* represents the building stock model sector described below. Note that loops *B–J* govern the transformation of the stock of buildings by way of the variable share of renovations implementing EE building designs

economical progress. Due to learning effects, economies of scale and scope, energy-efficient building designs in renovations improve and become cheaper. Loop D shows that technological and economical progress makes energy-efficient building designs more attractive for building owners. Loop E shows that technological progress makes energy-efficient housing more attractive for tenants. Loop F shows how public policy reacts to the emergence of energy security concerns and climate change and supports research and development of technology. Loop G shows that the availability of adequate technology intensifies adaptive pressure on public policy. Consequently, public policy accelerates the diffusion of energy-efficient building designs by creating financial incentives (loop H). Eventually, public policy also tightens mandatory standards (loop I) and increases the cost of fossil fuels (loop J).

Together, these feedback loops provide an “endogenous point of view” (Richardson 2011) on the diffusion of energy-efficient renovations. In fact, this representation of the structure of causality may be considered as an interdisciplinary synthesis of various individual pieces of empirical and theoretical research.

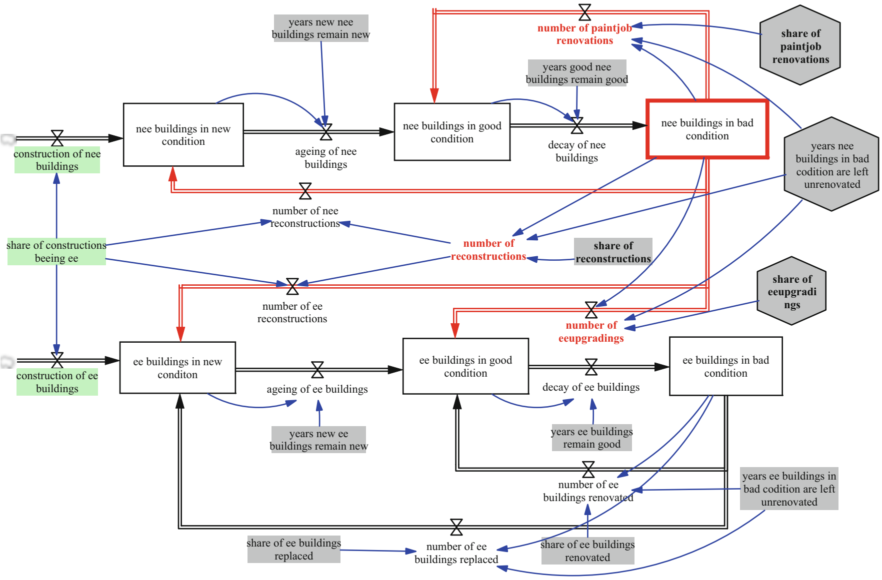

Fig. 7.2 Stock-and-flow-diagram of the building sector

However, causal loop diagrams have limitations. They are less detailed compared to actual simulation models and they can not be simulated by themselves (Sterman 2000). In particular, they do not allow eliciting behavioral aspects such as CO_2 emission trajectories. Therefore, we implemented this structure of causality into a full-fledged simulation model. In the following section, we describe how loop A was implemented as our building stock model sector.

7.4.2 *The Building Stock Model Sector*

Figure 7.2 shows the stock-and-flow diagram of the building sector of our model[3, 4]. Stock-and-flow-diagrams are used to represent the structures of a system in close relation to the equations that are actually simulated.

We consider buildings to be either in a new condition, in a good condition or in a bad condition. The number of buildings in each condition is accounted for by a stock. Over time, as buildings age, new buildings flow into the stock of buildings in good

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[3] In order to produce computer simulations, equations have to be specified in a computer simulation software such as VENSIM.

[4] Due to limitations in space, the following description is substantially abbreviated. A complete account of the building stock model sector is available in Müller and Ulli-Beer (2010) and Müller (2012, 2013).

condition and eventually they flow into the stock of buildings in bad condition. Only buildings in bad condition are renovated. We assume that it in average takes 55 years for a building to pass through all three stages and eventually be renovated. By combining these three stocks and the aging rates, an aging chain was formed.

Buildings are further differentiated according to their energy efficiency into non-energy-efficient (nee) or energy-efficient (ee) buildings.[5] Nee buildings in bad condition can be renovated with one of the following three basic renovation strategies. When a paintjob renovation is implemented, then a nee building in bad condition becomes a nee building in good condition. The energy efficiency remains unaltered. When an eeupgrading is implemented, then a building is moved into the energy-efficient aging chain and is also seen to be in good condition. Buildings can be torn down and reconstructed. In such a case, a building in new condition is built. Depending on the construction code, the building is reconstructed as a nee or an ee building.

Crucial in this building stock model are the variables *share of eeupgradings* and *share of paintjob renovations*. In the simulation model, they are calculated dynamically, based on the governance structure. Consequently, these two variables control what share of buildings is renovated according to the corresponding renovation strategy. The *share of reconstructions* is set constant at 5 %. The number of buildings under renovation in any year is calculated by dividing the *nee buildings in bad condition* trough the *years nee buildings in bad condition are left unrenovated*.

By underlying the diagram shown in Fig. 7.2 with equations and parameters we were able to simulate the evolution of the stock of buildings over time. In addition to the building sector shown in Fig. 7.2, we relied on further sectors to track energy coefficients, floor spaces and CO_2 emissions. Further, we relied on a series of exogenous inputs, such as past and projected data for the diffusion rates of oil and gas heating systems, the efficiency of heating systems, heated floor spaces and energy coefficients to simulate the model.

7.5 Model Behavior and Implications for Public Policy

7.5.1 Identification of Policy Levers from the Model Structure

Public policy intervenes into the stock of buildings by influencing policy levers with policies and instruments. Table 7.1 shows an evaluation of policy levers

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[5] Specifically, buildings are seen to be non-energy-efficient (nee) if the energy coefficient for heating is 193 MJ/m^2a or higher and they are considered to be energy-efficient (ee) if the energy coefficient for heating is below 193 MJ/m^2a. These values correspond to the Swiss Minergie label after 2003 and the mandatory governmental regulations after 2008 as defined by the Swiss conference of the cantonal energy directors (EDK 2008: 13).

Table 7.1 Evaluation of policy levers directly influencing the transformation of the stock of buildings

Lever	Evaluation
Increase share of eeupgradings	Crucial challenge
Decarbonize heating systems	Crucial challenge
Increase efficiency of heating systems	Substantial success achieved, continue interventions
Reduce the energy coefficient in the energy code	Substantial success achieved, continue interventions
Make new constructions energy-efficient	Substantial success achieved, continue interventions
Speed up renovations	Of questionable importance
Limit the construction of new buildings	Unrealistic

directly related to the stock of buildings. By simulating the model, we found that the *share of eeupgradings* and the *CO_2 emission rate* are particularly powerful policy levers. Using the other policy levers turned out to be unrealistic, of questionable value or unpractical because substantial success has already been achieved. For example, the construction of additional non-energy-efficient buildings has been eliminated by past changes to the building code (Jakob 2008) and hence it no longer is a usefull policy lever. Scenario analysis reported in Müller (2012) showed that accelerating the renovation cycle by 5 years does not substantially impact on the CO_2 emission rate in the long term and hence is of questionable importance.

In addition to the policy levers directly influencing the transformation of the stock of buildings, indirect policy levers could be identified. By reviewing the simulation model, policy levers capable of increasing the *share of eeupgradings* were found. These were listed in the left column of Table 7.4. The next section reports on results from quantitatively analyzing such indirect policy levers.

7.5.2 Analysis of Policy Levers by Themselves

In order to analyze indirect policy levers in a standardized manner, we increased each lever by 50 % in the year 2010. Then, we compared the model behavior relative to the base scenario in the year 2020. Our guiding question was whether the manipulation of a single policy lever could increase the *total share of eeupgradings* near unity. We found that there is no single policy lever that is capable of increasing the *share of eeupgradings* such that the CO_2 emissions are reduced substantially relative to the base scenario. Nevertheless, we found that the following policy levers influence the *share of eeupgradings* quite sensitively by themselves:

- Building owners' perception of the technological quality of energy-efficient building designs

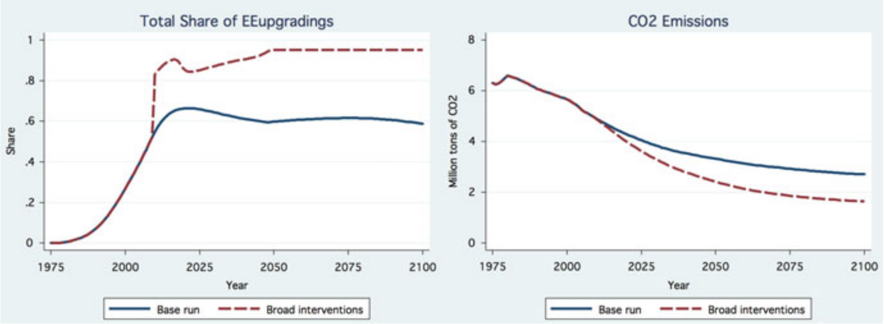

Fig. 7.3 Behavior of the simulation model in the base run (*straight line*) and after implementing a broad series of interventions (*dotted line*)

- Building owners' preference for energy-efficient building designs
- Probability that architects promote energy-efficient building designs
- Tenants' perception of technological quality of energy-efficient building designs
- Tenants' utility from co-benefits of energy efficiency
- Pressure from fossil energy shortage
- Longterm minimum energy coefficient of construction[6]

7.5.3 Analysis of a "Broad Interventions" Package of Policy Levers

In a next step, we simulated the effect of a broad package of interventions. This was simulated by conjointly increasing the sensitive policy levers by 50 % after the year 2010. We found that this almost instantly increases the *total share of eeupgradings* near to unity (see left exhibit of Fig. 7.3). In reality, such an increase would constitute an enormous policy success. The right exhibit of Fig. 7.3 shows the resulting behavior of the *CO_2 emissions*. In both scenarios, *CO_2 emissions* are reduced substantially over time, indicating the important contributions made by energy-efficient renovations to emission mitigation. The emission trajectory obtained in the base run scenario would already be a quite successful policy-outcome. It seems unlikely that a more ambitious emission trajectory could be obtained based on energy-efficiency alone than the trajectory obtained in the "broad interventions" scenario. A crucial question is whether the

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[6] The variable *longterm minimum energy coefficient of construction* was decreased by 50 %.

Table 7.2 Emissions and emission reductions in the "base run" and the "broad interventions" scenarios. Gives the emissions of the stock of buildings in the two scenarios in million tons of CO_2 per year (Mio.t.p.a.) and the emission reductions as percent changes relative to the years 1990 and 2010

	Base run			Broad interventions		
	Mio.t.p.a.	*Δ 1990*	*Δ 2010*	Mio.t.p.a.	*Δ 1990*	*Δ 2010*
1990	6.1			6.1		
2010	4.9	*−20 %*		4.9	*−20 %*	
2050	3.3	*−46 %*	*−33 %*	2.4	*−61 %*	*−51 %*
2100	2.7	*−56 %*	*−45 %*	1.6	*−74 %*	*−67 %*

emission reductions obtained in these two scenarios are sufficient in light of public policy goals.

Several approaches have been taken to deriving long-term policy goals in energy and climate policy. In the Swiss context, visions such as the 2,000-W-society or the 1-t-CO_2-society are frequently used to derive long-term policy goals. For example, the implementation of a 1-t-CO_2-society would require the average Swiss resident to reduce emissions to 2 t CO_2 per capita in the year 2050 and to 1 t CO_2 per capita in the year 2100 (Novatlantis 2007). In order to evaluate the implications of our simulation results, the visions of the 2,000-W-society or the 1-t-CO_2-society are not very practical. We found it more practical to compare emission reductions in percent rather than discussing what share of the 1-t-CO_2-allowance should be spent on the heating of multifamily buildings. Siller et al. (2007), for example, call for greenhouse gas emission reductions of around 80 % by 2050 (with 1990 as the base year) in order to limit global warming to 2 °C. More recently, the European Union communicated long-term emission reduction goals in the contexts of its "roadmap for moving to a competitive low carbon economy in 2050" (EU 2011). For the residential and service sector the roadmap calls for CO_2 emission reductions of around 90 % by 2050 (relative to 1990 emission rates). Concluding this discussion, we propose to set emission reductions of 90 % by 2050 (relative to 1990) as the long-term policy goal against which the emission trajectories of Switzerland's stock of buildings should be evaluated against. While Switzerland is not member of the EU, EU policies do influence Switzerland's policy-making, as the country typically strives to roughly align with the EU.

Table 7.2 shows the absolute CO_2 emissions and the emission reductions relative to the year 1990 that were obtained by simulating the two scenarios above. In the most optimistic "broad interventions" scenario, the CO_2 emissions are reduced by about 61 % by 2050 and by about 74 % by 2100. In the base scenario, emission reductions by about 46 % by 2050 and by about 56 % by 2100 were attained. Comparing these emission reductions against the long-term policy goal of a 90 % reduction by 2050, we find that even the emission reductions attained in the most ambitious "broad interventions" scenario appear not to be sufficient.

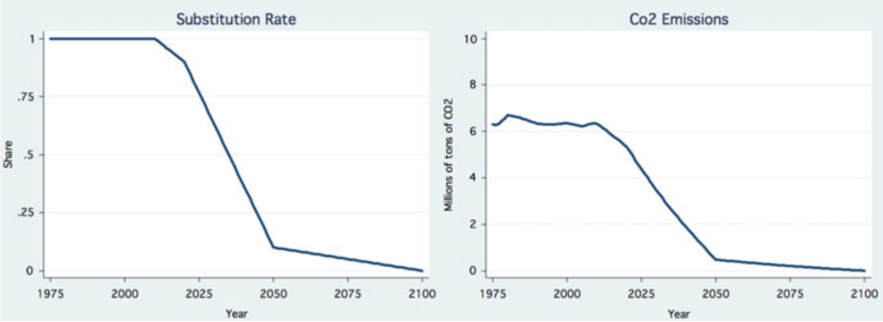

Fig. 7.4 Gradual substitution of fossil heating systems until 2050. The exhibit on the left shows the assumed substitution rate. The exhibit on the right shows the resulting emission trajectory

7.5.4 Analysis of a Forced Outphasing of CO_2 -Emitting Heating Systems

The emission reductions achieved in the 'broad interventions' scenario, based primarily on energy efficiency, are not sufficient to reach the long-term policy goal of 90 % reductions. This finding leads us to argue that further measures, in addition to energy efficiency, are needed. In particular, we call for a far-reaching decarbonization of Switzerland's stock of buildings.

In order to show how the decarbonization of Switzerland's heating systems would impact on the CO_2 emission rate, we conducted a further simulation. Specifically, we simulated the effect of reducing the diffusion rate of oil and gas heating systems. Technically, this was implemented by multiplying the diffusion rates of oil and gas heating systems with the variable *substitution rate* shown in the left hand exhibit in Fig. 7.4. The exhibit on the right hand in Fig. 7.4 shows the resulting CO_2 emissions. It becomes evident that the CO_2 emissions could indeed be reduced nearly to zero if an ambitious substitution program aimed at reducing the diffusion rate of oil and gas heating systems were implemented.

7.5.5 Discussion

In a nutshell, the findings obtained from analyzing the model's behavior can be summarized as follows. We found that by conjointly using highly sensitive policy levers, the *share of eeupgradings* can be increased near to unity. However, the emission reductions obtained from this proved insufficient. By out-phasing oil and gas heating systems, the *CO_2 emissions* could be reduced near to zero.

We find that our results fit the findings of other authors in the literature reasonable well. Siller et al. (2007), in a study of Switzerland's residential building sector, find that emission reductions of around 80 % (by 2050, relative to 1990) can be achieved based on a very strong combination of energy efficiency and renewables. TEP and ETH (2009) provide a model of the whole stock of residential buildings in Switzerland and consider space heating as well as warm water generation and appliances. They find that greenhouse-gases emissions can be reduced by 28–65 % by 2050, depending on what assumptions are made. Schulz (2007: 118) finds that heating systems based on oil and gas fuels could be largely avoided, even if the heated floor area would rise by an estimated 40 % until the year 2050. This could be achieved by relying on heat pumps and district heating based on combined heat-power generation (CHP) from natural gas and biomass. That would reduce the CO_2 emissions of residential buildings by about 80 %.

In conclusion, we find that public policy should attempt to reduce emissions by around 90 % by 2050, by increasing the share of eeupgradings near to unity and promoting the out-phasing of fossil-based heating systems. In the following section, we elaborate on the instruments and regulations that public policy should employ toward that goal.

7.6 Transformation of the Stock of Buildings

7.6.1 Instruments in Support of the Diffusion of Energy-Efficient Renovations

Inspired and guided by a “typology of tools for building sustainability strategies” (Kaufmann-Hayoz et al. 2001), we conducted a literature review of policies and instruments typically used in environmental policy (Müller 2012, 2013). Our goal was to find instruments that can be used to influence the wide range of policy levers listed on the left-hand side of Table 7.4. Table 7.3 shows the instruments that we found particularly promising.

For each policy lever shown in Table 7.4, we list the instruments that we deem adequate for influencing that policy levers. What is more, we list the group of actors that we deem capable of using an instrument to influence the specific policy lever. While we devised this typology for the case of Switzerland, we expect it to be a useful tool for analyzing energy and climate policy in other northern, industrialized countries. In particular, it could be used to systematically search for further public policy interventions. On a more general level, Table 7.4 illustrates that transformation processes are brought about by applying a wealth of instruments to many different policy levers.

