Chapter 2
Research Design and Methods

2.1 Introduction

The goal of this study is to develop a quantitative, dynamic simulation model of the diffusion of energy-efficient renovations and using it to understand how the diffusion of energy-efficient renovations can be accelerated. In order to develop the simulation model, I drew on a wide range of empirical and theoretical contributions found in the literature, and I also conducted my own empirical research. What I eventually arrived at is a synthetic, empirically grounded, dynamic theory in the form of a System Dynamics simulation model. The research design implemented in this study might best be described as *computer-assisted theory building with System Dynamics*.[1] This chapter is structured as follows. In Sect. 2.2, I describe the research design. In Sect. 2.3, I discuss the specific methods I used, and in Sect. 2.4, I discuss and reflect on the research design and methods used in this study.

2.2 Research Design

2.2.1 Systems Thinking and Theory Building

Definition of a Theory

According to Schwaninger and Groesser (2008, p. 448) a theory can be defined as a "structured, explanatory, abstract and coherent set of interconnected stateents about a reality." Theories can be differentiated according to their range as *general*

[1] In a recent article, Schwaninger and Groesser (2008) describe System Dynamics as model-based theory building. The research design of this study was strongly influenced by that article. However, in order to stress the theory building aspect rather than the simulation tools used to implement it, I here consciously use this term to describe the research design employed.

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theories, *middle-range theories* or *local theories*. While general theories attempt to provide highly generic or overall explanations of a wide range of phenomena, local theories attempt to explain highly specific situations (Schwaninger and Groesser 2008, p. 450). Middle-range theories are "theories that lie between the minor but necessary working hypotheses that evolve in abundance during day-to-day research and the all-inclusive systematic efforts to develop a unified theory that will explain all the observed uniformities of social behavior, social organization and social change" (Merton 1968, p. 39, quoted in: Schwaninger and Groesser 2008, p. 450). The theory I aim to develop is best classified as a middle-range theory. While theories can be developed based on a range of languages, I will specifically use a semimathematical language.

Semimathematical Languages for Dynamical Theories

Hanneman (1988, p. 17) differentiates between static and dynamic theories. Static theories focus on covariation and generally take the form "the greater the X, the greater the Y." In contrast, the focus of dynamic theories is on the process of change as the object to be explained. Theorizing that deals explicitly with dynamic processes may be more appropriate than static analysis if the goal is to understand change (Hanneman 1988, p. 19).

Furthermore, in order to build dynamic theories, Hanneman (1988, pp. 20–27) sees three different approaches that can be taken:

- *Everyday language*, enriched with generally accepted scientific writing principles (e.g., consistent use of terms, obligation to quote, etc.), is the most common form to express theoretical statements about change processes. However, theoretical statements made in everyday language have a tendency not to specify the relations among concepts precisely enough. Hence, the quality of the theory may be diminished by the characteristics of language.
- *Mathematical language*: Using mathematics for theory building has the advantage that all of the information included in a statement must be made explicit. However, mathematics may become inadequate once the issue under study gets more complex. Hanneman (1988, p. 25) argues that "most mathematical languages for stating theories of dynamics are more powerful than we need for simple problems, and not sufficiently powerful for complex ones."
- *Semimathematical languages* are the "languages" embodied in softwares such as Matlab, VENSIM, Stella/iThink or Powersim. On the one hand, they aim to overcome the practical, technical and stylistic limitations mathematical languages have in the context of building rich dynamic theories. On the other hand, they aim to overcome the limitations of everyday language (Hanneman 1988, p. 25). Semimathematical languages are systems of equations at heart but they facilitate the use of long, expressive variable names.

The stock-and-flow diagrams used to describe my simulation models are visual representations of the semimathematical language embodied in the software I use.

By underlaying stock-and-flow diagrams with equations in the computer program "VENSIM," a dynamic theory is expressed in a semimathematical language.

System Dynamics

System Dynamics (SD) was developed by Jay W. Forrester in the late 1950s and early 1960s by applying control principles from electric engineering to management and economics (Lane and Oliva 1998, p. 219). System Dynamics is best described as a methodology which can be used to describe the structure of causality driving change process. It can also be used to elicit the behavior brought about by complex structures of causality. In order to do so, change processes are modeled as dynamic systems, as a set of equations. Basically, any kind of change process can be modeled as a system, regardless whether it stems from the physical, ecological or social domain. Ideally, System Dynamics models are developed to meet a specific purpose. It is crucial that they represent reality in such a way that they are adequate representations of the specific aspect of reality under study. By comparing the model with observations of reality and improving it, a useful and empirically grounded description of the aspect of reality under study gradually emerges.