Table 7.3 Typology of instruments that can be used to influence the wide range of policy levers listed on the left-hand side of Table 7.4

	Instrument	Description
Command and control instruments	Emission regulations for heating systems	By regulating the emissions of heating systems, the application of current technology can be enforced and technological progress may be induced
	Relaxation of regulations	By relaxing limiting regulations (e.g. maximum floor space allowed by the building code), the economic viability of energy-efficient renovations may be increased
Economic instruments	Subsidies for energy efficiency and low-emission heating systems	By partially funding such investments, their attractiveness is increased. Subsidies are particularly interesting when combined with taxes on energy use and emissions
	Taxation of fossil-fuels	As the price of fossil fuels is increased, consumers substitute away from fossil-fuels
	Taxation of fossil heating systems	As fossil heating systems become more expensive, the attractiveness of alternative heating systems is increased. In contrast to taxing fuels, the taxation of (new) heating systems does not affect previous owners of fossil heating systems
Communication and diffusion instruments	Relying on word of mouth	Word of mouth refers to the attitudes and expectations that are communicated about a product or service among its potential or actual customers. For example, an architect owner may informally ask colleagues about their experiences with energy-efficient building designs. While the spreading of positive word of mouth might generally happen coincidentally, it could actually be an intervention that is at the disposal of actors in the construction and real-estate sectors
	Continuous training	Promoting continuous training enables actors in the construction and real-estate sector to obtain the know-how required to implement energy-efficient building designs
	Energy counseling	Promoting energy counseling would increase the knowledge base of decision-makers and nudge them toward more professional decision-making

(continued)

Table 7.3 (continued)

	Instrument	Description
	Establish standards	The establishment of standards, such as Minergie in Switzerland or the LEED standard in the US, reduces information and transaction costs. By referring to an established standard, building owners can now easily demand an energy-efficient building design without having to discuss technical details with architects
	Facilitate exchange among practitioners	By supporting the sharing of experiences among practitioners in the construction and real-estate sector, the diffusion of energy-efficient building designs and key technologies is accelerated
	Information campaigns	This refers to the communication of knowledge and the creation of awareness to specific groups
	Labeling	Labels can be used to communicate and certify difficult to observe attributes of a building, such as energy efficiency
	Marketing campaigns	Marketing energy-efficient building designs and their components aims to inform and convince potential customers
	Participate in the political process	Participation in the political process may be a highly effective intervention if the institutional framework can be shaped to support energy-efficient building designs
	Pilot and demonstration initiatives	Pilot- and demonstration initiatives acquaint actors in the construction and real-estate sector with technical innovations, thus accelerating the diffusion process
	Relying on word of mouth	Word of mouth refers to the attitudes and expectations that are communicated about a product or service among its potential or actual customers. For example, an architect owner may informally ask colleagues about their experiences with energy-efficient building designs. While the spreading of positive word of mouth might generally happen coincidentally, it could actually be an intervention that is at the disposal of actors in the construction and real-estate sectors
	Research and development initiatives	Initiating and supporting research and development leads to better and more cost-effective technologies

Table 7.4 Policy levers, instruments applicable to them and actors capable of implementing the instruments. Abbreviations: *B* building owners, *C* civil society actors, *G* governments of various levels, *I* industry actors (such as construction companies and architects), *S* scientists and actors from academia, *T* tenants

	Policy lever	Instruments
Building owners	Building owners’ perception of the technological quality of energy-efficient building designs	Information campaigns (G, I), pilot and demonstration initiatives (G, I, S), word of mouth (B, T)
	Building owners’ delay in the perception of technological quality	Information campaigns (C, G, I), pilot and demonstration initiatives (B, C, G, I), word of mouth (B, T)
	Financial attractiveness of eeupgradings for BOs	Relaxation of regulations (G), research and development initiatives (C, G, I), subsidies for energy efficiency (G), subsidies for low-emission heating systems (G), taxation of fossil-fuels (G), taxation of fossil heating systems (G), word of mouth (B, T)
	Probability that architects promote energy-efficient building designs	Continuous training (C, G, I, S), establish standards (G, I), facilitate exchange among practitioners (C, G, I), information campaigns (C, G, I), marketing campaigns (C, G, I), relaxation of regulations (G)
	Building owners’ preference for energy-efficient building designs	Energy counseling (C, G, I), emission regulations for heating systems (G, I), establish standards (G, I), information campaigns (C, G, I), labeling (C, G, I), marketing campaigns (C, G, I), pilot and demonstration initiatives (B, C, G, I), relaxation of regulations (G), subsidies for energy efficiency (G), subsidies for low-emission heating systems (G), taxation of fossil-fuels (G), taxation of fossil heating systems (G), word of mouth (B, T)
	Increasing the share of professional building owners	Implement “Immobility” cooperative society (C, G, I)
Tenants	Tenants’ perception of technological quality of energy-efficient building designs	Information campaigns (C, G, I), labeling (C, G, I), marketing campaigns (C, G, I), pilot and demonstration initiatives (B, C, G, I), word of mouth (B, T)
	Tenants’ utility from co-benefits of energy efficiency	Information campaigns (C, G, I), labeling (C, G, I), marketing campaigns (C, G, I)

(continued)

Table 7.4 (continued)

	Policy lever	Instruments
Technology	Effect of learning on construction costs of eeupgrading designs	Continuous training (C, G, I, S), facilitate exchange among practitioners (C, G, I), research and development initiatives (C, G, I)
	Effect of stricter standards on construction costs	Facilitate exchange among practitioners (C, G, I), research and development initiatives (C, G, I), relaxation of regulations (G), subsidies for energy efficiency (G)
	Architects’ perception of technological quality of energy-efficient building designs	Continuous training (C, G, I, S), establish standards (G, I), marketing campaigns (C, G, I), pilot and demonstration initiatives (B, C, G, I), research and development initiatives (C, G, I), word of mouth (B, T)
Civil society and the state	Yearly emissions of CO_2 compatible with the 2° goal	Participate in the political process (B, C, I, S, T)
	Pressure from fossil energy shortage	Marketing campaigns (C, G, I), participate in the political process (B, C, I, S, T), taxation of fossil-fuels (G),taxation of fossil heating systems (G)
	Perception of technological quality by civil society actors	Establish standards (G, I), information campaigns (C, G, I), pilot and demonstration initiatives (B, C, G, I), word of mouth (B, T)
	Threshold value until which subsidies are given	Participate in the political process (B, C, I, S, T)
	Reductions of the legal energy coefficient	Emission regulations for heating systems (G, I), establish standards (G, I), participate in the political process (B, C, I, S, T), research and development initiatives (C, G, I), subsidies for low-emission heating systems (G), taxation of fossil-fuels (G), taxation of fossil heating systems (G)

7.6.2 Regulations in Support of the Decarbonization of the Stock of Buildings

In the following, we discuss how a far-reaching decarbonization of Switzerland's heating systems could be achieved. In particular, we propose two regulations for discussion. In doing so, we are very well aware that several questions regarding political approval and practical implementation will remain open. Note that we propose these regulations as a complementary framework within which current efficiency-oriented energy policies would remain effective. We do not propose to replace current energy policies with the two regulations.

Regulation 1

Until the year 2050, zero- or low- CO_2 emission heating technology has to be implemented in every building built before the year 2000.

Regulating the emissions from heating systems should prove much easier than mandating energy-efficient renovations. Because the service life of a heating system is much shorter compared to the service life of a building, almost all heating systems should be expected to have exceeded their service life by 2050. With this regulation, fossil-based CO_2 emissions from heating systems would be banned. However, building owners would remain free to select the mix of insulation technology (façade insulation, efficient windows, etc.) and emission-free heating system that is best suited to their situation. The reason why we propose a command-and-control-type approach rather than market-based instruments (Kaufmann-Hayoz et al. 2001), such as a high tax on greenhouse-gases, is the prevalence of the investor-user dilemma (see above in Sect. 7.2). A tax on fossil CO_2 emissions might not prove an effective signal to the owners of rented buildings, because the tenants bear the cost of the tax. However, as a complement, an environmental tax on fossil-fuels could support the transformation of the stock of buildings and it might encourage renovations in owner-occupied buildings. This particularly holds when the earnings of the environmental tax are used to subsidize renovations.

If it is possible to create the strong expectation that in the next 40 years the stock of buildings will indeed be transformed to a situation of low or zero emission, then entrepreneurs and companies can expect a large future market. This should lead to the development of technologies and business models that become increasingly better and cheaper. Therefore, we expect the implementation of such a long-term policy to alter the costs and the quality of energy-efficient building designs beyond current practices. This is because actors in the construction industry would anticipate a big market and develop technologies and business models that implement low-emission heating and building designs at competitive prices, thus unlocking the innovativeness of entrepreneurs.

Regulation 2

Until the year 2020 building owners have to submit a roadmap that details how low-emission energy systems will be implemented in their building and how they intend to finance their road to a zero-emission building.

The purpose of this second regulation is to encourage building owners to consider the implementation of decarbonized building designs long before the actual deadline arises. The development of a long–term plan should allow building owners to plan and coordinate investment decisions for their buildings. By planning a series of consecutive measures, inefficiencies should be substantially reduced. For example, a lack of coordination and long term planning might lead a building owner to first exchange windows and heating systems and only several years later to insulate the façade. Yet in order to insulate, the windows have to be unmounted and repositioned, so it would have been cheaper to replace the windows during insulation. And after insulation, the heating system might be over-dimensioned for a now efficient building. Thus, a smaller and cheaper heating system could have been bought after insulation.

Generally, such a regulation would particularly benefit non-professional building owners, who often lack a coherent long-term strategy for their buildings and are more likely to suffer from such inefficiencies. They rather decide in a step-by-step fashion, frequently based on events in their personal lives. A further benefit of having a set of measures awaiting implementation is that it could encourage building owners to order construction during times of recession, when prices for construction are relatively low.

This proposal is complementary to current energy policies because it explicitly states a long-term goal and a date for achieving it without prescribing how building owners achieve these goals. Its temporal specification is such that building owners, construction companies, and technology developers would have enough time to adapt. The two regulations could nevertheless achieve a very ambitious policy goal; namely, the far-reaching decarbonization of the stock of buildings by the year 2050. This is a crucial difference to current policies addressing emissions by buildings. Implementation of the two regulations presented here would basically guarantee a far-reaching decarbonization of Switzerland's stock of buildings. In addition, these two regulations might prove effective in other northern, industrialized countries.

Of course, implementation of these regulations would require careful further analysis. Issues such as the conservation of heritage buildings or the question as to how non-complying building owners would be sanctioned pose special difficulties. Also, current energy and climate policy regulations as well as building standards would need to be scrutinized regarding their consistency in terms of these regulations.

7.6.3 A Business Model in Support of Non-professional Building Owners

Implementing near-zero-emission building designs in renovations, as implied by the two regulations introduced above, would increase the challenge of renovating. In such a situation, non-professional building owners should be considered to be a bottleneck, as they hardly have any chance to accumulate experience. In order to overcome this bottleneck, we propose to develop and actually implement a business model that solves several of the challenges that non-professional building owners face. By doing so, the transformation of Switzerland's stock of buildings toward low-emission, and perhaps even more generally toward sustainable housing, could be accelerated. Specifically, we propose the founding of a cooperative society that would work as a catalyst.

The cooperative society would assist building owners in dealing with various technical, financial, and procedural obstacles associated with renovations. It would ensure that the outcome of a renovation is adequate for the specific building in its specific situation; technically well built and cost-effective. In order to be perceived as credible, the cooperative society should seek endorsement from other actors, such as the federal office of energy or the Minergie Association. Its business model probably would need to address the following issues[7]:

- **Long-term planning**: The various elements of a building have different service lives and they should be replaced with consideration of possible path dependencies. Else, renovations may become overly expensive and ineffective. Long-term planning could avoid the risks of path dependency in sequential renovations. What is more, the cooperative society should assist building owners in long-term financial planning for renovations.
- **Value creation:** Buildings should be renovated in a way that maximizes the utility that tenants draw from it. This means that planning should raise the rent potential, reduce the risk of vacancy, and eventually increase the value of the building. Further, the business model should ensure that social and environmental values are considered adequately.
- **Assistance with technology choice:** For most building owners, searching for technical information is a time-consuming and costly process. Further, a substantial share of information on technical systems comes from vendors themselves. Hence, such information is not necessarily neutral or adequate. In order to respond to this, the cooperative society should provide neutral and up-to-date information on current technologies and cost.
- **Assistance with financial matters:** The cooperative society should assist building owners with organizing finance if sufficient reserves have not yet been accumulated before the renovation. This entails advising building owners on

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[7] Thanks to Mark Zimmerman (EMPA) for helpful comments by Email (September 21, 2011).

what subsidies to apply for and how to optimize taxes. Further, by bundling the demand of several building owners, it may be possible to negotiate discounts from vendors and construction companies.

- **Reduction of complexity:** Building owners should not have to deal with several companies. Instead, the cooperative society should coordinate among the companies involved and act as the single representative toward building owners, so that they can concentrate on the important decisions.
- **Managed care for buildings**: As an important aspect, the cooperative society should provide managed care or commissioning (Mills 2011) for buildings. This means that buildings should be evaluated at regular intervals in order to find optimization potential in the domains of energy and occupational health. Such a service would encourage long-term relationships with building owners. As a part of commissioning efforts, tenants should be taught as to how to use the technologies in their building in an optimal manner.
- **Strategic focus**: The cooperative society should not provide solutions for each type of building. Instead, the focus should be on buildings of frequent types. Its strategic focus should be on high volume of relatively similar buildings and cost reductions through economies of scale and scope and learning effects.

7.7 Conclusions

In this chapter, we addressed the question, how public policy could transform the stock of buildings toward energy efficiency and low emissions. Based on the arguments elaborated above, we propose the following condensed answer. Public policy should increase the share of renovations implementing energy-efficient building designs near to unity and prevent paintjob renovations. In order to do so, public policy should attempt to address all policy levers available and use a wide arsenal of instruments that influence those policy levers. However, it seems rather unlikely that energy efficiency alone will suffice to reduce emissions by 90 % by 2050 (taking 1990 as a base year). Therefore, public policy should promote the wide-spread decarbonization of fossil heating systems. In order to accelerate the diffusion of energy-efficient renovations and achieve a wide-spread decarbonization of the stock of buildings by 2050, public policy should implement the two regulations described in Sect. 7.6.2. The first regulation, prohibiting the emission of CO_2 from heating systems by 2050, would create adaptive pressure decades before the year 2050 and would serve as a framework within which all other public policy interventions can be placed in. The second regulation, mandating the development of a roadmap for the renovation of buildings by 2020, would ensure that building owners pursue a long-term perspective in their decision-making. In order to support the majority of non-professional building owners in dealing with the rising complexity of renovations, we propose that public policy plan, implement and support service innovations such as the cooperative society described in this chapter. We expect that such service innovations reduce policy resistance and enhance the economical, ecological and social value of the built environment.

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Part III

Research and Policy Implications: Mastering the Challenges of Socio-Technical Transitions in Theory and Practice

Chapter 8
Generic Structure to Simulate Acceptance Dynamics

Silvia Ulli-Beer, Fritz Gassmann, Mathias Bosshardt, and Alexander Wokaun

Abstract Social behaviour patterns and social equilibrium states are often guided by stable values such as social norms. However, changing environmental conditions (e.g. climate warming, resource scarcity) may require behavioural change and the acceptance of new technologies. Antecedents of aggregate behavioural change are value changes that predetermine when new behaviour patterns emerge and a new social equilibrium state can be reached. The paper addresses these phenomena. First, based on a waste recycling model, we explain these phenomena and develop a simple, generic mathematical model describing the basic traits of acceptance-rejection dynamics. Second, we propose a generic model structure for the simulation of acceptance-rejection behaviour that represents the dynamical characteristics of paradigm change processes. We show that a fourth-order potential function is a sine qua non for an adequate representation of a paradigm change. Third, we also explain why the well-known Bass model, is unable to capture acceptance and rejection dynamics.

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S. Ulli-Beer (✉) • F. Gassmann • M. Bosshardt • A. Wokaun
General Energy Dynamics of Innovative Systems, Paul Scherrer Institut, PSI Ost, Villigen 5232, Switzerland
e-mail: silvia.ulli-beer@bluewin.ch

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8.1 Introduction

Climate change and energy supply issues are triggering global socio-technological transformation processes, which are based on new technologies such as energy efficient low carbon vehicle or building technologies. In order to avoid costly, autonomous and radical change processes induced by market forces, key decision makers envision an ecological and effectively managed incremental pathway. Therefore, adequate transition management models are crucial, especially to increase the understanding of processes that influence the acceptance of new technologies.

In our paper, we define *acceptance* as the act of adoption, with approbation being a function of the attitude, the subjective norm and value system, and the perceived behavioural control (Ajzen and Fishbein 1980; Ajzen 1991). *Acceptance dynamics* describes stabilising social norm-building processes that consolidate observed behaviour patterns, and explains adjustment delays and efforts for behavioural change processes. We all know from personal experience that acceptance, either of new routines or technologies and products, is a complex process, which depends on numerous parameters and is subject to dynamics that we cannot normally understand, sometimes not even when related to our own decisions (Dörner 1980, 1993; Mathieson 1991). Our intention is to model acceptance dynamics averaged over a large population segment, rather than based on individual persons. With this simplifying condition, our problem becomes loosely related to widely used decision, choice or marketing models, such as, for example, logit, probit, or generalisations thereof (Train 2003). These models approximately describe variations of mean choices made by a population segment when attributes of products within a given product assortment change. A simple example would be the choice between different transportation systems (car, railway, bus, bicycle) characterised by attributes such as price, travelling time, number of bus/train connections per day, distance of next bus/train station, etc. The coefficients needed for these models can be derived from empirical surveys, from the literature, or from educated guesses. A precondition for successful applications of these models is constancy of the coefficients, i.e., people's general attitude towards the transportation systems considered does not change, the investigated overall system remains in the same action paradigm (Kuhn 1962; Dosi 1982). In this respect, these models are static and reversible: if, for instance, the price for gasoline (attribute for cars) rises and later falls to the previous level, the number of car users temporarily decreases and then again reaches the previous level. The state of the system is a function of the attributes only and never depends on its specific time evolution in the past; this is known in the organisational learning literature as *single loop learning* (Argyris and Schoen 1996). However, if people adapt to the transient situation of high gasoline prices and learn to value the advantages of public transport, the coefficients change and the system finds a different equilibrium after relaxation of the gasoline prices to the previous level (for the transition to innovative drive technologies see Janssen et al. 2006; Struben and Sterman 2008). Such processes are similar to the *double loop learning* concept (ibid.) and are a form of paradigm shift involving endogenous preference and value change. Such a new action paradigm also constitutes a new stable equilibrium in the social system that is stabilised by a specific behavioural norm acting as a system endogenous force. These observations indicate that acceptance models need to be able to describe a multistable system. In order to adequately describe and simulate the transition from one state to another, relationships between an endogenous norm-building process and exogenous forces such as increasing prices need to be understood. In the literature, there are several theories and first simulation frameworks (e.g. Rasmussen et al. 1985; Ulli-Beer et al. 2004) that describe such phenomena. However, their generic dynamic properties are so far only vaguely understood and described. Hence, in this paper, we will investigate the generic dynamics of acceptance, i.e., we will abstract from all specific properties of real systems and retain only their general common structure leading to the above-mentioned basic phenomena of acceptance dynamics.

The contribution of this paper is twofold:

- We describe generic characteristics of acceptance and rejection dynamics.
- We suggest generic model properties for an adequate simulation of acceptance dynamics.

Based on existing theory about complex systems and social behaviours, we will develop a conceptual understanding of acceptance phenomena from a highly aggregated perspective. Then, we will illustrate acceptance dynamics, with its basic characteristics of social behaviour (acceptance/non-acceptance of a new normative behaviour), using a simplified waste recycling model with two stable equilibria developed by Ulli-Beer et al. (2004) and Ulli-Beer (2006). We will show that a simple mathematical transformation is able to describe both extremes of acceptance and rejection dynamics. The deduced mathematical model describes a familiar physical process involving a light ball rolling downhill. Through analytical investigations and numerical experiments, we will discuss the parameters and the role of the fourth-order potential within the framework of acceptance dynamics. Further investigations show that the widely used Bass diffusion model is not qualified for adequately representing acceptance and rejection dynamics, since it does not encompass both extremes of behaviour. After establishing the understanding of acceptance dynamics in this way, we will discuss research implications and conclusions for the further development of acceptance models.

8.2 The Theoretical Foundation of Acceptance Dynamics

A linear change in the preferences for different, already existing routines may be seen as an incremental adjustment process. This characteristic leads us to call such adjustment processes *continuous change with a linear relationship between the prevalence of observed behaviour and social norm-building process*. However, in this paper, we refrain from providing pure choice models and introduce acceptance dynamics of *discontinuous change characterised by a nonlinear relationship between the prevalence of observed behaviour and social norm-building*. This change process refers to a seemingly abrupt change of preferences for newly evolving routines.

By involving the establishment of new evaluation processes and changing behaviour patterns, the acceptance dynamics model goes beyond already existing choice and continuous change models. It includes behaviour characteristics of self-organised nonlinear systems. In social sciences, self-organisation becomes visible in fashion trends, the evolution of social norms, value and belief systems, languages, or routines. Hence discontinuous acceptance dynamics comprises phenomena such as multistability, hysteresis, and critical parameter values (tipping points) (for a short overview of these concepts, see Gassmann et al. 2006). Hence, the purpose of this article is to identify, describe and analyse such generic properties for the acceptance model. In the following, we synthesise the most important concepts that explain the different choice and behaviour characteristics in social systems.

Psychological theories are helpful in understanding static choice situations. Empirically well supported theories on altruism and planned behaviour highlight the influence of a social norm (i.e. what significant others think is the right thing to do) on the personal norm (i.e. what the person him or herself thinks is the right thing to do) in a decision process. A social norm turns into a subjective personal norm as soon as it is internalised. A social norm acts as a rule and standard of a group, and guides or constrains individual behaviour. If the awareness of a problem and the ascription of responsibility are high, a social norm will translate into behaviour. Hence, the social norm acts as a stable guiding norm as long as the circumstances are not changing dramatically, generating a strong system inertia and social path dependency. A simple error detection and correction process within a fixed guiding norm is also called single loop learning, and describes a reversible adjustment process (Argyris and Schoen 1978). Argyris and Schön (1978) also explain how guiding norms are changed by a double loop learning process. In a double loop learning process, the error detection and correction process involves the modification of the guiding norms and its adjustment to a changing environment. In a social context, such a norm adjustment process is not linear, but rather nonlinear due to critical mass effects. In other words, the emergence of a new social norm needs to attain sufficient weight and power before it can replace the old norm and may influence the decision process of a huge group or the mass market. As soon as the new social norm is strong enough, a rapid change in behaviour patterns can be observed due to the endogenous goal-seeking process of the single loop learning process. Such a nonlinear norm change process is characterised by irreversibility and multistability.

With the term of acceptance dynamics, we describe decision situations that include the emergence of a new appropriate norm in a changing environment, triggering preference changes at the individual level. It describes real-world situations that might show a discontinuous change in behaviour patterns, e.g. societies that begin to recycle their garbage instead of land-filling. An adequate representation of such real-word situations with a simulation model requires the influence of the norm functions to be non-linear. This necessity is the reason why traditional choice models with constant elasticities are insufficient to represent real-world situations, which include discontinuous acceptance dynamics (see Fig. 8.1).

8.3 Modelling Acceptance Dynamics

8.3.1 The Example of Waste Recycling

To illustrate acceptance dynamics, we present a model developed by Ulli-Beer (2006) to simulate waste separation and recycling by citizens with a garbage bag charge imposed. A special weight was put on the formulation of the decision process guiding citizens' behaviour to separate their garbage by addressing interactions between contextual and personal factors (Kaufmann et al. 2001). It was assumed that people decide once whether or not to separate their garbage and thus initiate a new routine (Dahlstrand and Biel 1997). This implies that people can be divided into two main groups: a group x, which is willing to separate, and a group $1 - x$, which is not. In each group, subgroups were distinguished, mediating the transition of individuals between the main groups. Figure 8.2 shows the main structure of the model resembling an electronic flip-flop, i.e., the basic bistable device of computers. If the majority of people are willing to separate (x close to unity), the perceived social norm exerts a pressure on the remaining fraction $1 - x$

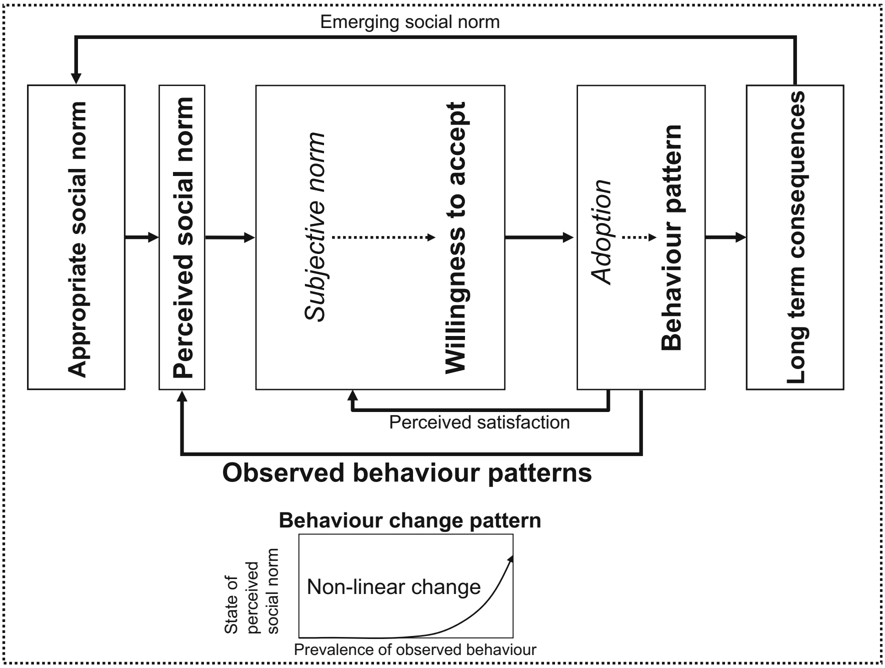

Fig. 8.1 Discontinuous acceptance dynamics that include a paradigm change due to undesired long-term consequences of the old paradigm arises in situations where behaviour patterns influence the perceived social norm *non-linearly*, hence changing the overall willingness to accept a new subjective norm after having passed a threshold value or a critical mass. In contrast to the inner *perceived satisfaction* loop, which reflects a continuous and reversible goal-seeking mechanism, the outer *nonlinear* change loop explains discontinuous and practically irreversible dynamics. It can stabilise the system in different states. In order to change a social norm, new behaviour options or patterns must become clear. Their prevalence must pass a threshold that often requires external stimulation, which induces extra transition costs

of non-recyclers and motivates them (lower processes in Fig. 8.2). These processes stabilise the system on the recycling side ($x \approx 1$). Analogously, if the majority of people are not willing to separate (x near to zero), the perceived norm will drive remaining recyclers to lose their motivation to continue and thus the system is stabilised on the non-recycling side ($x \approx 0$). The garbage bag charge helps to stabilise the recycling state of the system by compensating time investments in separating activities and other inconveniences (e.g. unattractive collection points because of overcrowding) imposed by recycling.

8.3.2 The Generic Structure of the Waste Recycling Model

To find the generic structure of the waste recycling model presented above, we simplified it by combining together all functionally related parameters and naming

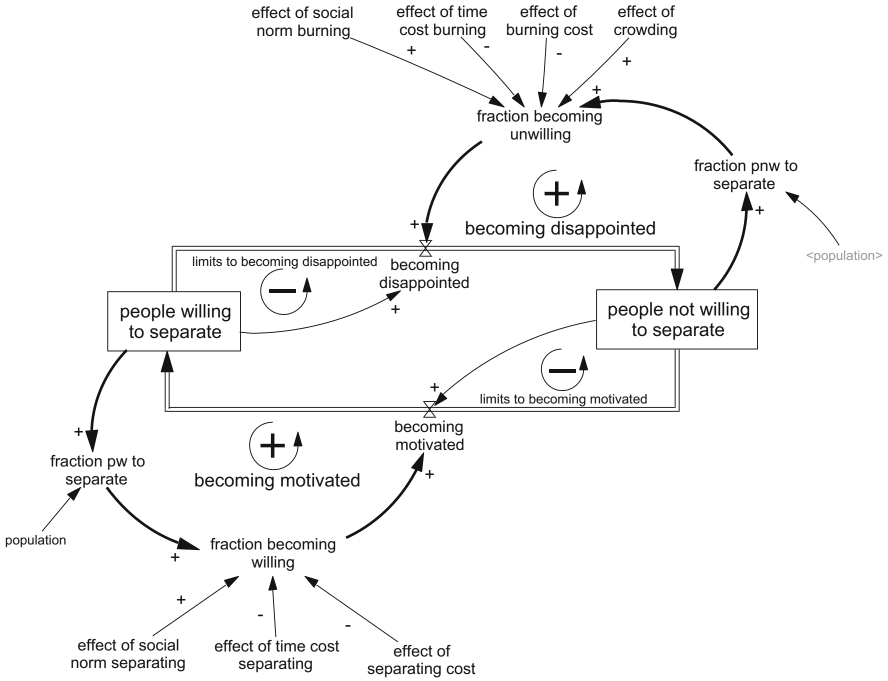

Fig. 8.2 Simplified structure of the model to simulate waste separation and recycling. Changes in citizens' willingness to separate lead to stabilisation of the system either on the recycling side or the non-recycling side (Ulli-Beer 2006: 120)

the two groups of people: adopters x and non-adopters $y = 1 - x$. The structure of this simplified model is shown in Fig. 8.3.

Two reinforcing loops are triggering exponential growth processes, while two balancing loops are limiting them. If the bandwagon loop is dominant, adopters will exhibit s-shaped growth. Hence, adoption increases to a level limited by internal norm forces and external pressure and by the number of non-adopters available to be converted. Conversely, if the parachute loop is dominant, the adopters' population shows an s-shaped decline pattern, which again is controlled by internal norm forces and external pressures as well as the decreasingly available adopters.

The mathematical transformation (see Appendix A.1) of the waste recycling model into generic form shows that the dynamics can be formulated on the basis of a function V(x):

$$\begin{gathered}\frac{dx}{dt} = -\frac{dV(x)}{dx} \\ V(x) = \frac{1}{12\tau_R} x^2 \left\{ 6\nu_2 - 4(\nu_1 + 2\nu_2)x + 3(\nu_1 + \nu_2)x^2 \right\}\end{gathered} \tag{8.1}$$

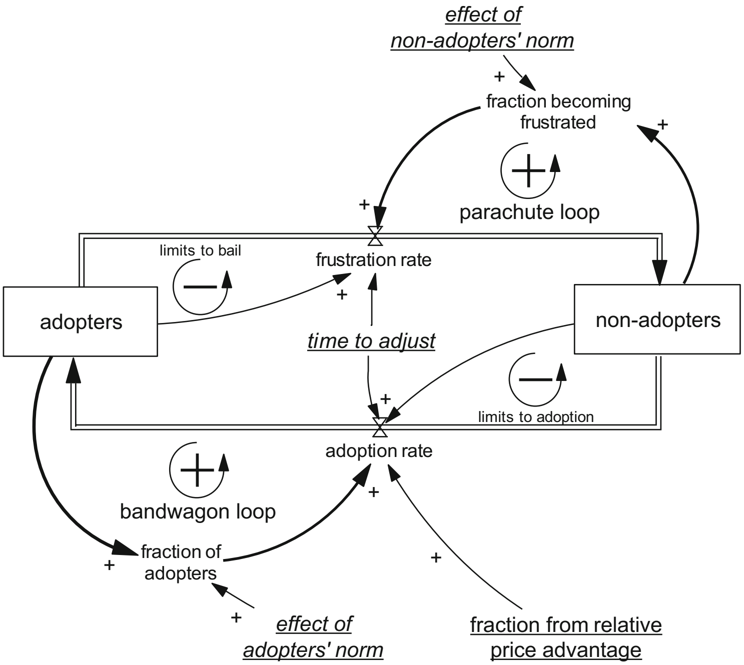

Fig. 8.3 Structure of the simplified version of the waste recycling model. Underlined text refers to parameters. The two parameters "fraction from relative price advantage" and "fraction from relative time costs" may be seen as external forces

The function V(x), represented in graphical form in Fig. 8.4 for the special (symmetric) case $\nu_1 = \nu_2$, is called "potential" in the physical sciences. The minima of V(x) are stable and the maxima are unstable equilibria or fixed points of the dynamics. *The stable minima of V(x) are created by stabilising feedback loops (limits to bail and limits to adoption)*. In our case, the *perceived social norm*, involving the two norm-weight parameters ν_1 and ν_2, is the process shaping the potential and the strength of the two reinforcing loops, which are interpreted as the endogenous executed force of the dynamic norm-building process: If most people separate waste, the non-separators are motivated to do so, strengthening the bandwagon (ν_1 = effect of adopters' norm); if most people do not separate waste, the separators lose their motivation and stop separating their waste, strengthening the parachute loop (ν_2 = effect of non-adopters' norm).

8.3.3 Behaviour of the Generic Acceptance Model

The model is able to exhibit two modes of behaviour, seeking two different equilibria. The path depends on the initial value of adopters determining the initial strength of the two reinforcing loops (see Fig. 8.5).

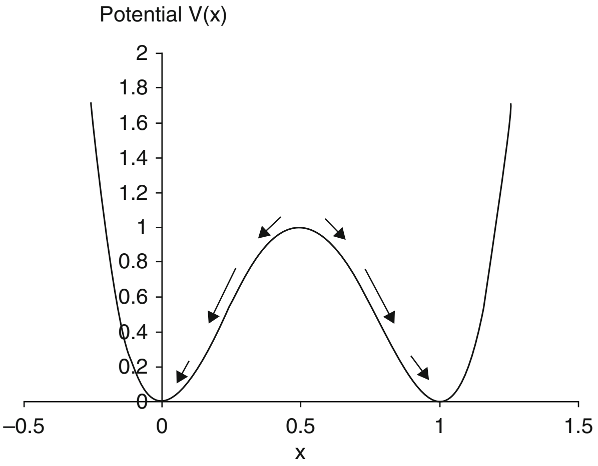

Fig. 8.4 Double-well potential (see Appendix A.2) for the symmetric case with $v_1 = v_2 = v$ and $t_R/v = 1/32$ giving $V(x) = 16 \times 2\cdot(1-x)2$. Both minima of V(x) are stable, i.e., the system state is attracted towards the two points $x = 0$ and $x = 1$, as indicated by arrows. The maximum in-between them is unstable: The dynamics Eq. 8.1 will drive the system away from the initial condition $x = 0.5$ (number of adopters equal to number of non-adopters), as soon as a small external force (e.g. a statistical fluctuation) induces a deviation from the equilibrium point $x = 0.5$

Inducing some small force such as a price advantage (see Fig. 8.3 as well as Appendix A.3) increases the adoption rate and may change the dominance of the guiding loops, leading to irreversible dynamics. This can clearly be seen in a phase plot diagram depicting the trajectory of the adoption rate versus the adopters' share. In Fig. 8.6, different cases are shown.

Without forces and with any initial deviation from the critical value of 50 % adopters share (unstable equilibrium point), the model will either seek the stable equilibrium points at one hundred percent (line 1 with an initial adopters' share of 51 %) or zero percent adopters' share (line 2 with an initial adopters' share of 49 %). Hence, lines 1 and 2 depict the internally driven development process that is dependent on its initial state.

Inducing an effective force or an incentive that is sufficiently long will lead to a behaviour change based on a shift in loop dominance. Figure 8.6a depicts this case with an initial state of 25 % adopters' share plus a constant external force that increases the adopter rate exogenously beyond the internal norm effect, which would have been too weak for a behaviour change. The transient force is maintained until an adopters' share of around 60 % is reached. When the transient force is ceased quickly, the adoption rate falls rapidly to its endogenous level. Due to the increased adoption share, the endogenous norm effect is now strong enough to maintain a successful adoption path (line 3).

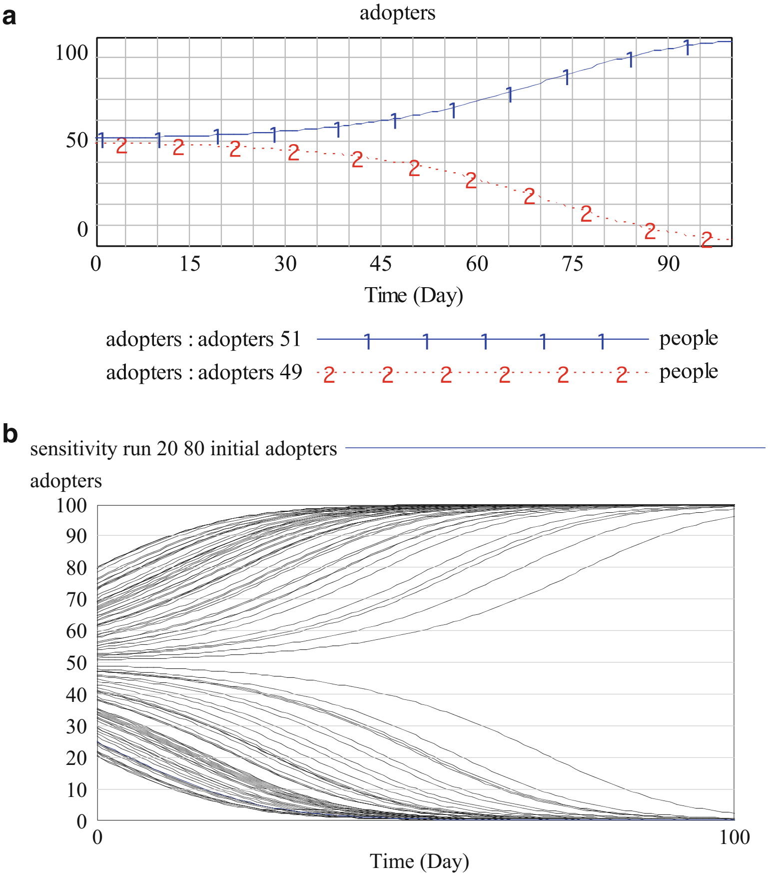

Fig. 8.5 Behaviour mode of the generic model structure. A successful initiative depends on a critical mass of adopters. Hence, the model is parameter-sensitive concerning the initial value for adopters. Given a symmetric structure as in our case, the critical value would be 50 people (50 % from 100 potential adopters). At this value, the model is in an unstable equilibrium

Additional policy experiments show that not only the magnitude but also the duration time of an incentive is decisive for an effective diffusion process. If the active time period is short, it needs a very strong force in order to induce sustained behaviour change. In Fig. 8.6b, two additional development trajectories are shown: the case of a very weak force (line 4) and the case of a stronger force that is ceased too early (line 5). As soon as the incentives are stopped, the adoption rate decreases abruptly and seeks the stable equilibrium at 0. The adoption rate may improve for a short time but cannot sustainably break the dominant parachute loop.

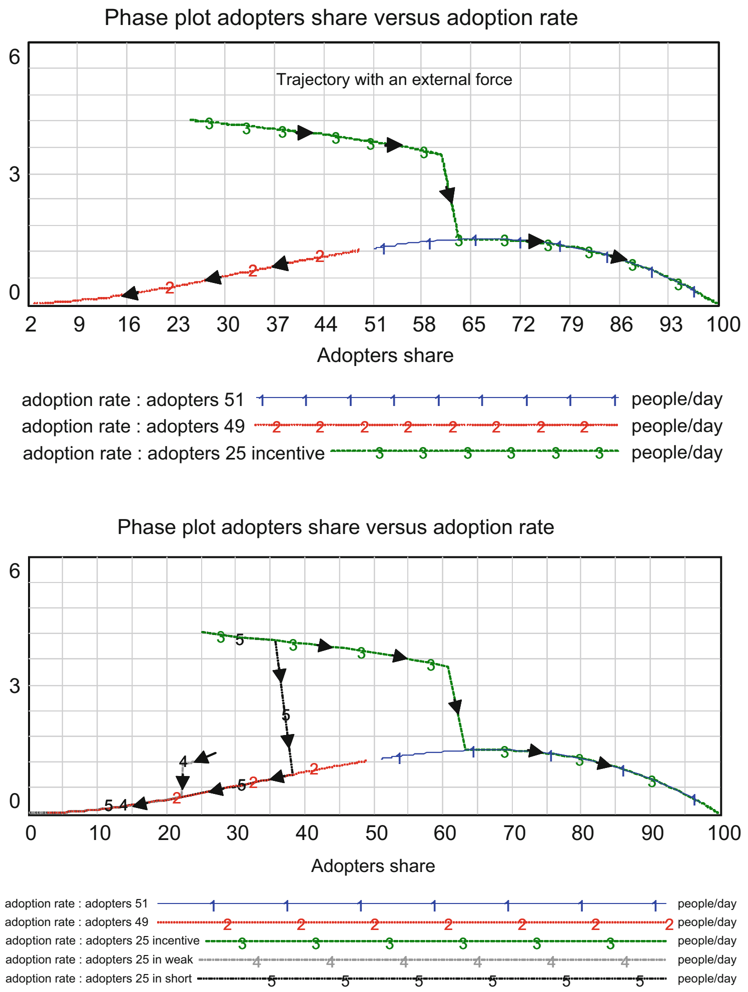

Fig. 8.6 Effect of different incentives on the adoption curve and the adoption rate. Figure 8.6a (*top*) inducing an effective transient force. Figure 8.6b (*bottom*) testing the effectiveness of different forces by a system state of 25 % adopters' share: Line 3 shows an effective transient force; Line 4 describes a too weak incentive; Line 5 shows that even a strong incentive may not be successful if its duration is too short

8.4 Model Properties

8.4.1 *The Mechanical Light-Ball Model as a Metaphor*

The model behaviour that we have analysed using simulation experiments can be compared with a light ball that is rolling on a landscape with two valleys and a ridge. Such analogous mechanical metaphors are often used in physics, chemistry, or biology, because they explain the dynamics of a process in such a way that everybody can relate to personal experience from everyday life (e.g., in Sterman 2000: 351), the ball metaphor is used for the explanation of *path dependence*). In addition to a better intuition of the dynamics of a process, the mathematical transformation allows further analyses of the model properties.