The central building blocks of a System Dynamics model are called *stocks*. They are changed over time by in- and out*flows*. The dynamics of a system can be shown to result from the interactions between its stocks and flows over time, in particular from circles of causality called *feedback-loops* (see Sects. 2.3.5 and 2.3.6). Usually, auxiliary variables are used to control flows.

Elements of the System Dynamics Modeling Process

According to Sterman (2000, p. 85), "there is no cookbook recipe for successful modeling, no procedure you can follow to guarantee a useful model. Modeling is inherently creative." However, this does not mean that modeling should proceed ad-hoc. In order to guide the modeling process, several logical steps have been proposed in the System Dynamics literature. I found the following:

- Richardson and Pugh (1999, p. 16) propose the following seven stages: (1) system identification and definition, (2) system conceptualization, (3) model formulation, (4) analysis of model behavior, (5) model evaluation, (6) policy analysis and (7) model use or implementation.
- Sterman (2000, p. 85) conceptualizes the System Dynamics modeling process as consisting of the following five steps: (1) problem articulation (boundary selection), (2) formulation of dynamic hypothesis, (3) formulation of a simulation model, (4) testing, (5) policy design and evaluation.
- Citing Maani and Cavana (2000), Jackson (2003, p. 69) reports (1) problem structuring, (2) causal loop modeling, (3) dynamic modeling, (4) scenario planning and modeling, (5) implementation and organizational learning as the distinct steps towards the development of an SD model in the context of management.

- In addition, the following eight heuristic principles for model-based theory building by Schwaninger and Groesser (2008) have important implications for the System Dynamics modeling process: (1) Issue orientation, (2) Formalization, (3) Generalization, (4) Validation, (5) Explanation, (6) Falsification, (7) Process design, (8) Concept of learning.

As can be seen from the examples above, there is some variation in the processes found in the literature. Yet fundamental discrepancies regarding how modeling should proceed do not seem to exist. Further, all contributions insist that modeling is of an iterative nature, and hence these steps should not be considered to be strictly sequential. Reviewing the modeling processes found in the literature, I identified the following four steps which serve the requirements of my study best (in brackets the corresponding chapters are given).

1. Description of the problem situation (Chaps. 3, 4 and 5)
2. Development of a dynamic hypothesis (Chap. 6)
3. Quantitative modeling and testing (Chap. 7, Appendix C)
4. Scenario and policy analysis (Chap. 8)

2.2.2 Related Methodologies

The research design of this study is partially inspired from other social science research methodologies, in particular Soft Systems Methodology (SSM) and Grounded Theory, which both can be seen as epistemically related to System Dynamics. SSM enriches the systemic perspective of System Dynamics, whereas Grounded Theory provides useful insights into theory building. Grounded Theory contributes to the research design of this study the concept of 'theoretical sampling' of data or interviewees, its insistence on iterative research and the provision of methodical guidance in the analysis of the interviews.

Soft Systems Methodology

Soft Systems Methodology (SSM) was developed over the last few decades by Peter Checkland and colleagues at Lancaster University. At the core of SSM lies the insight that most situations can be usefully analyzed by treating them in a systemic way. By developing systems-thinking models of a problem situation, a debate over culturally feasible and systemically desirable changes can be initiated among participants of the problem situation. This shared understanding of the problem situation then forms the basis for taking action in order to improve the situation.[2]

[2] Seminal publications on SSM are Checkland (1993, 2005) or Checkland and Scholes (1998).

At a very basic level, the concept of the *system* refers to the idea that a set of elements are connected together and form a whole. More precisely, Checkland (1993, p. 317) defines a system to be

> (...) a model of a whole entity; when applied to human activity, the model is characterized fundamentally in terms of hierarchical structure, emergent properties, communication, and control. (...) When applied to natural or man-made entities, the crucial characteristic is the emergent properties of the whole.