To describe the generic dynamics of the acceptance model in mathematical terms, the axes of the graph in Fig. 8.4 can be interpreted as horizontal and vertical directions in the Earth's gravity field. The double-well potential transforms into two valleys separated by a ridge in between. According to Eq. (8.1), locations with horizontal gradients are equilibrium points and the variation of x (dx/dt now called velocity) is proportional to the negative value of the slope (−dV/dx). A sphere rolling over the "orography" V(x) would show the correct equilibrium points, being stable in the valley floors and unstable on top of the ridge. However, friction is important for the sphere coming to rest in one of the two equilibria. In Appendix A.2, we show that the generic dynamics of the acceptance model are approximately reproduced by an inflated, light plastic ball with an air friction force proportional to its velocity. Such a light ball quickly finds an equilibrium between the friction force and the gravitational acceleration, resulting in a velocity that is approximately proportional to the slope at every point x. After some linear transformations, the light-ball dynamics can be written in the form[1]:

$$\begin{gathered}\alpha u = \alpha \frac{dx}{dt} = -\frac{dV}{dx} + F(t) \\ V(x) = \frac{x^2}{8\tau}\left\{\frac{x^2}{8\tau\eta} - 2\right\}\end{gathered} \tag{8.2}$$

In order to analyse the effect of policy incentives, an external force F(t) has been introduced (as explained in Appendix A.2). The stable equilibria (with F = 0) are located at

$$x_s = \pm\sqrt{8\tau\eta} \tag{8.3}$$

The parameter η *is the height of the "activation potential"* (Fig. 8.7) and τ *is the* endogenous time constant of the system near its stable equilibria xs (Appendix A.2).

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[1] The unit equation of the first equation in Eq. 8.2 is the following: kg/s · m/s = mkg/s2. α is the friction parameter with the units kg/s. In the following, we set this parameter to unity being dimensionless. Therefore, the units of velocity and force become identical.

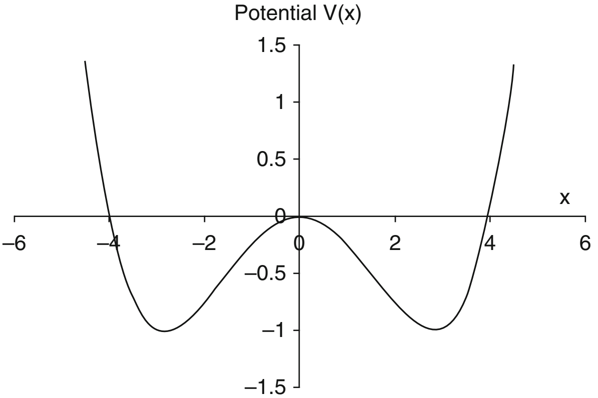

Fig. 8.7 Potential V(x) according to Eq. 8.2 for $\tau = \eta = 1$. The stable equilibria are at $x_s = \pm 2.828$, the unstable equilibrium is at $x_u = 0$. The potential is symmetric with respect to the axis $x = 0$

The generic acceptance model Eq. 8.1 becomes equivalent[2] to the mechanical light-ball model Eq. 8.2 with the following choice of its parameters:

$$\tau = \tau_R/\nu$$
$$\eta = \frac{1}{32\,\tau_R/\nu} \tag{8.4}$$

τ and η refer to the light-ball model, whereas τ_R and ν are the relevant parameters in the waste recycling model Eq. 8.4 shows that the effective time constant τ_R/ν is the only relevant parameter for this special symmetric case of the generic acceptance model.

For the more general asymmetric case, the minimum of the potential at $x = 1$ (waste is recycled) becomes higher (i.e. less stable than the minimum at $x = 0$, staying at $V = 0$), and the "ridge" separating the two minima increases and moves towards $x = 1$, with growing v_2 (see Fig. 8.4). This is plausible because, with increasing effect of the non-adopters' norm v_2, the recycling mode becomes less stable and harder to achieve, and thus would need a larger external force (e.g. garbage bag charge) to reach and stabilise the adoption mode.

8.4.2 Transient Forces and System Response

In acceptance dynamics, we call for trajectories to represent state transitions beginning at the left equilibrium point and leading to the right one. We will proceed

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[2] To make the two potentials identical, an additional linear transformation of the x-coordinate and a vertical translation would be necessary. These transformations are not relevant and are therefore omitted.

in two steps, beginning with the reaction of the system to small transient external forces. Then, we will elaborate the quite different system response to large transient forces.

System response to small transient forces: In the social sciences, the reaction of a social system to small variations of prices, taxes, subsidies, etc. are often described by elasticities e, i.e., the variables are assumed to be related by a power law $y = cx^e$. In our case, the relation between force F_0 and deviation δ is linear (see Appendix A.3, Eq. 8.31), equivalent to an elasticity $e = 1$, and our constant τ is the proportionality coefficient (c in the relation $y = cx^e$). Note that in our light-ball model, τ also describes the endogenous relaxation time, i.e., τ is at the same time a system-internal time constant and a proportionality coefficient for the limit of small forces. This is a generic result that holds for every potential V(x), as shown in Appendix A.3. It should also be noted that the system always relaxes to the original equilibrium (here to $x_s = -2.828$) when the small external force is removed, i.e., the system does not learn, and nor is there any paradigm change in this fully reversible case.

System response to large transient forces: For large external forces, analytical calculations become difficult due to the non-linearities of V(x). Here, simulations come into play and help us to understand the basic dynamics of the system. By imagining a light ball pushed by an external force over the central ridge of the potential V(x) (see Fig. 8.7), it is clear that a transition from the negative to the positive attractor (due to a shift in loop dominance, a paradigm change, or double-loop learning) cannot happen unless the external force F brings the system at least to the local maximum of the potential at $x = 0$. From there, the internal dynamics drive the system downhill to either attractor without any force applied. To reach $x = 0$ by application of a constant force F_0 during a time interval T, two conditions must be fulfilled: F_0 must exceed the largest opposing force exerted by the potential V(x) and T must be sufficiently long to allow the system to reach $x = 0$. The respective necessary conditions are the following:

$$\begin{aligned} F_0 &> \max\left\{\frac{dV}{dx}\right\} = \sqrt{\frac{8\eta}{27\tau}} \\ F_0 T &> \sqrt{8\tau\eta} \end{aligned} \tag{8.5}$$

The first condition states that the force F_0 has to exceed the maximum slope of V(x) (see Appendix A.3, Eq. 8.40). The second condition represents the fact that the system state x has to be pushed from the left equilibrium point to zero by the force F_0 (see Appendix A.3, relation Eq. 8.41).

Figure 8.8 shows the simulated product $F_0 \cdot T$ (called transition cost as it is the product of the applied force, e.g., subsidies, taxes, with the time during which the force must be active) as a function of the applied force that is necessary to bring the system to the critical point $x = 0$. The graph clearly indicates when the relations Eq. 8.5 are good approximations: The minimum force necessary to induce a

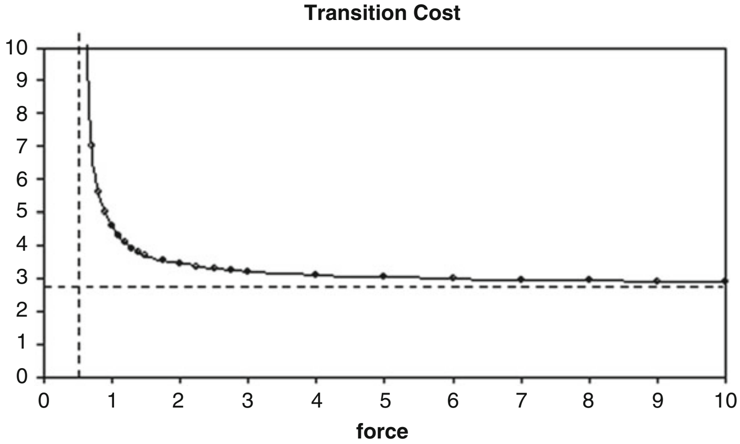

Fig. 8.8 Transition cost ($F_0 \cdot T$) versus force (F_0) for $\tau = \eta = 1$ necessary to bring the system to the critical point $x = 0$. The broken vertical line shows the first condition and the broken horizontal line the second condition of Eq. 8.5. To induce a state transition, a minimum force of about 0.5 is needed; the lowest transition cost of nearly 3 is approximated when large forces are applied

transition, described by the first inequality, holds for *small forces* (for this case, the second inequality gives far too low transition costs). For *large forces*, the potential becomes negligible and the zero-potential limit (second inequality in Eq. 8.5) becomes a good approximation (in this case of large forces, the first inequality is fulfilled anyway). Figure 8.8 clearly demonstrates that the cheapest way (i.e. resulting in the lowest cost) to induce a transition is to apply large forces (realistically around four to six times the minimum force). As soon as the critical point of the system (at $x = 0$) is passed, its internal dynamics will drive it into the second equilibrium, and an external force is no longer needed.

These results confirm the behavioural characteristics described by the simulation experiments above, but also go beyond these by highlighting not only conditions for successful transition but also efficient ones.

8.4.3 The Bass Model as a Simplified Acceptance Model

Generic models can be useful to detect common as well as distinctive properties of related models. We demonstrate this by showing that our generic acceptance-rejection model comprises the widely used Bass model (Bass et al. 2000). We first show that the two models are nearly equivalent for specific parameter values describing the case of a successful acceptance regime. We also describe the mathematical properties of the two models, which explain why the acceptance model is able to represent both acceptance *and* rejection behaviour while the bass model only describes a successful acceptance regime.

According to Appendix A.4, it is straightforward to bring our light-ball model into approximate coincidence with the Bass model. We identify

- The normalised number of items sold with the system state:

$$F = x$$

and the selling rate with the velocity of the ball:

$$f = u = dx/dt$$

- $x_s + F_0\tau$ with the ultimate market potential set to 1:

$$\eta \approx \frac{(1 - F_0\tau)^2}{8\tau}$$

This condition follows from relations Eqs. 8.42 and 8.31 in Appendices A.3 and A.4, respectively.

- The coefficient of innovation with the external force:

$$p = F_0$$

- The coefficient of imitation with the inverse of the internal time constant:

$$q = 1/\tau$$

With these equivalences, the constant sale rate Eq. 8.47 for small t becomes identical in both models. This linear growth of the normalised number of items sold is followed by an exponential growth in both models, with the only difference being that the ball model (cf. Eq. 8.43) has a time constant twice as large compared to the Bass model (cf. Eq. 8.49), i.e., the ball model grows more slowly than the Bass model. The position of the maximum slope (x) becomes $1/3^{1/2} \approx 0.58$ (on the y-axes) in the ball model Eq. 8.44, being slightly larger than in the Bass model, where the maximum slope is found near 0.5 Eq. 8.50. This difference affects maximum sale rates: Comparison of Eqs. 8.44 and 8.50 shows that maximum sale rates are $27^{1/2}/4 \approx 1.3$ times smaller in the ball model than in the Bass model. For the market saturation phase (i.e. $D = x$ near to unity), both models show an exponential approximation of the ultimate market potential with the same time constant $q = 1/\tau$ (comparison of Eqs. 8.27 and 8.52). Figure 8.9 shows respective trajectories for both models for $p = 0.01$ and $q = 0.1$.

It should be added here that the two models could be made *exactly identical* by replacing the fourth-order potential Eq. 8.2 of the ball model by an appropriate third-order potential with only one instead of two minima (see Eq. 8.53).

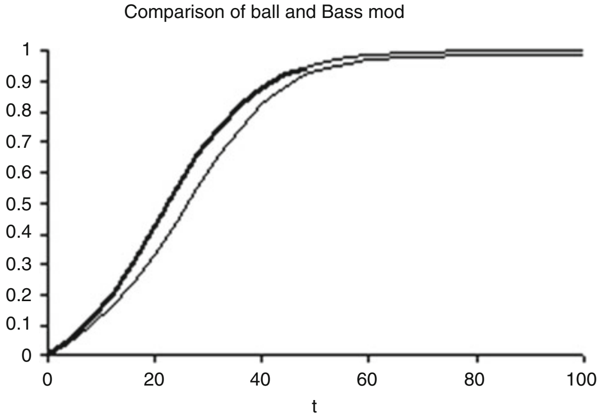

Fig. 8.9 The ball model (*thin line*) is compared to the respective Bass model (*thick line*) for $p = 0.01$ and $q = 0.1$. As explained in the text, the ball model is somewhat lower after the initial linear growth phase

It is important to understand that the ball model can be simplified to the Bass model by replacing the fourth-order potential with a third-order potential. As the third-order potential has only one minimum, the respective model (i.e. the Bass model) is limited to describing only successful market diffusion into one stable state (the ultimate market potential). However, to represent acceptance *and* rejection behaviour, a potential with two minima (i.e. at least of fourth-order) is required. In the acceptance model, the fourth order results from the non-linearity of the norm building process. The behavioural implication between one and two minima is a fundamental difference. With two minima, new phenomena arise, such as multistability (acceptance and rejection), hysteresis and critical parameter values (social norm effects).

8.5 Discussion and Research Implications

We realised that the term generic is associated with somewhat different meanings in different scientific communities. Our interpretation of a generic model throughout this paper is compatible with Paich (1985), and states that it should give the basic qualitative properties of a phenomenon by abstracting from all less important specific properties. However, the separation of important from less important properties cannot be made by a procedure based on first principles and always includes some subjective freedom or “grey zone”. Generic can be understood on different levels. The higher the level of details, the more realistic, interesting and colourful a description becomes, but also more different types arise. The differentiation process can be continued, leading to a tree-like structure. On each higher level, more and more specific descriptors will be necessary. The characteristic feature of this differentiation is an ever growing difficulty of distinguishing between the different types the higher the level is. The questions about generic models lie at the very heart of modelling science and help to structure the "modelling landscape". We can recall here that this same idea was expressed by Jay W. Forrester at the end of his banquet talk at the 1989 System Dynamics Conference at the University of Stuttgart (Germany): "Whether we think of pre-college or management education, the emphasis will focus on *generic structures*. A rather small number of relatively simple structures will be found repeatedly in different business, professions, and real-life settings."

Another open question concerns our choice of a physical model (a light ball rolling downhill) to describe a social phenomenon. It is a fact (but also an unanswered philosophical question) that simple mathematical equations can be used to describe basic physical phenomena. As it is good modelling practice to start with a simple model for acceptance dynamics, it is no surprise that such an approach can be interpreted in a physical way. The advantage of this circumstance is our deep understanding of light-ball behaviour based on our experience gained from childhood, which helps us understand directly the solution manifold of the differential equation defining our acceptance model. It is this understanding that helped us to conjecture the basic equivalence of the Bass diffusion model with our generic acceptance model.

The physical analogue helps us even further, namely to extend the presented model to include additional phenomena. A natural extension would be to introduce the acceleration term of the Newtonian equation, $m \cdot du/dt$, which was neglected for a first version of the model. This term would allow overshoot and damped oscillations and the physical analogue would be a *heavy* sphere rolling downhill. Another extension would be the introduction of a stochastic external force or *noise* (in the physical literature; this would be called a "coupling to a heat bath with temperature T" defining the variance of the fluctuations). This extension would replace the description of an average population by the description of an ensemble of individuals being subjected to numerous external influences pushing in all directions (Rahn 1985). Again, physics would guide our intuition to anticipate the range of phenomena we could expect by this extension. Among other effects, we would expect the following phenomena (for an overview on noise phenomena, see the introduction of Gassmann (1997)):

- Noise-induced state transitions: a part of the population (expressed by a probability) would "cross the hill towards the other state" even in the absence of a constant external force F. Within the innovation theory, this part is called "innovators". In chemistry, this generic effect leads to chemical equilibria (mixture of reactants and products of a reaction) which depend on temperature. The (light or heavy) ball analogy makes this dependence plausible and understandable without first deducing it from the mathematical equations. We understand, for example, that the fraction (probability) of the population sitting in the lower valley would be higher than the fraction in a higher positioned valley (for the case of an asymmetrical potential V(x)): The chemical reactions run from higher internal energy to lower internal energy, the height of the activation potential (i.e., the hill separating the two valleys) together with temperature defining the reaction rate (Arrhenius law). In the framework of social behavioural models, noise would establish a link to choice models such as, e.g., the well-known logit model.

- *Noise-induced oscillations*: in the heavy ball model, noise would activate the system to oscillate in its eigenfrequency around a stable equilibrium.
- *Stochastic resonance*: The effect of a small external force is amplified by the presence of noise. This counter-intuitive effect makes some marine animals hear very weak sound signals in the presence of large background noise produced by wave-induced turbulence (Sutera 1981; Dykman et al. 1995).

The above given examples for natural extensions of our generic acceptance model show some far-reaching effects resulting from the introduction of simple new terms into the governing equation. Further research will show which extensions make the most sense for application within a socio-economic framework.

8.6 Conclusions

We have shown that the simple dynamics $dx/dt = -dV(x)/dx + F$, representing a light ball rolling over a double-well potential V and being influenced by an external force F, is able to describe

- The linear reaction of the system resulting from small forces
- The acceptance behaviour resulting from large transient forces
- The dependence of transition cost on the magnitude of the force
- The waste recycling model of Ulli-Beer (2006)
- The Bass diffusion model

and helps to make the class of acceptance phenomena turn into a more tractable issue. In the discussion, we made clear that this generic model can be extended to higher levels of detail. It has the potential to inspire model development and to generate new research questions, e.g., for the systematic investigation of acceptance dynamics in innovation systems, leading to a better understanding of socio-technological transformation processes.