Consequently, *Systems Thinking* makes use of the concept "system" to order thinking about the world. In SSM this is contrasted with the notion of *Systems Practice*, which implies using systems thinking to initiate and guide actions that are taken in the real world (Checkland 1993, p. 4).[3] This is done by setting "some constructed abstract wholes (often called 'systems models') against the perceived real world in order to learn about it" (Checkland and Scholes 1998, p. 25).

For this study this means that the term "system model" should be understood to be synonymous with the terms "(local) theory" and "model," *as long as the theory- or model-building endeavor relies on a systems thinking perspective*. It is possible to fully integrate SD and SSM.[4] However, I do not aim to integrate SD and SSM in this study. Rather, SSM is used to provide selected concepts such as the concept of the problem situation used in Chap. 3, as well as a general methodical guidance.

Grounded Theory[5]

The beginning of grounded theory can be traced to the publication of a book entitled *The discovery of grounded theory* by Glaser and Strauss (1967). Since then, a large body of social science research has been produced with this methodology. Grounded theory is to be understood as a conceptually condensed, methodologically justified and internally consistent collection of proposals that have proven useful for the production of rich theories within the context of social sciences (Strübing 2004, p. 7). Grounded Theory heavily relies on an iterative research process that focuses on the repeated comparison of theoretical concepts with empirical data (Oxford Dictionary of Sociology 1998, grounded theory).

2.2.3 Description of the Research Process

The research design, as I described it above, had to be further specified. In particular, appropriate methods had to be chosen and applied in a sensible and efficient manner.

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[3] See Jackson (1991, 2000, 2003) for introductions into the broad field of Systems Thinking.

[4] See for example Lane and Oliva (1998), Rodriguez-Ulloal and Paucar-Caceres (2005) or Paucar-Caceres and Rodriguez-Ulloal (2006).

[5] The following discussion of grounded theory is highly stylized towards its usefulness for this study. See Strübing (2004) or Flick (2005, Chap. 15) and the literature quoted therein for a more comprehensive discussion of Grounded Theory as a standalone research methodology.

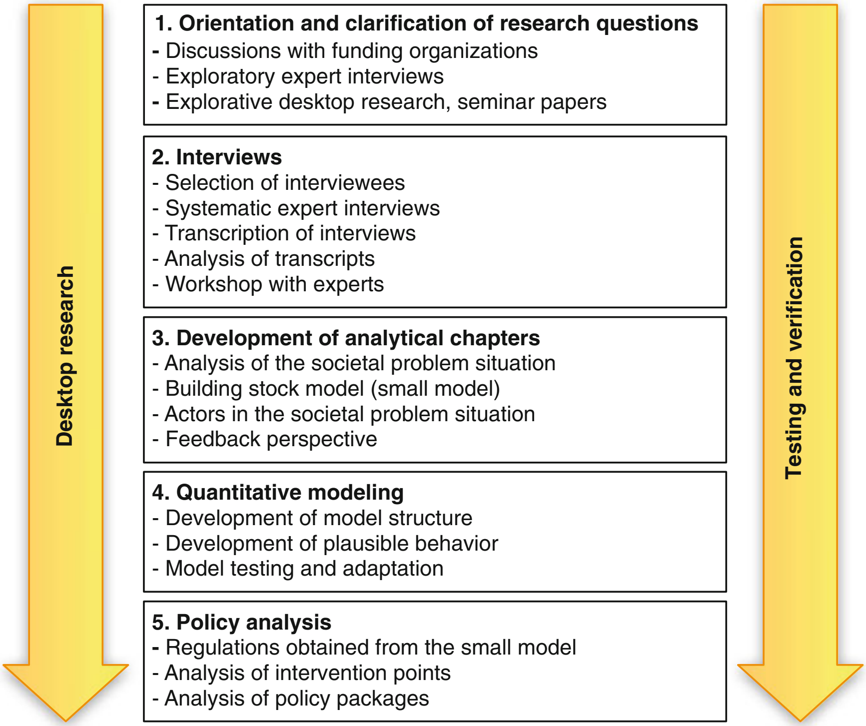

Fig. 2.1 The research process of the study

Figure 2.1 summarizes the most important steps of the research process in a linear fashion. Of course, several iterations between the different phases occurred, and in consequence the research process was anything but linear. In the following, I report on the research process. Further details on methods are provided in Sect. 2.3.