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Appendix

Generic Structure of the Waste Recycling Model

The 50 parameters and 33 nonlinear functions of the original waste recycling model have been reduced to the two parameters P and τ_R, and the two functions f(x) and g(y) with the following meanings:

P = overall population
X = number of adopters
Y = number of non-adopters
τ_R = time to adjust
f(x) = influence of the adopters' norm on non-adopters
g(y) = influence of the non-adopters' norm on adopters

The dynamical equations of the simplified model are

$$\begin{aligned}\frac{dx}{dt} &= p(x,y) - q(x,y)\\ \frac{dy}{dt} &= q(x,y) - p(x,y)\end{aligned} \tag{8.6}$$

with the condition

$$P = x + y \tag{8.7}$$

and the two functions being defined by

$$\begin{aligned}p(x,y) &= \frac{f(x)/P}{\tau_R}y\\ q(x,y) &= \frac{g(y)/P}{\tau_R}x\end{aligned} \tag{8.8}$$

The two dynamical Eq. 8.6 for the two population groups x and y, together with the condition Eq. 8.7, can be expressed by one dynamical equation for x, describing the balance of the adoption rate p(x,y) and the frustration rate q(x,y). These two rates are defined symmetrically with the functions f(x) and g(y), and involve the time constant τ_R Eq. 8.8. The influence f(x) of the adopters' norm on non-adopters vanishes for x = 0, because there is no adopters' norm established without adopters. With only a few adopters, their influence is still negligible, suggesting a horizontal tangent f'(0) = 0. With an increasing number of adopters, however, their influence becomes important. The most simple functions f(x), and analogously g(y), which fulfil these three conditions, are quadratic polynomials:

$$\begin{aligned} f(x) &= \nu_1 \cdot x^2 \\ g(y) &= \nu_2 \cdot y^2 \end{aligned} \tag{8.9}$$

The two new parameters ν_1 and ν_2 describe the strength of the effect of the adopters' norm and the non-adopters' norm, respectively. We apply the following normalisation to further simplify the equations:

$$\begin{aligned} x' &= \frac{x}{P} \\ y' &= \frac{y}{P} = 1 - x' \\ \nu'_1 &= P \cdot \nu_1 \\ \nu'_2 &= P \cdot \nu_2 \end{aligned} \tag{8.10}$$

With the substitutions Eq. 8.10, the dynamical Eq. 8.6 take a simple form. For the sake of convenience, the dashes are omitted in the following:

$$\frac{dx}{dt} = \frac{\nu_1 + \nu_2}{\tau_R} x(1 - x)\left(x - \frac{\nu_2}{\nu_1 + \nu_2}\right) \tag{8.11}$$

Equation 8.11 can be transformed into the following elegant form including a potential V(x):

$$\frac{dx}{dt} = -\frac{dV(x)}{dx} \tag{8.12}$$

With the potential V(x) according to Eq. 8.13, the generalised Eq. 8.12 becomes identical to the special dynamics Eq. 8.11:

$$V(x) = \frac{1}{12\tau_R} x^2 \left\{6\nu_2 - 4(\nu_1 + 2\nu_2)x + 3(\nu_1 + \nu_2)x^2\right\} \tag{8.13}$$

This double-well potential (a polynomial of fourth order) has the following extremes:

$$\begin{aligned} V(0) &= 0 \\ V(1) &= \frac{\nu_2 - \nu_1}{12\tau_R} \\ V\left(\frac{\nu_2}{\nu_1 + \nu_2}\right) &= \frac{1}{12\tau_R}\left(\frac{\nu_2}{\nu_1 + \nu_2}\right)^3 (2\nu_1 + \nu_2) \end{aligned} \tag{8.14}$$

The first two extremes at x = 0 and x = 1 are stable minima and the third is an unstable maximum in between. In general, the potential Eq. 8.13 is asymmetric, because the minimum at x = 1 is above or below the x-axis, if ν_2 is larger or smaller than ν_1, respectively. For the special symmetric case $\nu_1 = \nu_2 = \nu$, the extremes Eq. 8.14 of the potential Eq. 8.13 simplify to:

$$\begin{aligned} V(0) &= 0 \\ V(1) &= 0 \\ V\left(\frac{1}{2}\right) &= \frac{1}{32\tau_R/\nu} \end{aligned} \tag{8.15}$$

The graph of this symmetric double-well potential is shown in Fig. 8.4 in the main text. Within the framework of the waste recycling model, the variable x (percentage of adopters) is confined to the interval between 0 and 1. To make the stable minima better visible, the potential V(x) is given for an extended x-range.

Our analysis shows that at least one of the two functions f(x) and g(1 − x), describing the effect of the perceived social norms, must be nonlinear to be able to lead to two simultaneously stable minima of the potential V(x). If both functions are assumed to be linear, the respective potential is a third-order polynomial with only one global minimum at x = 0 or at x = 1 (y = 1 − x) for the slope of f being smaller or larger than the slope of g, respectively. For this case with linear functions f and g, the basic character of the system would be different: As soon as the effect of the adopters' norm had a larger slope than the effect of the non-adopters' norm, the system would undergo a transient from x = 0 (not recycling) to x = 1 (recycling), without any external force (garbage bag charge) needed. For the case that the slope of the effect of the adopters' norm would be smaller compared to that of the non-adopters' norm, a garbage bag charge would push the system towards x = 1, but no paradigm change would occur, stabilising this state: As soon as the charge were relieved, the system would fall back to x = 0. This analysis demonstrates that *one of the most important decisions during the modelling process is the choice of the shape of the norm-functions f and g*. In the model validation process, observational evidence suggesting linear or nonlinear norm functions would therefore be of prime importance.

Another remark concerns the discrepancy of the numbers of parameters and functions between the full model and the simplified generic model. In every model useful for practical purposes, a large number of parameters are needed, because the important effective parameters (in our case τ_R, ν_1 and ν_2) must be related to practically relevant input parameters. The strength of the generic model, however, is not its application to simulate observed processes, but to help us understand its basic behaviour and to give us an idea of its solution manifold. It contains only a very limited number of effective parameters and functions, and thus shows us *the relevant combinations of parameters and functions* defining the trajectories to be expected.

The Light-Ball Metaphor

We consider a light air-inflated plastic ball with mass m moving downhill with velocity u. Its dynamics can be formulated with the notion of *potential energy* V(x) (in the physical literature, V(x) is called *gravitational potential*) in the following way:

$$
\begin{aligned}
V(x) &= m \cdot g \cdot h(x) \\
m \cdot \frac{du}{dt} &\approx -\frac{dV}{dx} - \alpha \cdot u \\
u &\equiv \frac{dx}{dt}
\end{aligned}
\tag{8.16}
$$

where g is the gravitational acceleration, t is time, and h(x) describes the height of a graph of the potential function V(x) with one horizontal dimension x. Multiplication of the slope dh/dx by -mg gives the force -dV/dx accelerating the ball downhill.[3] The term $-\alpha \cdot u$ describes the frictional braking force of the air (according to Stokes' law, this frictional force is proportional to velocity u). Our experience tells us that such a light ball, after a short initial acceleration phase, rolls downhill at a constant speed, only depending on the slope. To simplify our dynamics Eq. 8.16, we therefore neglect the inertia term by setting

$$
m \cdot \frac{du}{dt} = 0 \tag{8.17}
$$

and find the approximate dynamics:

---

[3] Relations (B-1) are an approximation for small slopes. For an infinite slope, the force according to (B-1) becomes infinite, in contrast to the physical force for the free fall being -mg. However, this discrepancy for steep slopes does not disturb our metaphor, because in real applications, slopes are normally small.

$$u = -\frac{dV}{dx} \tag{8.18}$$

The parameter α has been set to unity because it does not affect the character of the solutions of Eq. 8.18. In the physical literature, this approximation is called *overdamped limit*, because the respective system approaches an equilibrium point gradually rather than with damped oscillations. This property can be demonstrated, e.g., for the equilibrium point in a quadratic potential V = x^2 situated at x = 0. Introducing this most simple nonlinear potential into Eq. 8.18 gives

$$u \equiv \frac{dx}{dt} = -\frac{d}{dx}x^2 = -2x \tag{8.19}$$

with the solution

$$x(t) = x_0 e^{-2t} \tag{8.20}$$

where x_0 is the initial position of the ball and t is time. Equation 8.20 describes a trajectory approaching the equilibrium point x = 0 gradually, without oscillations. Mathematically, the ball would need an infinite amount of time to reach x = 0, but for practical applications, t = 3 is already sufficient, giving a distance to zero of less than 1 % of the initial value x_0.

For a multistable system, we need at least two stable equilibria, described by a double-well potential V(x). A simple form of such a potential is a polynomial of fourth order:

$$\begin{aligned} V(x) &= ax^2\{x^2 - 2\mu^2\} \\ -\frac{dV}{dx} &= -4ax\{x^2 - \mu^2\} \end{aligned} \tag{8.21}$$

To prevent the ball escaping to infinity, we assume a ≥ 0. At x = 0, we find an unstable equilibrium, and two locally stable equilibria are located at x = ±μ. Combined with Eq. 8.18, we get the following dynamics:

$$\frac{dx}{dt} = -4ax\{x^2 - \mu^2\} \tag{8.22}$$

To assign simple meanings to the two parameters a and μ, we define two new parameters τ and η (their meanings will be explained below):

$$\begin{aligned}\tau &= \frac{1}{8a\mu^2} \\ \eta &= a\mu^4\end{aligned} \tag{8.23}$$

and write the dynamics Eqs. 8.21 and 8.22 with these new parameters:

$$\begin{aligned}\frac{dx}{dt} &= \frac{x}{2\tau}\left\{1-\frac{x^2}{8\tau\eta}\right\}+F(t) \\ V(x) &= \frac{x^2}{8\tau}\left\{\frac{x^2}{8\tau\eta}-2\right\}\end{aligned} \tag{8.24}$$

In addition, an external force F(t) has been introduced. The stable equilibria (with F = 0) are now located at

$$x_s = \pm\sqrt{8\tau\eta}$$

The parameter η *is the height of the "activation potential"* (e.g. the unstable equilibrium) with its top at $x_u = 0$ lying in between the two stable equilibria at x_s, as can easily be verified:

$$V(x_u) - V(x_s) = 0 - \frac{8\tau\eta}{8\tau}\left\{\frac{8\tau\eta}{8\tau\eta}-2\right\} = \eta \tag{8.25}$$

τ is the endogenous time constant of the system near its stable equilibria x_s. This can be verified by linearisation of the dynamics around x_s. To this aim, we replace x with the new coordinate ξ, being the distance from x_s:

$$\xi = x - x_s \tag{8.26}$$

After introducing Eq. 8.26 into Eq. 8.24, we linearise the dynamics for small ξ and get the approximate differential equation for the trajectory in the neighbourhood of the stable equilibria

$$\frac{d\xi}{dt} \approx -\frac{1}{\tau}\xi \tag{8.27}$$

with the solutions

$$\xi(t) \approx \xi_0 e^{-\frac{t}{\tau}} \tag{8.28}$$

ξ_0 is the initial position of the ball at $t = 0$. By definition, τ is the time constant for the relaxation of the system to its equilibrium point $\xi = 0$, which had to be shown.

For a graphical representation of the potential V(x) according to Eq. 8.24 for $\tau = \eta = 1$, see Fig. 8.7 in the main text.

Light-Ball System Response to Transient Forces

Small Transient Forces

We apply a small constant force F_0 and ask for the deviation δ from the force-free equilibrium point at position $x_s = -(8\eta\tau)^{1/2}$:

$$\delta = x + \sqrt{8\tau\eta} \tag{8.29}$$

We substitute x in Eq. 8.24 by δ according to Eq. 8.29 and ask for the stationary solution by setting the time derivative to zero. This leads to the following relation between F_0 and δ:

$$\delta\left\{\delta^2 - 3\delta\sqrt{8\tau\eta} + 16\tau\eta\right\} = 16\tau^2\eta F_0 \tag{8.30}$$

For small δ, the bracket in Eq. 8.30 reduces to the constant term and we get approximately:

$$\delta \approx F_0 \cdot \tau \tag{8.31}$$

An example for a dynamical simulation with $F_0 = 0.1$ is given in Fig. 8.10. Note that the bracket of Eq. 8.30 reads for $\tau = \eta = 1$ and $\delta = 0.1$: $(0.01 - 0.85 + 16)$. Clearly, the first two terms are negligible compared to the constant third term!

The internal time constant τ of the system is identical to the proportionality constant mediating between an applied small external force and the resulting deviation δ according to Eq. 8.31. To prove this generic result, we approximate an arbitrary potential V(x) around one of its minima by a second-order polynomial:

$$V(\xi) = \frac{\xi^2}{2\tau} \tag{8.32}$$

with the coordinate ξ being the distance from the respective minimum. From the dynamic equation

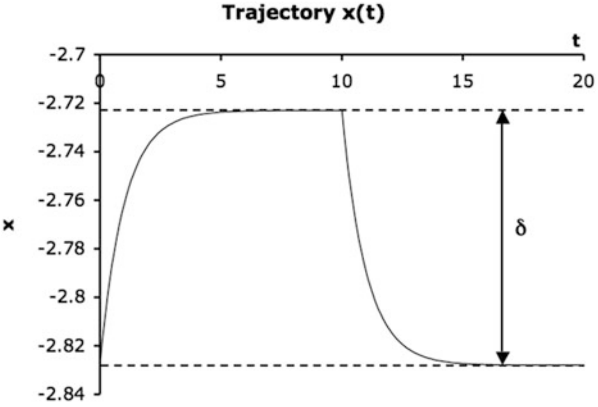

Fig. 8.10 Trajectory beginning at the left equilibrium (xs = −2.828) for a constant external force F0 = 0.1 in the time interval t = 0…10. For t > 10, F0 = 0 is assumed. After a few τ have elapsed, a new equilibrium position is found with a distance δ from the stable force-free equilibrium point. The simulated δ is 0.105, as indicated by the double arrow. The approximation Eq. 8.31 gives δ = 0.100, only 5 % smaller than the simulated δ.

$$\frac{d\xi}{dt} = -\frac{dV}{d\xi} + F_0 = -\frac{\xi}{\tau} + F_0 \tag{8.33}$$

with the solution

$$\xi(t) = \xi_0 \cdot e^{-\frac{t}{\tau}} \tag{8.34}$$

for $F_0 = 0$, we immediately find the first meaning of τ being the system-internal relaxation time constant. From the same dynamical Eq. 8.33, we get the deviation δ of the equilibrium point for small forces F_0

$$\frac{d\xi}{dt} = 0 = -\frac{\delta}{\tau} + F_0 \tag{8.35}$$

leading directly to Eq. 8.31, where τ has the second meaning as a proportionality constant between an applied small external force and the resulting deviation.

Large Transient Forces

To induce a transition from the left equilibrium point to the right, the transient force F_0 must be able to push the ball up the steepest slope of V(x). With the dynamic equation

$$\frac{dx}{dt} = -\frac{dV}{dx} + F_0$$
$$V(x) = \frac{x^2}{8\tau}\left\{\frac{x^2}{8\tau\eta} - 2\right\} \tag{8.36}$$

this first condition is equivalent to

$$\frac{dx}{dt} = -\frac{dV}{dx} + F_0 > 0 \tag{8.37}$$

for the most positive slope of V(x) occurring at x_m with

$$\left.\frac{d^2V}{dx^2}\right|_{x_m} = 0 \tag{8.38}$$

From Eqs. 8.36 and 8.38, we find

$$x_m = -\sqrt{\frac{8}{3}\tau\eta} \tag{8.39}$$

leading with Eq. 8.37 to the *first necessary condition*

$$F_0 > \sqrt{\frac{8}{27}\frac{\eta}{\tau}} \tag{8.40}$$

Another condition to induce a transition refers to the duration T of the force F_0. For the best case of a flat potential V(x) = 0, Eq. 8.37 defines a constant velocity dx/dt = u = F_0. With this velocity u, the system state must travel at least from the left equilibrium point to zero during T, giving the *second necessary condition*

$$u \cdot T = F_0 \cdot T > \sqrt{8\tau\eta} \tag{8.41}$$

Bass Dynamics with the Light-Ball Model

We define the system state x of the *light-ball model* as the number of items sold until time t and concentrate on the portion of the potential V(x) between x = 0 and x = $x_s + F_0\tau$ (x_s = positive stable equilibrium for $F_0 = 0$). The system dynamics with small external force $F_0 > 0$, according to Eqs. 8.2 or 8.24, is the following:

$$\frac{dx}{dt} = \frac{x}{2\tau}\left\{1 - \frac{x^2}{8\tau\eta}\right\} + F_0 \tag{8.42}$$

For small x, Eq. 8.42 reduces to dx/dt = F_0 leading to a linear growth of x. At larger x, for $x^2 << 8\tau\eta$ and $F_0 << x/(2\tau)$, we find approximately an exponential growth of x with time constant 2τ:

$$x(t) \approx x_0 e^{\frac{t}{2\tau}} \tag{8.43}$$

For x_m with maximum slope of V(x), F_0 can be neglected and we find:

$$\begin{aligned} x_m &\approx \sqrt{\frac{8\tau\eta}{3}} \\ \frac{dx}{dt} &\approx \sqrt{\frac{8\eta}{27\tau}} \end{aligned} \tag{8.44}$$

Finally, for x near the equilibrium $x_s + F_0\tau$, we find an exponential approximation with time constant τ according to Eq. 8.27.

The *Bass model* is generally presented in the following form:

$$\frac{f(t)}{1 - F(t)} = p + qF(t) \tag{8.45}$$

where f(t) stands for the sale rate of a product and F(t) for the total amount of items sold until time point t. p is called *coefficient of innovation* and q is the *coefficient of imitation*. If we use the relation f = dF/dt, we can write the Bass model in the form:

$$\frac{dF}{dt} = (p + qF)(1 - F) \tag{8.46}$$

For small F (near t = 0), the dynamics reduces to

$$\frac{dF}{dt} \equiv f \approx p \tag{8.47}$$

giving a constant sale rate f = p and a linear increase of the total amount F of items sold. For a time interval, where qF > > p and F << 1, the approximate dynamics are

$$\frac{dF}{dt} \equiv f \approx qF \tag{8.48}$$

leading to an exponential growth of both, F and f with time constant 1/q:

$$\begin{aligned} F(t) &\approx F_0 e^{qt} \\ f(t) &\approx qF_0 e^{qt} \end{aligned} \tag{8.49}$$

The maximum slope of F (maximum selling rate f) is found from Eq. 8.46 at F_m lying near 50 % of the ultimate market potential (which is normalised to 1) for the majority of situations characterised by $p << q$:

$$\begin{aligned} F_m &= \frac{1}{2}\left(1 - \frac{p}{q}\right) \approx \frac{1}{2} \\ f_m &\approx \frac{q}{4} \end{aligned} \tag{8.50}$$

For F near to unity, we find from the approximated dynamics

$$\frac{dF}{dt} \approx q(1 - F) \tag{8.51}$$

the trajectory

$$F(t) \approx 1 - e^{-qt} \tag{8.52}$$

i.e., an exponential approximation of the ultimate market potential with a time constant 1/q.

By comparing each of the three phases (initial linear growth, exponential growth, final exponential approximation of the ultimate market potential) described by the two different models, we find the following equivalences:

- By definition

$$F = x$$

- Following from the definition

$$f = u = dx/dt$$

- $x_s + F_0\tau = 1$ and $x_s^2 = 8\tau\eta$

$$\eta \approx \frac{(1 - F_0\tau)^2}{8\tau}$$

- Equation D-1 for small x compared with Eq. 8.47

$$p = F_0$$

- Time constant τ from Eq. 8.27 compared with Eq. 8.52

$$q = 1/\tau$$

It should be added here that the two models could be made *exactly identical* by replacing the fourth-order potential Eq. 8.24 of the ball model with the third-order potential

$$V(x) = \frac{x}{\tau}\left\{\frac{x^2}{3} - \frac{x}{2}(1 - F_0\tau) - F_0\tau\right\} \tag{8.53}$$

Here, F_0 would no longer be an external force, but an additional parameter shaping the potential V(x). Equation 8.53 is proven to be correct by the substitutions x → F, $1/\tau \rightarrow q$, $F_0 \rightarrow p$ and comparing dF/dt = −dV(F)/dF with Eq. 8.46.

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Chapter 9

Social Dynamics Overriding Utility Evaluations for Good and Bad: Implications for the Design of Sustainable Food Security Policies in Sub-Saharan African Countries*

Birgit Kopainsky, Katharine Tröger, Sebastian Derwisch, and Silvia Ulli-Beer

Abstract Sub-Saharan African economies depend heavily on agriculture. Seed from improved varieties and other inputs are imperative to the transformation of the agricultural sector from subsistence farming to small-scale commercial agriculture and thus to increasing food security on the continent. Farmers make the decision to adopt seed from improved varieties based on a number of seed attributes. These range from tangible attributes such as input costs and yield to intangible attributes such as trust in seed from improved varieties. In the course of adoption decisions, social dynamics involving trust can over-ride objective evaluations of tangible attributes. This makes it difficult to design sustainable adoption policies in an intuitive way. For this purpose we develop a system

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B. Kopainsky (✉)
System Dynamics Group, Department of Geography, University of Bergen, Postbox 7800, 5020 Bergen, Norway
e-mail: birgit.kopainsky@geog.uib.no

K. Tröger
Agri-food and Agri-environmental Economics Group, Institute for Environmental Decisions, ETH Zurich, Sonneggstrasse 33, 8092 Zurich, Switzerland

S. Derwisch,
System Dynamics Group, Department of Geography, University of Bergen, Postbox 7800, 5020 Bergen, Norway

Consultative Group on International Agricultural Research, Central Advisory Service on Intellectual Property (CAS-IP), Via dei Tre Denari 472, Maccarese, 00057 Rome, Italy

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

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dynamics model and combine it with conjoint analysis. Conjoint analysis allows us to elicit smallholder farmers' choice preferences in detail and to add precision to the structure of the model. The simulation framework helps to improve our understanding concerning the dynamic implications of accumulation processes relating to trust and skill. We test this approach with empirical data for maize in Malawi. Model simulations demonstrate that effective adoption stimulation policies should focus on measures that build trust in improved maize varieties instead of increasing their potential yield even further and in this way contribute to food security.

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9.1 Introduction

Climate change will have a significant impact on the livelihoods of the rural poor in developing countries. Food security consequences are a particular concern as hundreds of millions of people who already struggle to get by may be faced with more frequent droughts, flooding and heat waves that can devastate crop harvests. Reductions in yield in some African countries could be as much as 50 % by 2020, and net crop revenues could fall by 90 % by 2100 (Boko et al. 2007). Agriculture in developing countries thus faces the challenge of undergoing a considerable transformation in order to meet the challenges of achieving food security and responding to climate change (FAO 2010).

Most of the world's hungry live in South Asia and sub Saharan Africa. The crop with the largest projected negative impacts of climate change is maize in Southern Africa, currently the most important source of calories for the poor in this region (Lobell et al. 2008). Seed from improved varieties and other agricultural inputs such as fertilizer and crop protection products are imperative to the transformation of the agricultural sector from subsistence farming to small-scale commercial agriculture. Quality seed can play a critical role in increasing agricultural productivity and thus food security as well as farmer incomes. It determines the upper limit of crop yields and the productivity of all other agricultural inputs into the farming system (Maredia et al. 1999). The development of new crop varieties is also a key factor to shape the future severity of climate change impacts on food production (Lobell et al. 2008).

Improved varieties developed by the national and international agricultural research centres very often fail to be adopted by smallholder farmers (Morris et al. 1999). This paper looks at the determinants of farmers' adoption of seed from improved varieties. We specifically focus on improved seed for food crops such as maize and on the transformation process from subsistence agriculture to small-scale commercial agriculture, which is particularly relevant on the background of food security and poverty alleviation. Subsistence agriculture is characterized by the use of seed from local maize varieties obtained from informal sources such as on-farm saved seed and seed exchange with neighbours. Small-scale commercial agriculture, on the other hand, relies on seed from improved maize varieties that require purchasing additional inputs such fertilizer but that also generate higher yields and that have additional varietal traits such as drought tolerance or pest resistance. Saving hybrid maize seed, one specific form of seed from improved varieties, is not possible. The transition from subsistence agriculture to small-scale commercial agriculture thus also involves socio-technical changes (e.g., changes in value systems or social norms) that result in different farming practices.

Seed from improved varieties are new agricultural technologies or agricultural innovations. Adoption and diffusion are the processes governing the utilization of innovations. Adoption studies analyse factors that affect if and when a farmer will begin using an innovation (as measured e.g. in whether or not a farmer uses seed from improved varieties or how much of their land they cultivate with such seed). Diffusion, on the other hand, can be interpreted as aggregate adoption. Diffusion studies analyse how an innovation penetrates its potential market (as measured e.g. in the share of farmers who use seed from improved varieties or in the share of land in total agricultural land that is cultivated with such seed). The literature about adoption of new agricultural technologies is abundant (for reviews see e.g. Marra et al. 2003; Sunding and Zilberman 2001; Stone 2007). The existing literature about farmer adoption of new technologies addresses two main issues (Kopainsky and Derwisch 2009):

1. Determinants of utility and objective evaluation of this utility. Pure utility evaluations would suggest an s-shaped growth in the area cultivated with seed from improved maize varieties in case improved seed generates higher yield at affordable prices compared to seed from local varieties (i.e., additional costs for agricultural inputs such as seed and fertilizer are offset by the additional revenue generated by increased yield).
2. Social dynamics that over-ride or replace objective evaluations of a new technology's utility. The compatibility of an innovation with the existing values, past experiences, and needs of potential adopters (Rogers 2003) is one important dimension of social dynamics. Other dimensions include processes of social learning, in which adoption decisions are based on teaching and imitation (Munshi 2004).

This differentiation between utility evaluations and social dynamics is in line with other innovation adoption and diffusion studies in the system dynamics field in general (Milling 1996, 2002). Additionally, Dattée and Weil (2007), Struben and Sterman (2008) and Ulli-Beer et al. (2010) include social norm concepts to more objective aspects in simulation models about the adoption and diffusion of energy efficient technologies. Based on these studies and on the observed stagnation of adoption levels, we postulate that the compatibility concept is responsible for stabilizing the subsistence farming regime (compatibility with subsistence farming). Furthermore, trust building in improved seed is crucial for the transformation towards small-scale commercial agriculture, which also involves the development of adequate skills, i.e., of new farming practices.

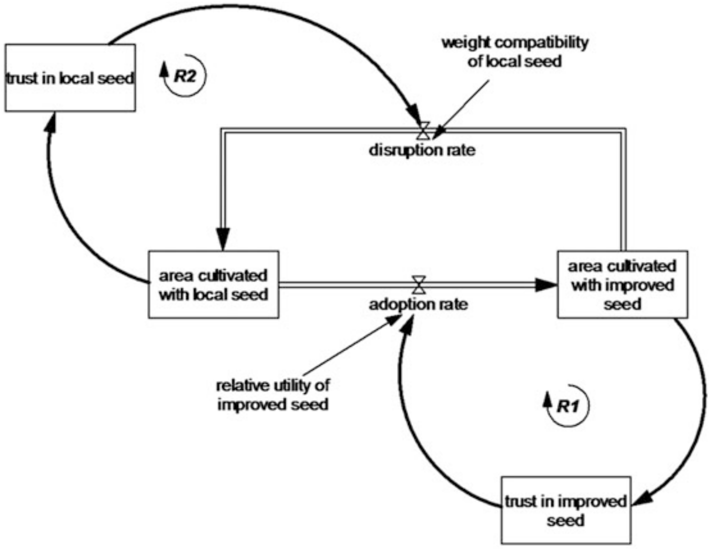
Capturing the transition process from the subsistence to the small-scale commercial farming regime and supporting the transition with adequate policy instruments requires a dynamic perspective and a socio-technical policy analysis framework that integrates utility evaluations and social dynamics. Utility evaluations have been implemented for decades and improved continuously (Marra et al. 2003). So far, however, little attention has been paid to representing social dynamics in policy analysis frameworks.

In this paper, we develop and calibrate a system dynamics model (Forrester 1961) that represents social dynamics and utility evaluations for the case of the adoption of seed from improved maize varieties in Malawi. In order to stimulate the adoption of seed from improved maize varieties, Malawi, for example, introduced a farm input subsidy program in the early 1990s. As a consequence, adoption rose to approximately 30 % in the 1990s but has stagnated on this level since 2000. With our model, we show that a dynamic perspective and a socio-technical policy analysis framework provide more differentiated explanations of observed adoption rates in the past and result in more differentiated policy implications than purely utility-based frameworks.

The next section introduces the conceptual framework that combines the tangible (utility evaluations) and intangible (social dynamics) aspects of adoption and diffusion of agricultural innovations. The subsequent section describes the methods used for calibrating the simulation model, focusing on conjoint analysis. The section “simulation results” compares policies that aim at increasing the diffusion of seed from improved maize varieties. In the “discussion and conclusion” section we distil the additional policy insights that can be gained with our socio-technical policy analysis framework compared to pure utility evaluation frameworks.

9.2 Conceptual Framework

The structure of the simulation model is based on a previous literature review about the adoption seed from improved varieties (Kopainsky and Derwisch 2009) and the acceptance dynamics framework described in Ulli-Beer et al. (2010). The acceptance dynamics framework includes an endogenous social norm-building process. This is important as an appropriate simulation model for our research purposes needs to be able to address the phenomenon of a tipping point or a critical



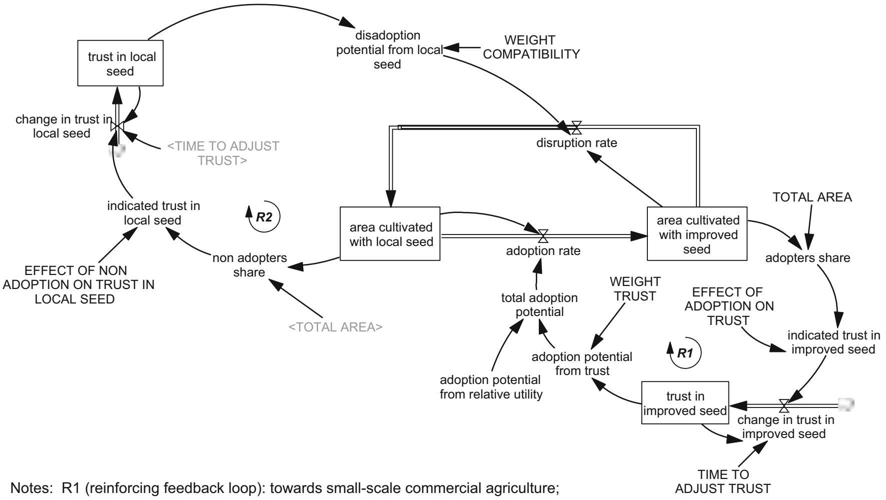
Notes: R1 (reinforcing feedback loop): towards small-scale commercial agriculture; R2: back to subsistence agriculture

Fig. 9.1 Core structure of the innovation adoption and diffusion model

mass that would determine whether seed from improved maize varieties as new technologies will fail or succeed in the market in the long run (Philips 2007).

Adoption and diffusion of seed from improved maize varieties depend on how farmers evaluate the new seeds and act on the evaluations. In its most basic form these evaluations can be described as a simple adoption structure with a stock of non adopters, a stock of adopters, an adoption rate linking the non adopters to the adopters and a discard rate that turns adopters back to non adopters (Fig. 9.1). Adopters' and non adopters' impact on the diffusion process are measured as percentages of the total area cultivated with maize, i.e., as percentage of total maize area cultivated with seed from local varieties and percentage of total maize area cultivated with seed from improved varieties. Only so called hybrid maize varieties are counted as improved maize varieties. Due to their different agronomic and biological characteristics, composite or open pollinated varieties (OPV) are not counted as improved maize varieties in the context of this paper. The "trust in local seed" and "trust in improved seed" stocks in Fig. 9.1 represent the two different social norms underlying subsistence and small-scale commercial farming.

The adoption rate in Fig. 9.1 is determined by utility evaluations and trust in seed from improved maize varieties. The relative utility of improved seed depends on the utility of improved seed compared to the utility of local seed. Utility is determined by common product attributes including the economic parameter of input costs and the varietal attribute of yield. These product-specific attributes are arguments in a multinomial logit model. Input costs in the case of seed from improved varieties



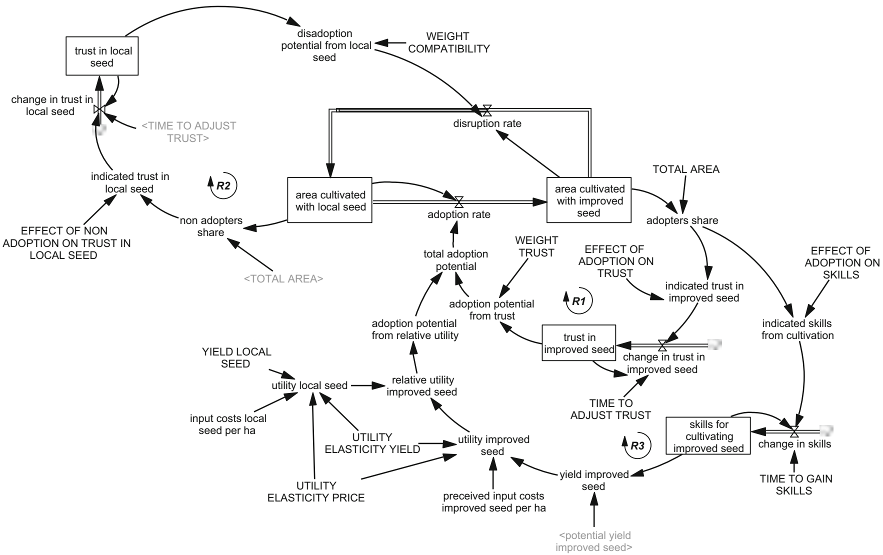
Notes: R1 (reinforcing feedback loop): towards small-scale commercial agriculture;
R2: back to subsistence agriculture

Fig. 9.2 Building trust in improved seed and stabilizing trust in local seed

include the actual seed costs plus the costs of fertilizer. Input costs in the case of seed from local varieties are the price of maize grain, which in turn can be used as seed for the next production season.

Adoption research has documented numerous cases in which local cultural practices and beliefs determine which innovations are adopted (for a review see Stone 2007). In such cases, farmers copy other farmers on the basis of prestige, regardless of that farmer's actual success with the innovation. Farmers also adopt an innovation when and because it has been adopted by many others. These social processes are described by the trust structure in Fig. 9.2. The adopters' share, i.e., the share of the total maize area cultivated with seed from improved maize varieties on the total maize area, is an indicator for the level of trust in improved seed. This causality is also postulated by social impact theory (Latané 1981). Indicated trust in seed from improved maize varieties depends nonlinearly on the area cultivated with improved seed. Sociology literature (e.g. Johnson et al. 2006; Shelling (1971) provides evidence that trust building in a dynamic perspective must be nonlinear and that the nonlinear effect of adoption on trust is of an s-shaped form.

The link between the adopter stock and the trust building process forms a reinforcing loop (*R1*, "towards small-scale commercial agriculture"). This loop either locks the system into a local seed trajectory or reinforces the adoption of improved varieties. Similarly, the discard rate is determined by a reinforcing feedback loop (*R2*; "back to subsistence agriculture"), where the stock of trust in local seed depends nonlinearly on the share of non adopters, i.e., on the share of the total maize area cultivated with seed from local varieties (Fig. 9.2).



Notes: R1 (reinforcing feedback loop): towards small-scale commercial agriculture;
R2: back to subsistence agriculture;
R3: skills development.

Fig. 9.3 Skills development process

Innovation adoption and diffusion are also influenced by an additional learning process in which farmers develop the skills needed for fully exploiting the potential of seed from improved varieties (*R3*). Individual learning improves the farmers' ability to implement the new technology and to make better decisions about improved seed. By conducting their own trials or accessing information on trials by others, farmers develop the skills that are required for realizing the yield and thus the revenue potential of improved seed (e.g., Abadi Ghadim and Pannell 1999; Foster and Rosenzweig 1995). This skills development process is illustrated in Fig. 9.3. As in the case of social learning, indicated skills for cultivating improved seed depend nonlinearly on the area cultivated with improved seed. Skills are adjusted to indicated skills with an adjustment delay. Skills can assume values from zero to one and they determine the degree to which the actual yield potential of seed from improved maize varieties can be exploited through adequate use of inputs (seed and fertilizer) as well as production techniques. As noted above, the link between the adopter stock and the skills development process forms the reinforcing loop (R3) that might lock the system into a local seed trajectory (subsistence farming practice) or reinforce the adoption of improved seed (small-scale commercial farming practice).

The development of skills is not the only factor influencing yield. Depending on the ratio between the costs per kg of fertilizer and grain, the so called fertilizer-to-grain-price ratio, it is profitable or not to purchase and apply fertilizer. Fertilizer is purchased at low values of these ratios and it increases the yield potential of improved seed and thus the utility of improved seed. At the same time, however, the input costs for improved seed rise and reduce the utility of improved seed. The specific values of the fertilizer-to-grain-price ratio and particularly the contributions of yield and costs to the utility of improved seed will determine the overall impact of fertilizer costs on adoption. It is thus important to have sound estimates for these parameters. Total adoption potential is the sum of the adoption potential from trust and the adoption potential from relative utility (weighted by seed availability). To determine the relative weights of utility evaluations and trust we use conjoint analysis.

9.3 Calibration Methods

9.3.1 Multiple Data Sources

For the calibration of the simulation model we used a combination of methods. These are summarized in Table 9.1. Of these methods, conjoint analysis will be described in more detail. We complemented the existing data from statistical and other sources with a household survey. Household data for 210 farmers in two agricultural regions in Malawi were collected using a questionnaire that covered a wide range of issues. In the context of this paper we will primarily report on the section that contained the evaluation of the conjoint analysis stimuli.

9.3.2 Conjoint Analysis

When farmers choose between seed from improved maize varieties and seed from local varieties, a range of information is available to them. Their choice will involve trade-offs between numerous attributes. Conjoint analysis is a very widely used marketing research method for analysing such trade-offs (Green et al. 2001).

The controlled experimental design of conjoint analysis yields insight into the composition of farmers' preferences (Hair et al. 2010). According to consumer theory, a product or good is not directly the source of utility for the consumer. Instead, the consumer draws the utility from the different characteristics or attributes of the product/good (Lancaster 1966). Conjoint analysis therefore decomposes the utility of the good, in our case maize seed, into its attributes. Alternative seed-bundles with simultaneously varied attributes are presented to the respondent, in our case the farmers, so that they can state their relative preference.