Orientation and Clarification of Research Questions

The study started from a desire to address the general question.[6] Due to the complexity of the whole situation, System Dynamics quickly emerged as the methodology of choice. However, as a first step, more specific research questions had to be developed. This entailed an orientation phase. During the orientation process, informal discussion with experts and colleagues proved helpful. Furthermore, exploratory desktop research and some exploratory expert interviews helped to develop preliminary insight into the societal problem situation under study and into the research

[6] It reads as follows: How can the diffusion of energy-efficient renovations of (residential multifamily) buildings be accelerated in order to reduce Switzerland's emission of CO_2? (also see page 4).

literature. During this phase, I wrote a series of seminar papers for the mandatory doctoral coursework at University of St. Gallen. The coursework proved quite helpful as it allowed me to begin to structure the results from exploratory research, and to clarify the research design, methods and conceptualization of this study. The feedback gained in this early phase significantly helped to shape the study.

Interviews

Between fall 2007 and summer 2008 I prepared and conducted a series of systematic expert interviews. Specifically, I selected and contacted interviewees involved with recent construction projects in the city of Zürich. Based on the insights obtained from the orientation phase, I prepared a questionnaire and used it to conduct open, semi-structured expert interviews. The interviews were recorded, transcribed and later analyzed regarding their content. The systematic interviews contributed to an enriched understanding of the societal problem situation. They allowed me to understand drivers and barriers to the diffusion of energy-efficient renovations from the perspective of practitioners. Further, I could identify the major actors involved in the societal problem situation. In addition, I attempted to develop a causal loop diagram explaining the diffusion process based on the insights from the systematic interviews. These insights were discussed at the first workshop with a group of practitioners (see Müller and Ulli-Beer 2008).

Development of Analytical Chapters

The orientation phase and the interviews made me realize how complex the societal problem situation was. In order to structure the many aspects, I chose to develop four analytical perspectives. There, I analyzed the societal problem situation (Chap. 3) and I developed a small simulation model of the dynamics of the building-stock (Chap. 4), which would later serve as a module in the large simulation model. Further, I analyzed actors (Chap. 5) and developed an explanation of the diffusion of energy-efficient renovations (Chap. 6). These chapters served as the basis of the development of the large System Dynamics model.

Conceptualizing these analytical chapters helped me to develop an aggregate perspective that was nevertheless grounded in the stories and insights obtained in the interviews. Comparing the—rather awkward—causal loop diagrams presented in Müller and Ulli-Beer (2008) with the much more precise and consistent causal loop diagram presented in Chap. 6 exemplarily shows how I gradually arrived at a more aggregate perspective.

Quantitative Modeling

Developing the structure of the large simulation model was substantially facilitated by the analytical chapters, as I could draw on the insights presented there. In contrast, it was much more difficult to calibrate the model. This was because I hardly ever had time series data of the variables used in the model. Therefore, I often had to draw on non-numerical data in order to elicit a plausible model behavior. For the same reasons, I generally could not test quantitatively how well the model reproduced empirical behaviors and therefore I had to rely on plausibility considerations instead.

Ultimately, developing the structure, calibrating the model's behavior and testing the model were closely related activities. Typically, I would run the model after every change in the structure to ensure that the change improved the model. When the model failed to produce the expected behavior, I would change its structure or parameters until I was satisfied with the results. Similarly, policy analysis also contributed to model testing as implausible results lead to several improvements in both models.

Policy Analysis

In a System Dynamics context, policy analysis is the practice of using a simulation model to find interventions which affect one or several reference modes in a desired manner. In my study I used both, a small model of Switzerland's stock of buildings and a large model of the diffusion of energy-efficient renovations, to conduct policy analysis. The small simulation model was used to run several scenarios representing different policies. Policy recommendations were elicited based partially on the simulation results. In the case of my large simulation model, I systematically analyzed how certain parameters responded to a 50 % increase after the year 2010. In addition, I analyzed several sets of intervention levers.

Continuous Activities

Between summer 2006, when Dr. Ulli-Beer and me wrote a proposal for funding, and early 2012, when this study was completed, spectacular changes occurred in the societal problem situation addressed by this study. The literature, both scientific and from practitioners, addressing the fields of climate change, energy use and buildings developed spectacularly. Therefore, I conducted desktop research and testing and verification of my results throughout the research process.