In our study we applied traditional conjoint analysis (Hair et al. 2010), which assumed additive part-worth utilities with (nonlinear) part-worth relationships between attribute levels and utility. The first step in conjoint analysis is to identify the set of independent product attributes that are important to farmers in making their choice about which maize varieties to adopt. Interviews with plant breeders

Table 9.1 Data sources and values for the calibration of the simulation model

Specified model variables	Variable value	Data source
Initial value 'area cultivated with improved seed'	17 [%]	Statistical data (MOAFS 2008, 2010)
Initial value 'area cultivated with local seed'	83 [%]	
Time series for model calibration and behaviour reproduction tests		
'Area cultivated with improved seed'		
'Area cultivated with local seed'		
Time series 'yield improved seed' for calibration of lookup function 'effect of adoption on experience'		Statistical data (MOAFS 2008, 2010); variety release reports Ministry of Agriculture
'Potential yield improved seed with fertilizer'	6 [t/ha]	
'Initial skills for cultivating improved seed' based on the comparison between yield potential and actual yield in 1995	30 [%]	
'Yield local seed'	0.75 [t/ha]	
'Seed need per ha' (Heisey et al. 1998)	0.02 [t/ha]	Agricultural literature
'Fertilizer need per ha' (Benson 1999)	0.1 [t/ha]	
'Potential yield improved seed without fertilizer' (Gilbert et al. 2002)	1.5 [t/ha]	
Shape and values lookup function 'effect of fertilizer-grain-price ratio on use of fertilizer' (Gilbert et al. 2002)		
Time series for model calibration and behaviour reproduction tests:		Working documents Ministry of Agriculture; interview data; Harrigan 2008
'Grain price'		
'Fertilizer costs'		
'Seed costs'		
Time series for model calibration and behaviour reproduction tests (based on an average farm size of 0.25 ha):		Statistical data (MOAFS 2008); working documents Ministry of Agriculture; interview data; Harrigan 2008
'Fertilizer costs weighted with subsidies'		
'Seed costs weighted with subsidies'		
Shape and values lookup function 'effect of adoption on trust'		Adoption literature (Ulli-Beer 2004; Ulli-Beer et al. 2010) approaches in sociology (Johnson et al. 2006; Latané 1981; Shelling 1971)
Shape and values lookup function 'effect of adoption on skills'		Same as trust lookup
'Weight compatibility with subsistence farming', based on information	10 [%]	Interview data; variety release reports Ministry of Agriculture

(continued)

Table 9.1 (continued)

Specified model variables	Variable value	Data source
about the average lifetime of variety of ten years		
'Time to adjust trust' based on the average time between time of first awareness of improved maize seed and time of first adoption of improved maize seed	5 [years]	Household survey, descriptive statistics
'Utility elasticity yield'	0.3	Household survey, conjoint analysis
'Utility elasticity price'	−0.002	
'Weight trust'	26 [%]	
'Initial trust in improved seed'	10 [%]	Interview data, assumptions
'Time to gain skills'	2 [year]	
'Time to adjust costs perceptions'	1 [year]	
'Time to adjust perception of fertilizer-grain-price ratio'	1 [year]	

and farmers resulted in the selection of five attributes that are important for varietal choice: brand, yield, maturity, grain texture, and price. Brand is an attribute that represents intangible characteristics of a variety and, in our study, is considered a proxy for trust in seed from improved varieties. Maturity refers to the time the maize plant takes to mature, i.e. the time between seeding and harvesting. Grain texture describes the hardness of the grain. Each attribute can assume several values (called levels), as listed in Table 9.2.

The next step is to design a survey questionnaire with potential products that farmers can evaluate. The combination of attributes and levels of each potential product is called stimulus. From the attributes and levels presented in Table 9.2, a total of 216 stimuli would result. These were reduced to a set of 18 stimuli using an orthogonal array design. Each stimulus was subsequently presented as a coloured card mimicking a bag of seed. Icons were used to make the attributes readable also for illiterate farmers (Fig. 9.4). Farmers were shown one stimulus after another and they had to judge each stimulus on a seven point rating scale ranging from "won't buy at all" to "will definitely buy".

From the data generated by the questionnaires it is possible to calculate preference scores for all attribute levels in the final step of conjoint analysis. The analysis produces a set of 'part-worths' or averaged importance scores for the attributes that are ratio scaled and sum to 100 %. Data analysis also allows calculating the part-worth utilities for the attribute levels and thus the utility elasticity of changes in the attribute levels. Averaged importance scores (part-worths) for all respondents are shown in the second last column in Table 9.1. In the last column, the table also lists those utility elasticities (part-worths utilities) that are relevant for the system

Table 9.2 Attributes and their levels, importance scores and utility elasticities

Attribute	Level				Averaged importance score	Utility elasticity
Brand	None	Seed company 1 (Seed Co)	Seed Company 2 (Montsanto/Dekalb)	seed Company 3 (Pannar)	26	
Yield	Same as local variety	Higher than local variety			22	0.3
Maturity	Early	Medium	Late		17	
Grain texture	Soft	Medium	Hard		20	
Price [Mkw][a]	150	300	450		15	−0.002

[a] Malawian Kwacha (local currency)

Fig. 9.4 Example of a stimulus

dynamics simulation model. Table 9.1 shows that “brand” is the most important attribute to overall product preference and contributes about a fourth to overall product utility. Farmers thus seem to have strong attitudes towards brands. Utility elasticities for brands varied for the different brands included in the conjoint analysis design. However, the directions were as expected. The introduction of a brand potentially raised the utility from being negative to a positive score. Branded seed thus seems to increase trust and reduce uncertainty in the view of

Table 9.3 Theil statistics for the comparison between data and Base Run

RMSPE	$U(^M)$	$U(^S)$	$U(^C)$	R2
0.16	0.01	0.04	0.95	0.41

farmers. The direction of the utility estimates for the attribute "yield" followed the expected direction from being negative when yield potential of improved varieties was the same as that of local varieties to being positive when it was higher than that of local varieties. Maturity and grain texture are varietal attributes that are very relevant for breeding choices. However, these two attributes are not included in the system dynamics model as they are not subject to endogenous change. Their influence has been condensed into exogenous input parameters. Yield, on the other hand, changes endogenously as the exploitation of the full yield potential of improved varieties depends on farmers' experience with cultivating improved varieties (Fig. 9.3). Price with its negative utility elasticity is part of the model as it constitutes one of the major policy variables.

9.4 Simulation Results

The simulation model runs over the time horizon of 1995–2050. The historical period (1995–2009) starts after a major political change in the 1990s with the first ever multi-party elections in 1994. Ever since, the political conditions have been comparable to the current situation. The period between 2010 and 2050 allows studying the potential long-term dynamics of a societal change process such as the transformation from subsistence to commercial agriculture.

9.4.1 Base Run

Figure 9.5a compares historical data about the adoption of seed from improved maize varieties (as measured in the share of the total smallholder maize area dedicated to improved seed) with simulated adoption. The short term fluctuations in adoption in the past are a consequence of annual modifications in the input subsidy scheme.[1] The simulation model does not capture these short term changes. However, it is able to follow the trend in the data. The overall fit between data and simulation is confirmed by the results of the Theil statistics in Table 9.3, which decomposes the overall root mean square percentage error (RMSPE) into the error due to bias (U^M), error due to unequal variation between data and simulation (U^S) and error due to unequal covariation (U^C). As the error is concentrated in unequal covariation and the model purpose is to study long term development patterns (instead of cycles in the data) the error can be considered unsystematic (Sterman 1984).

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[1] For a historical overview of food security policies in Malawi see Harrigan (2008).

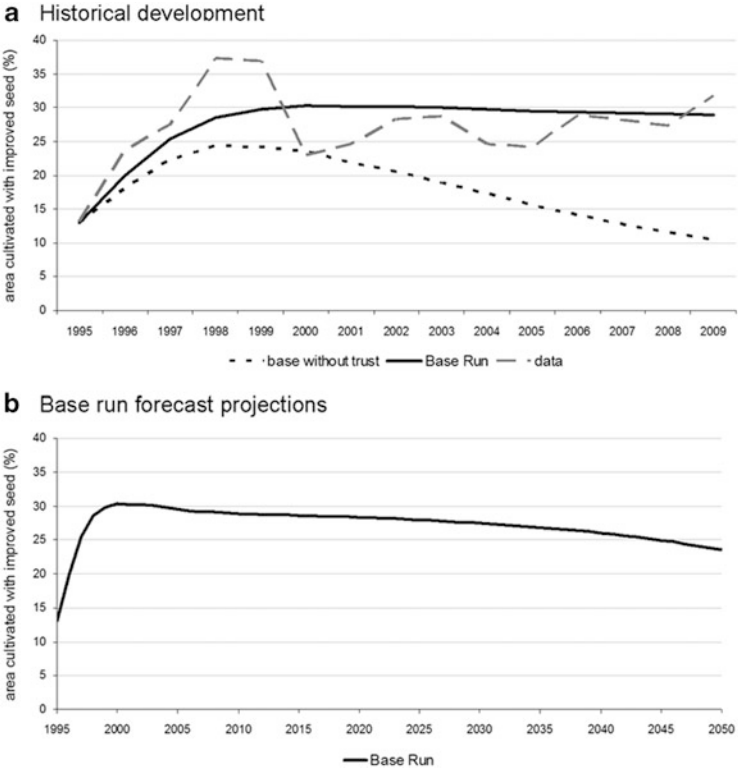

Fig. 9.5 Base Run

In the second half of the 1990s, input costs (seed and fertilizer costs) were rising moderately while at the same time the seed-to-grain price ratio (an indicator for the affordability of seed) decreased markedly. This combination seems to have been sufficient for stimulating adoption and causing the marked increase in the area cultivated with seed from improved varieties. In the early 2000s adoption stagnated and has since been of the order of 30 %.

In addition to the two varietal attributes of input costs (price) and yield competing for the overall effect on the relative utility of improved seed, the trust building process plays an important role for explaining historical behaviour ("base without trust" in Fig. 9.5a). Without the reinforcement between adoption and trust, overall adoption would not have reached the levels recorded by the data and it would have declined constantly after the initial increase in the second half of the 1990s. The reinforcement between adoption and trust (R1) during the time with low input prices for improved seed enabled the development of skills that are necessary for realizing (some of) the yield potential of improved seed (R3 in Fig. 9.3). When input prices started to increase, the skills could compensate for some of the negative impact of higher prices on the utility of improved seed. The trust building process

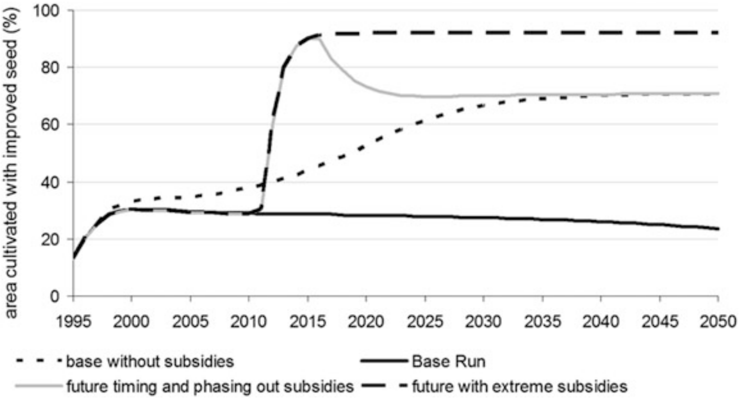

Fig. 9.6 Tests with input subsidies

thus played an important role in dampening the effect of short-term utility evaluations and it also helps to keep adoption at fairly stable levels in the Base Run projections into the future (Fig. 9.5b).

These projections are fairly insensitive to variations in most model parameters. The sensitive parameters (time to adjust cost perceptions, time to adjust fertilizer perceptions, and weight of compatibility with subsistence farming) are based on quite reliable estimations (Table 9.1). In the subsequent paragraphs, we will analyse the role of utility evaluations and trust on the future development of smallholder farmers' maize production in Malawi.

9.4.2 Utility Evaluations

The utility of improved seed can be influenced either via the input costs of improved seed or the yield of improved seed. Figure 9.6 provides a series of policy tests with different formats of input subsidies, i.e., with different ways of timing and calibrating subsidies for improved seed and fertilizer. It compares the Base Run behaviour to the behaviour of the hypothetical situation where there would have been no subsidies at all, neither in the past nor in the future ("base without subsidies"). The simulation results in Fig. 9.6 highlight that unsubsidized inputs are not an impediment to the adoption of seed from improved varieties. The difference between the "Base Run" and "base without subsidies" scenarios lies in the total use of fertilizer. Farmers in the "base without subsidies" scenario use less fertilizer per ha and in total have lower input costs per ha than farmers in the "Base Run" scenario. This increases the utility of improved seed, stimulates adoption and helps building both trust in improved seed and skills for cultivating improved seed, thus locking the system into an adoption trajectory.

Inspired by the steady growth in adoption in the hypothetical "base without subsidies" scenario, two future oriented scenarios test the impact of a policy that

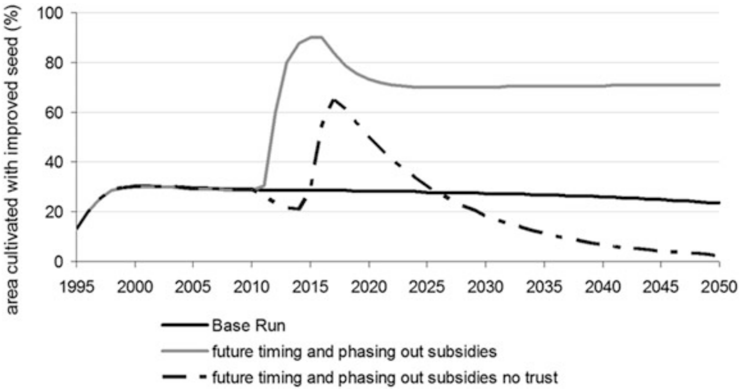

Fig. 9.7 Input subsidy tests without trust

heavily subsidizes both seed and fertilizer ("future with extreme subsidies", where seed and fertilizer costs are near zero as of 2010) and a policy that equally heavily subsidizes seed and fertilizer for a 5 year period (2010–2015) and then removes all subsidies so that, as of 2016, farmers have to purchase improved seed and fertilizer at their true costs ("future timing and phasing out subsidies").

Very high adoption levels are achieved in the "future with extreme subsidies" policy that assumes input costs near zero as of 2010. This scenario, however, seems fairly unrealistic. Figure 9.6 shows that a short term push in input subsidies (2010–2015) can be replaced by no subsidies at all (as of 2016) and still lead to rather high adoption levels ("future timing and phasing out subsidies" scenario). The behaviour in this scenario is determined by a short term increase in the relative utility of improved seed (as its input costs are near zero and yield is higher than that of local varieties) that enables sufficient growth of trust and skills to sustain adoption even for the time where input subsidies are removed.

9.4.3 Trust Building Process

The importance of the trust building process in addition to utility evaluations is highlighted in Fig. 9.7. The figure compares the Base Run and the "future timing and phasing out subsidies" behaviour (see Fig. 9.6) with the behaviour for the same timing and calibration of input subsidies but with the trust building process disabled as of 2010 ("future timing and phasing out subsidies no trust"). The results visualize how trust helps smoothing adoption and locking the system into an adoption growth or adoption decline path.

Figure 9.8 confirms the key role that trust plays in the adoption process by comparing Base Run behaviour with a development where neither yield nor input costs are changed in the future. The only policies implemented are aimed at

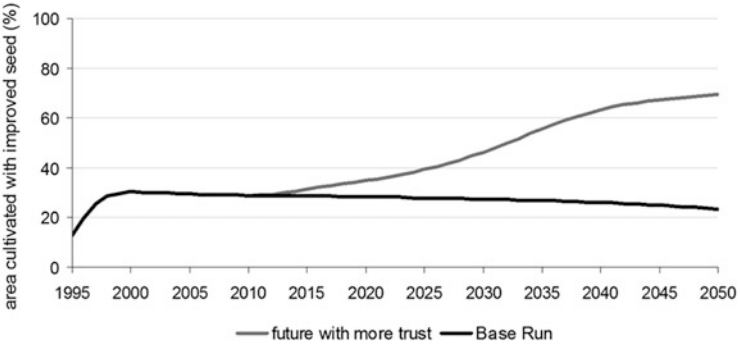

Fig. 9.8 Trust tests

building trust, either through information or more direct advising of farmers of the benefits, compatibility and acceptability of cultivating seed from improved maize varieties. These policies are sufficient to induce a sustained growth in the adoption of seed from improved maize varieties. Adoption does not grow more if trust related policies are combined with increasing the potential yield of seed from improved maize varieties or with investments in skills (not shown in the figure as the behaviour pattern does not differ from the "future with more trust" pattern).

9.5 Discussion and Conclusions

This paper developed a dynamic socio-technical framework which aimed to improve understanding of the transformation from subsistence farming to small-scale commercial agriculture and to test policies supporting this transformation. The simulation model formalized the adoption determinants and processes described in the literature and confirmed by empirical analyses. The most important determinants were the utility of local seed and improved seed, trust in improved seed, compatibility with subsistence farming practice (which is based on the use of local seed), and skills for cultivating improved seed. The dynamic processes of trust building and skills development coupled with utility evaluations determine the adoption and discard rates that explain the diffusion of seed from improved maize varieties.

Model calibration drew from conjoint analysis to determine the specific weight of utility and trust in the adoption decision. The system dynamics simulation model, on the other hand, provided an endogenous perspective on the accumulation of trust and skills, and thus on their strength over time. Therefore, the simulation framework, both in terms of structure and policy implications, goes beyond purely static utility evaluation models, even if these are sometimes complemented with a weight representing social factors.

Model analysis showed that the social dynamics of trust building has the power to over-ride utility evaluations in the adoption decision. In addition, the socio-technical simulation model has the characteristic that specific parameter constellations lead to a tipping point indicating the existence of unstable equilibrium positions of sustained adoption or discard. As soon as the tipping point has been passed, policy stimulation may be removed, or, policy stimulation needs to be reinforced until the tipping point has been reached, respectively.

The compatibility concept is responsible for stabilizing the subsistence farming regime, while the accumulation of trust and skills regarding improved seed support the transformation to small-scale commercial agriculture. Trust could thus be identified as important policy lever. The trust building process plays a central role in smoothing short term changes in input costs that would lead to major fluctuations in adoption if adoption was a purely utility driven decision making process. This smoothing gives time for developing the required skills to better realize the high yield potential of improved seed.

From a policy implication perspective, effective adoption stimulation policies should thus focus on measures that build trust in seed from improved maize varieties. For example, seed companies can effectively market their seed by either advertising it through different media or by distributing free seed to key farmers in a region. If the seed performs well on these farms seed companies can organize field demonstrations for a large number of farmers (see Stone 2007). This strengthens the word of mouth effect from adopters to non-adopters and thus trust building. Another strategy for building trust in improved seed is participatory breeding (e.g. Witcombe et al. 1999). Participatory plant breeding is a long-term process and involves farmers in the entire breeding process so that farmers from the earliest stages have information about the characteristics of the varieties under development and on their potential profitability. Farmers can determine which traits should be pursued in the development of a new variety. Participatory plant breeding is very likely to increase trust in improved seed because farmers are involved in the definition of the characteristics that new varieties need to have (compatibility with current practices and technologies). The theory of normative conduct (Cialdini et al. 1990; Kallgren et al. (2000) gives additional policy insight. Drawing on that theory, effective adoption stimulation policies should focus on making adoption visible as much as possible, for example by clearly indicating the fields cultivated with seed from improved maize varieties.

As trust may over-ride utility evaluations, it does not necessarily lock the system into a desirable growth process. Trust can overwrite yield and input costs and cause farmers to continue purchasing seed from improved maize varieties when this option is, from a utility point of view, clearly inferior to seed from local varieties. Stone (2007) provides compelling evidence how such processes can not only lead to heavy financial burdens of smallholder farmers but also to a loss in skills appropriate for dealing with variations in farming conditions.

The diversification of smallholder agriculture away from pure maize production is an important element of long term food security strategies (for a discussion in Malawi see e.g. Harrigan 2008). The policy tests with the timing and calibration of future input subsidies show that funds for supporting diversification could be made available after a relatively short transition period, when a self-sustaining adoption regime with high trust and skill levels is at work. During the transition period, the adoption of seed from improved maize varieties would have to be pushed with specific input subsidies until the tipping point has been crossed. However, after this temporary push, adoption of seed from improved maize varieties would become a self-sustaining growth process without the need of further subsidies. The funds that would thus become available could then be invested in the design and implementation of diversification strategies. The implementation of such diversification strategies constitutes a series of additional adoption processes – that probably will best be analysed with an extended dynamic socio-technical transition framework. With this paper we have provided a methodology that allows testing adoption policies in a dynamic framework and thus a starting point for the design of future food security strategies.