2.3 Methods

2.3.1 Literature Review

Reviewing the literature is a routine component of academic writing. Because this study is mostly a synthesis of existing knowledge, it is appropriate to consider the literature review as an important methodical component. A limitation of the broad scope of my study is that I cannot claim to have a comprehensive knowledge of the literature relating to all the aspects of my study.

I primarily selected publications according to the contribution they could make towards the development of the model. This means that I also relied on non-peer-reviewed publications from fields of practice, such as the construction industry or governmental offices. I deemed such contributions to be important regardless whether they were peer-reviewed or not. Throughout the research process, I distinguished between the following three types of publications.

- Articles in peer-reviewed journals or publications which underwent other kinds of rigorous review by peer scientists.
- Scientific reports from or for practitioners, for example from government agencies or contracting research agencies.
- All other types of reports of practitioners, which do not adhere to scientific standards but may nevertheless provide insight into domains where there is no scientific literature.

Using the fist two types of publications posed no special difficulties. The literature published in peer-reviewed journals provided both empirical and theoretical insight. The rich and extensive literature produced or commissioned by government agencies proved to be particularly useful regarding empirical aspects. Publications of the third type sometimes also provided important insights. However, I was much more critical to publications of that type and tried to triangulate their validity with other sources where possible.

2.3.2 Selection of Interviewees

The question, whom to interview, is an important aspect of any method which relies on interviews. Several approaches can be found in the literature. In survey research, statistical representativeness is the 'gold standard' of empirical work. This is typically achieved by randomly selecting members of the population studied Diekmann (1999). When face-to-face interviews are preferred to mail or phone surveys, statistical representativeness can generally not be achieved for practical reasons. This is because face-to-face interviews easily take 1 or 2 h, and statistical representativeness easily requires 200 or even much more interviews. However, the idea that the sample of persons interviewed should be representative of the population under research is not alien to researchers using face-to-face interviews. For such methods, several distinct approaches are described in the literature (Flick 2005, Chap. 7). A frequently used approach, called *theoretical sampling*, was developed in the context of the Grounded Theory methodology (Glaser and Strauss 1967). There, the selection of interviewees is guided by the research process itself. As new insights emerge during the research process, researchers need to find new interviewees from whom they expect new insights into the phenomena under study (Flick 2005, p. 102). Another approach is to determine important categories across which the sample of

Table 2.1 Sample of the explorative interviews

Frequency	Description of interviewees
4	Senior researchers at institutions of higher education
1	Senior member of Zürich's construction department
1	Executive member of a building association in Zürich
1	Architect in the city of Aarau

interviewees needs to vary and then select interviewees such that all categories are represented.

In my study, I used an approach somewhere between the openness demanded by Grounded Theory and the confinement of pre-determined categories. Actors within the value creation chain involved with the renovation of buildings were selected according to quite pre-determined categories. Yet, those categories were partially based on the insights from the exploratory interviews. Actors outside the value creation chain were selected during the research process as their importance became evident. My research design, as introduced above, relies on three different types of expert interviews, namely *exploratory expert interviews*, *systematic expert interviews* and *validating expert interviews*. In the following, I briefly describe the interviewees in these three types of interviews.

Exploratory Interviews

In total, I conducted 7 exploratory interviews for this study (see Table 2.1). The interviewees came mostly from institutions of higher education. The interviews with the researchers and the member of the public administration helped to quickly gain insight into the societal problem situation. In contrast, the exploratory interviews with an architect and a member of a building association led to more operational knowledge and exemplarily showed the range of knowledge which could be elicited from practitioners.

Systematic Interviews

In order to find interviewees for the systematic interviews, I searched for recent renovations in or near the city of Zürich.[7] By using recently renovated buildings as a reference, representatives of actors inside the value creation chain could be identified. For each of the reference buildings, I interviewed a representative of the building owner, the responsible architect and a representative of the construction company where possible. All reference buildings were residential multifamily buildings in the

[7] I am deeply indebted to Dr. H. Gugerli for supporting me in this phase.

greater Zürich area. In line with the scope of this study (as discussed on p. 17), only buildings where the flats were rented to tenants were considered.

A conscious limitation of my sampling for the systematic interviews is that I did not consider tenants. This is for two reasons. First, I thought that building owners base their decisions on their perception of tenants rather than on the actual behavior of tenants. Therefore it seemed much more important to know how building owners perceive the prospects of renting energy-efficient housing. Second, I thought that qualitative interviews with tenants would not be very yielding. In contrast to the other actors in the value creation chain (professional building owners, architects and construction companies), tenants do not routinely rent flats or have professional knowhow in that domain. Therefore, survey methods reaching out to large numbers of tenants would probably provide some insight.[8]

In addition to the experts from the value creation chain, a number of representatives from actors outside of the value creation chain were interviewed in the systematic interviews. These were from various associations. Table 2.2 shows the structure of the sample of interviewees in the systematic interviews.

Validating Expert Interviews

As part of the testing and verification of my work in general and the simulation models in particular, I conducted validating expert interviews. In particular, I discussed different stages of Chaps. 4 and 6 as well as both simulation models with a small number of experts. Table 2.3 shows the composition of the sample of these experts.

Table 2.2 Sample of the systematic interviews

Frequency	Description of interviewees
5	Professional building owners[a]
3	Architects
3	Representatives of construction companies
1	Swiss real-estate association SVIT
1	Swiss tenants' association
1	National association of building associations

[a] Including persons trained as architects who now are employed by building owners as asset managers

[8] In fact, I am not aware of any empirical research in decision making of tenants. Discrete choice experiments over a statistically representative sample might yield conclusive insights regarding tenants' willingness to pay for energy-efficiency in rented apartments.

Table 2.3 Sample of the validating interviews

Frequency	Description of interviewees
4	Researchers at institutions of higher education
1	City of Zürich's construction department
1	Canton of Berne's energy department (AUE)
1	Federal Office for the Environment (BAFU)

2.3.3 Expert Interviews

Exploratory Expert Interviews

Exploratory expert interviews served as an important starting point. They helped to orient myself in the first phase where I worked on the clarification of my research questions and the research design. Further, they helped me develop the questionnaire for the systematic expert interviews.

For the exploratory interviews, I did not yet have a questionnaire. Instead, I prepared myself for each interview with a mind-map which contained several aspects I wanted the interviewees to elaborate on. Among these were the questions, why and how buildings got renovated and what kind of actors were involved. In two cases, interviewees described the renovation process of a recently renovated building. In other cases, interviewees elaborated more on technological aspects or the institutional context. The exploratory expert interviews might best be characterized as problem-centred expert interviews with a strong narrative element (Flick 2005, Chap. 9).

Typically, an exploratory or systematic interview lasted between 1 and 2 h and proceeded according to the following pattern: At the beginning of each interview, I asked for permission to record the interview and assured my interviewees confidentiality. With one exception, all interviewees allowed audio recording.

Systematic Expert Interviews

In order to gain a deeper, more representative perspective on the societal problem situation, I conducted 14 systematic expert interviews. All of these interviews were conducted with a questionnaire that followed the same logic (see electronic supplement for a typical questionnaire). However, I made some minor adjustments for each interview in order to account for the specific context an interviewee was in. A typical interview proceeded along the following lines:

- In a preliminary step, I asked some questions concerning the professional background of the interviewee. Then, I briefly introduced the different blocks of the interview, in order to give the interviewee an overview of my interests.

- As a first step, I asked the interviewee to elaborate on the motivation for renovating. This question was directed to either the reference building or buildings in general when the interviewee was not involved in a recent renovation.
- As a second step, I asked interviewees to describe the renovation process and identify the actors that were involved. In particular, I asked which actors influenced the energy efficiency of the renovated building. For each such actor, I additionally asked what interest he or she has in energy efficient buildings.
- As a third step, I asked my interviewees what societal actors or what external developments (such as rising energy prices or technological progress) could create pressure towards energy efficiency in renovations.
- Finally, I ended the interview by asking very specific questions that had emerged during the interview or that remained unclear. After the interview, I thanked my interviewees, invited them to participate in a workshop and gave a small gift as a token of appreciation for their time.