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Chapter 10
Lessons Learned from Integrative Transition Simulation

Silvia Ulli-Beer

Abstract This chapter provides the multi-dimensional governance matrix of sustainability transitions that has been informed by the distinct research approach of integrated transition simulation (ITS), as described in Chapter 3 and applied in the reported case studies. We found that four determinants in the real-world context (i.e., the messy problem situation, the fragmented knowledge, the distributed decision making and the dynamic complexity) are hindering the consolidation of expectations and decision-making in value. This chapter argues that on the one hand public authorities are responsible for initiating adequate governance structures to overcome them. For this task, five governance principles are suggested. On the other hand six management issues are highlighted that private entrepreneurs need to address in such sustainability transitions. Finally this chapter emphasizes integrated transition simulation as a tool that supports coherent reasoning about effective governance mechanisms and adequate implementation plans.

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

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10.1 Introduction

In the preceding chapters, we have reported research that should enhance systemic understanding and knowledge on transformation processes of energy technology change.

In this chapter, we provide a summary on the two overall guiding research questions addressed in the case studies:

- What determinants, mechanisms, and actors foster or hinder the spread of clean and energy-efficient technologies within a socio-technical system?
- How should a socio-technical transformation be governed?

  The answer to this second question is provided in the form of main governance and management principles that have been derived from the single case studies.

  We also reflect on the chosen approach of integrative transition simulation and conclude with a methodical question and answer, respectively.
- How can deterministic simulation modeling support sustainability transitions?

10.2 Determinants, Mechanisms and Actors

Many of the specific determinants that foster or hinder the spread of clean and energy-efficient technologies are linked to one distinct characteristic of a sustainability transition. It is the normative change characteristic that is involved in such transitions.

A successful sustainability transition depends on how well new values and beliefs can be developed in a society. It depends on how well product attributes such as energy-efficient or renewable energies create additional perceivable utility for a society and for single decision makers (Jaffe et al. 2005). However, four major real-world conditions, which hinder this normative change process, have been identified and discussed throughout the book. These are the following four systemic determinants (Table 10.1).

Messy problem situation: The problem situation in socio-technical transitions is often a messy problem for many actors that may be part of the solution. It is not clear what exactly the problem is, or who has the competencies, means, and responsibilities to address it. Finally, there does not exist any broadly diffused inter-subjective understanding regarding the most promising approaches to address it. Therefore, actor identification and problem structuration are important activities that should take place at many different local settings and distinct actor groups. But this first step is often not taken, because it is not clear which actors are responsible to manage such a first problem-structuring initiative.

Fragmented knowledge: There exist promising socio-technological problem-solving approaches in national, sectoral, or technological innovation systems. But

Table 10.1 A synthesis on governance responsibilities in socio-technical transitions tasks

Determinants that hinder socio-technical transitions	Public authorities need to organize governance structures at the system level	Private entrepreneurs need to take management responsibility at the (inter-) organizational level
	Governance principles to be considered	Management issues to be addressed
1. Messy problem situation	Identify local action potentials	Logic of a transition initiative
2. Fragmented knowledge	Initiate local initiatives (support coordination in value creation networks)	Local response options
3. Distributed decision making		Rent-seeking opportunities (Identify short-term deployment opportunities)
4. Dynamic complexity	Manage the sequences of innovation, market formation, and standardization	Long-term improvement incentive
Nested balancing and reinforcing causalities	Enforce desirable governance structures (environmental policymaking)	Increasing return opportunities
Slow-changing system states (lock-in and inertia)	Integrate research and technology policy Rollout of local initiatives	Inertia for good and bad

these are "single knowledge points," which are located with different organizations and actors (c.p. Ven 1986). Such solution approaches involve different kinds of knowledge, e.g., different kinds of technological knowledge, knowledge on management and governance principles, or organizational knowledge. These "single knowledge points" need to be connected to a coherent problem-solving strategy that can be tested, evaluated, and refined. Most promising dominant design principles of socio-technical "platforms" should be identified and broadly diffused between local actor groups.

Distributed decision making: Technology change toward sustainable energy futures is driven by actors and foremost by entrepreneurs able to take risks and invest present resources into future expectations about economic opportunities of sustainability transitions. The task of entrepreneurs is to choose the right risk and to test new business models. Risk-avoiding behavior, i.e., staying with well-tried business models and technologies with established organizational structures and actor and value networks, creates rigidity; this is the most harmful state of a system in a changing environment. Drucker (1970, 2009) describes economic progress as the ability to take greater risk and not avoiding it. Sustainability transitions require coordinated and concerted risk taking by many actors in order to induce system-wide change in a socio-technical system. Therefore, consolidated perceptions and expectations about economic opportunities within a value-creation actor network needs to be formed. This is a critical premise for an aligned investment of present resources by distributed decision makers. Associations and public-private partnerships or learning alliances are promising organizational structures that may help to elaborate, evaluate, and refine an intersubjective expectation with adequate activities.

Dynamic complexity: A sustainability transition involves fast- and slow-moving system states and variables that are interdependent. The interdependencies involve *circular causality-structures* that are balancing or reinforcing. Balancing causalities tend to push the system states toward (implicit) goals. Reinforcing causalities accelerate changes in system states. The nested structure of balancing and reinforcing causalities are often a black box for actors. This may not cause a problem for unchanged courses of action and behavior trajectories. But, if a course of action should be changed (i.e., change in the development direction of a socio-technical system), an adequate understanding of the circular causalities is critical for the creation and management of new development paths.

A concerted change initiative specifically needs to pay attention to the *slow changing system states* that may reach critical threshold values. These may involve hidden system states, such as value changes in value networks, the power of different actors groups, or a changing willingness to comply with an initiative. Different action initiatives may impact on these states, and the pace of technological progress, in particular. Any single action may be perceived as ineffective, but the sum of an aligned action portfolio may help to reach a critical mass and induce a critical change in these slow-changing variables. This means that historically grown *lock-in* effects may be overcome. Due to the slow-changing states, such path creation processes require time. Short-term deliberation of return on investment is not an adequate evaluation parameter yardstick for such change initiatives. But this yardstick remains valid for incremental technological improvement strategies; it should even help to finance the creation of new paths that are based on radical/disruptive innovations, and that only become profitable in the mid- or longer term.

Long lifecycles of products or the built infrastructure create system *inertia* that cannot be overcome by pure path creation strategies. System inertia depends on managing the scrappage rate of a fleet or the renovation rate of the built infrastructure. The depreciation of undesired capital stocks should be accelerated. Reinvestments in the old building stock without strongly decarbonizing the energy-technology will slow down any change process.

10.3 Governance Principles

The second leading research question, how should a socio-technical transition be governed, has led to conclusions that highlight promising principles of governance of socio-technical transition. These governance principles have been identified for the specific class of transitions that focus on transitions toward near zero emissions in housing and road transportation.

Identify the local action potential: End-use energy technologies incorporated in road transportation and housing have been identified as sensitive leverage points for local actors to increase national energy security and to reduce GHG emissions. This means that local actor groups have the potential to make a significant difference, if they establish adequate governance structures for socio-technical transitions toward near zero emission transportation and housing.

Buildup of an aligned value creation network: Pioneers of the supply side, concerned actors of the demand side, together with advocacy coalitions, public authorities, and policymakers, can cause a pragmatic paradigm change in the direction of technology development and the development of the selection environment.

Manage the sequences of innovation, market formation, and standardization: Improvement trajectories emphasizing energy-efficiency need to be supported by tightening standardization in order to cause widespread diffusion of energy-efficient solutions. The chronological sequence of rule change in the market and by legislation is critical to build up support for legislation in democratic societies (i.e., to cross the political tipping point). New energy-efficient solutions should first demonstrate relative attractiveness and reliability. This means that product variants should first be able to trigger *evolutionary economic rule change* through (niche) market selection and prove its utility in the society. This supports the formation of distinct actor networks and advocacy coalitions. Eventually, major actors help to administer new rules, resulting in a so-called *socio-institutional rule change*. However, it is often required to highlight social benefits of product variants for evolutionary economic rule change (e.g., by measures such as labeling). Likewise, sustainable eco-investments in the existing built environment (e.g., existing buildings) are complex for single decision makers. This fact creates an opportunity for energy-focused retrofitting services that help to identify the most sustainable solutions. Such new services can become an important element in support of evolutionary economic rule changes.

Enforce desirable governance structures: Adequate governance structures are those that create reinforcing acceptance dynamics for energy-efficient designs: Supporting measures should highlight desirable evolutionary economic rule change and foster direct socio-institutional rule change, such as standardization. However, while such an induced technology change approach is necessary, it is not sufficient to reach the imperative targets of GHG emission reduction. *Solution-directed* strategies of technology management and research policy are required that allow for both the short-term deployment of advanced technologies and long-term development of alternative technologies and fuels at the local level (Weiss and Bonvillian 2009). This means that a socio-technical transition is hindered as soon as any bottleneck in the governance structures emerges; being either in the front end or back end of technology development and deployment.

Integrate research and technology policy: Technology management and policy should simultaneously support both incremental (or add-on) solutions in the late stage development and more radical technological solutions in an early stage of technological development. This fosters systemic technology competition (e.g., sailing ship effects) and knowledge spillover in technology development. Such an integrated technology policy approach may require adequate organizational forms of public-private technology and innovation partnerships. Such partnerships should cluster both short- and long-term projects, which are guided by a common long-term vision and dynamic targets.

Rollout of initiatives: Exemplar activities and their rollout are important at local levels (i.e., highly populated municipalities and cities with established innovation system structures) for four important reasons. First, they enable social learning on competitive technological pathways. Second, they enhance trust building between actors. Third, they lead to a concerted buildup of adaptive capabilities and capacities. Finally, successful local initiatives lead to the buildup of political legitimacy for further socio-institutional rule change in support of sustainability transitions.

These principles outline a multi-dimensional governance approach of socio-technical transitions. They take account of the heterogeneous actor groups, the nested feedback loop that control (un)desirable attributes of technologies, innovations and infrastructures. In real world contexts, the interdependencies should be made transparent in order to set up the relevant information feedback between the involved actors within adequate organizations. A *transparent picture* helps to clarify the logic of complex socio-technical transitions initiatives. *Any single bottleneck* in the interdependencies may lead to transition failures. Adequate *information flows* between the interdependent actors becomes as critical as adequate resources, capabilities, capacities, and eco-technologies. Coherent short- and long-term technology-push approaches help to accelerate the rate of technology change. Further on, the sequence of rule change and the tightening of standards are critical for successful legislation and meeting the imperative GHG emission targets in democratic societies.

These governance principles provide guidelines for public authorities to prepare adequate frame conditions for socio-technical change initiatives. They need to be fostered by a sound management of single initiatives and clear responsibilities.

10.4 Management Issues to Be Addressed

From a systemic perspective, six management issues should be emphasized that are decisive in a socio-technical transition context. In the following, main questions to be addressed by the management of single initiatives are pointed out for each issue.

Logic of a transition initiative: What is the motivation for the initiative? How do our actions, strategies, or expectations endogenously (or not) change goal gaps within socio-technical systems? How will they influence aggregate behavior patterns concerning technology choice and GHG emissions in a consistent way?

Local response options: What are the response options of concerned actors in their local action context? What potential exists if the most energy-efficient technologies are employed? What are the incentives to deploy them? How can we create incentives to deploy them? Are our guidelines appropriate?

Rent-seeking behavior: What adequate maneuvering helps deploy short-term benefits? Where can local emissions be reduced in the local action context? Where can resource efficiency be increased at low costs? The answers that address economical and environmental rent-seeking behavior provide guidelines for the supply side to develop adequate solutions.

Illustrative Examples

Many firms may still have improvement potentials within their fleet management concerning fuel consumption. Specifically, managers of *public* car fleets should put a strong emphasis on reduced fuel consumption in vehicle purchase decisions. Such a strategy is coherent with the logic of providing a public good and the principle of resource efficiency that is both economically and ecological beneficial. Procurement guidelines should also include clear requirements concerning emission standards that go beyond legislated standards. Due to delayed standard-setting processes and advanced vehicle technologies, such “rent-seeking behavior” is promising in respect of economical and environmental benefits. This demand-side energy consumption and emissions management approach may include a requirement to test alternative vehicle technologies. In Switzerland, for example, the management of the mail delivery car fleet has successfully implemented just such a consistent exemplary procurement strategy.

For the housing sector, Müller et al. suggest the development of roadmaps for the retrofitting of single buildings in respect to their CO_2 emission-reduction pathways (see Chap. 7). Other promising approaches are energy service contracts in addition to public policymaking and legislation.

Long-term improvement incentives: How should we monitor the performance of our local strategies to increase resource efficiency and decrease GHG emissions? How should we formulate tightening target setting as a long-term incentive for improvements?

Illustrative Examples

Environmental management systems should be adapted for fleets and existing buildings. Currently, for example, such efforts are underway in Switzerland with pioneering public fleets. For the building sector, the legislation is proposing an energy card for buildings that provides the relevant information for a consequent management of the building stock.

These principles point to the importance of environmental management approaches. They provide the relevant information feedback for considering environmental attributes in the purchase and retrofitting decisions. In this manner, they act as the important feedback mechanism from the demand to the supply side that induces a paradigm change in technology development.

Increasing return opportunities: What increasing returns dynamics can we trigger with our strategies? What is the promise of long-term success? How do we need to adjust our business model to deploy them? How can we monitor the development of the relative attractiveness of eco-innovations and their market potential?

Inertia for good and bad: Where does the inertia of change come from? How should we manage them? How can we deploy them for good? Which short-term fluctuation do they help to damp (Table 10.1)?

10.5 The Promise of Transition Modeling

The multi-dimensional governance matrix of sustainability transitions has been informed by the distinct research approach of integrated transition simulation (ITS), as described in Chap. 3. The case study approach on socio-technical transitions applies system dynamics for theory enhancement and policy analysis.

In the following, the specific benefits of this approach for practitioners will be summarized by addressing the methodological question:

- How can deterministic simulation modeling support sustainability transitions?

We recall that the distinct characteristic of a sustainability transition is its normative change process that differentiates it from pure economically driven innovation and growth processes. It involves a societal desired change in the direction of technology development. Such a directional change depends on consolidated perceptions and expectations within value networks about opportunities, on the one hand. On the other hand, it requires coordinated and concerted decision making within these actor networks. But the four determinants in the real-world context (i.e., the messy problem situation, the fragmented knowledge, the distributed decision making and the dynamic complexity) are hindering the consolidation of expectations and decision making in value networks.

The research reported in this book gives evidence that integrated transition simulation is helpful in mitigating the four real-world challenges, due to the five strengths the method offers.

1. *Problem structuring:* Integrative transition simulation provides sound methodical guidance for structuring a dynamic problem situation. It helps to reflect on the relevant actors involved in a problem situation that appears to be messy at the outset. The approach helps to identify the critical elements and boundary of the socio-technical system and to link decision rules to performance characteristics of selected indicators.
2. *Knowledge integration:* Various aspects of a transition challenge are relevant for a clear picture about factors and processes that hinder or support the transition process. These aspects include technology and infrastructure development,

innovations processes, technology assessment and acceptance dynamics, societal learning, politics, and standardization. The system approach helps to identify and integrate the relevant knowledge for socio-technical problem solving. Often, detailed knowledge is available, but it needs to be linked to the identified problem situation in order to draw helpful conclusions. Here, ITS helps to link the fragmented knowledge in such a way that a clearer picture emerges that is grounded in the relevant data.

3. *Tagging of governance mechanisms:* The success of a socio-technical transition depends on the buildup and support of governance mechanisms that drive the performance. Often, actors have a black-box understanding about the critical governance mechanism and the interdependencies. Here, the mapping tools of ITS allow for the elaboration and visualization of a nested set of reinforcing or balancing feedback mechanisms critical for a successful socio-technical transition. In this, it tags systemic governance mechanism.

   This understanding helps to design and implement the adequate information feedback structures, which foster socio-technical transition. In other words, it visualizes the logic of transitions initiatives and provides the arguments for why single local activities are critical for global societal development goals.
4. *Process explanations:* The ITS approach allows analyzing tipping behavior characteristics of diffusion and development processes. This knowledge is important to understand the critical system state, a development state where the timing of policy measures is important. If supporting policy measures are withdrawn too early, the performance of the system may fall back on the old level, since the new regime has not yet gained enough momentum to become self-sustaining. In a democracy where new standards need to be approved by a constituency, the timing of standard setting or enforcement requires careful processual understanding concerning technology development levels and societal beliefs. In addition, ITS provides a better understanding about system elements, which may create path dependency. For example, variety creation in an early phase of technology development may help in a latter phase, single technology to break through with fewer efforts, since the dominance of the incumbent technology has been weakened by the advent of several new competitors.
5. *"What if" analysis:* The simulation model can be used to test the impact of different policies and strategies in a virtual but well-defined socio-technical system. Sensitivity analysis allows identifying robust implementation strategies in an uncertain environment. In this manner, not just the opportunities but also the threads of a transition initiative can be tested in advance. This provides a helpful understanding for long-term policy and strategy planning processes in a distributed decision-making environment.

Figure 10.1 summarizes the main benefits of ITS. It is a tool that supports coherent reasoning about effective governance mechanisms and adequate implementation plans. It facilitates both the consolidation of perceptions and expectations about opportunities and threads of a socio-technical transition and coordinated and concerted decision making within actor networks.

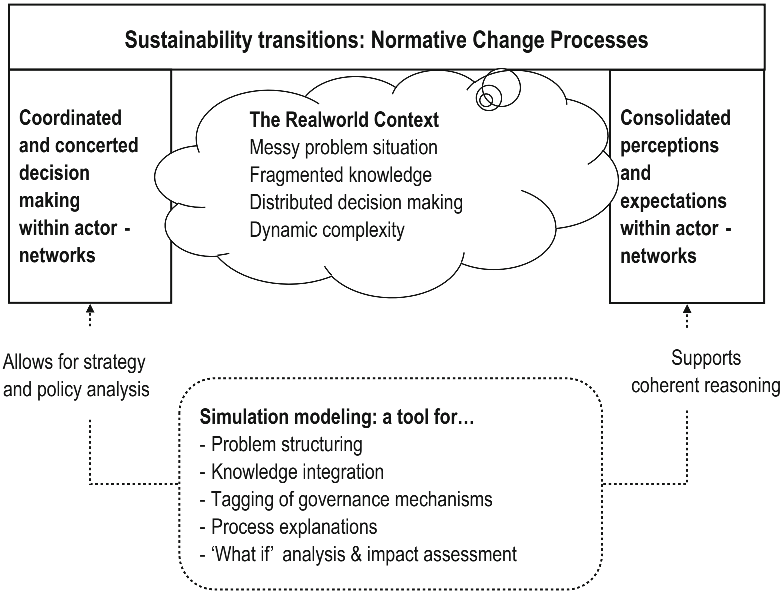

Fig. 10.1 The main benefits of Integrated Transition Simulation (ITS) for sustainability transitions

In view of these insights and promises, it can be expected that the elaboration of generic transition simulation models on eco-innovation, diffusion and standardization may be a worthwhile further step that may become the background of a computer-aided quality control approach of long-term socio-technical transition initiatives. Therefore, adequate expertise in both modeling and data mining, as well as long-term change processes is required. Such an expertise can be gathered in a well-blended team of experts from different disciplines and action contexts.

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