The systematic interviews are best described as open, semi-standardized expert interviews (Flick 2005, pp. 117–145). In my expert interviews, the persons interviewed were of interest because of their knowledge in a specific field rather than because of their personal characteristics. Expert interviews are generally conducted with a list of pre-formulated questions (questionnaire). Rather than simply answering "yes" or "no" to the questions of the interviewer, it is common that the participants enter into a dialog. Such interviews are qualified as *open* interviews. Because the interviewer needs to participate in the speech-situation during the interview, it is unlikely that a questionnaire can be implemented step by step as envisioned prior to the interview. Rather, this type of interview should be characterized as *semi-standardized*: More important than precisely following the questionnaire is that the interviewee takes on the responsibility of presenting an issue according to her or his perspective. This means that my interviews resembled narrative interviews at part. In particular, I tried to give interviewees the "responsibility" for the narration of the situation in the exploratory as well as in the systematic expert interviews. In order to do so, I first asked my interviewees to respond to my general question as extensively as they could. In that first phase, I mostly participated in the speech situation by asking for greater detail or clarifications. Only after interviewees had finished their narrations did I ask more specific questions from my questionnaire. For example, a typical interviewee might name four of five actors involved with the renovation of a building. On my questionnaire, however, I had an extensive list of potentially relevant actors. Once the interviewee finished elaborating, I specifically asked whether the other actors were important or not.

Validating Interviews

As the study progressed, I presented preliminary findings to colleagues and practitioners with particular expertise. The purpose was to test whether my work seemed reasonable to them and to get further insights in places where the study needed further refinement. These interviews were conducted in a rather informal manner.

2.3.4 Transcription and Analysis of Interviews

Transcription of Interviews

Soon after holding an interview, I transcribed it from the recordings. I transcribed from spoken Swiss-German into written standard German.[9] I took great care not to alter the meaning during transcription. In line with Deppermann (2001, p. 39) I tried to maintain precision on words and significant signs. However, because I was only interested in the content and the information my interviewees stated explicitly, I did not need a sophisticated transcript. Had I intended to perform linguistic or hermeneutic analysis, then much greater precision would have been required. In my case, however, I ignored obviously irrelevant passages and meaningless filling sound from the transcripts.

Coding

I imported the transcripts into MAXQDA,[10] a software that supports the analysis of textual data. I coded the texts with codings that emerged throughout the process (see electronic supplement). During the coding process, spontaneous ideas and insights were written as short, informal memos and linked to the passage in the text which triggered the reaction. I coded the transcripts several times. Initially, I coded the texts in an explorative manner, as I tried to find meaningful concepts and tie them to passages in the text. Later, I coded the texts to ensure consistent application of the codings. In the literature, this has been called "open coding." Open coding is often followed by axial and selective coding. Thereby, researchers aim to bring the concepts identified in a text into relation to each other (axial) and eventually derive the core concepts of the issue under study (selective) (Flick 2005, p. 259).

Interpretation and Use of Text Passages

In my study, I did not apply axial and selective coding in order to develop a theory. Instead, I used the coded passages for content analysis. This means that I switched methodologically from an open approach inspired by grounded theory to the more closed approach of content analysis. The open approach was used to empirically

[9] Swiss German consists of several distinct dialects which however are generally not written. Instead, standard german ("high german") is used for all written purposes.

[10] See http://www.maxqda.com for further information on the software.

investigate relevant categories. Specifically, I aimed to reduce my material to the core information.

According to Flick (2005, 280f.), content analysis typically relies on three different techniques. The material can be summarized and paraphrased. It can be explicated in order to clarify diffuse or unclear passages by drawing on contextual materials. Or researchers may conduct structuring content analysis which aims to find types, regularities or dimensions. In my study I mainly used structuring content analysis. articularly in Chap. 5 where I describe actors and present different types of actors, I systematically use text passages to justify my typologies argumentatively. In order to do so, I sometimes paraphrase statements of interviewees and explicate the meaning of it. This however mostly contributes to structuring analysis.

I finally translated the quotes I used in the study from German to English. I took great care to stay as close as possible to the wording used by my interviewees. However, if an interviewee answered "yes" to a question, I reformulated the question as a statement.

2.3.5 Causal Loop Diagrams[11]

Causal Loop Diagrams (CLDs) are a device for graphically describing the feedback structure of systems. Specifically, CLDs are used to depict the structure of causality between variables rather than the structure of correlation between variables. A causal loop diagram consists of variables that are linked with an arrow according to the direction of causality: For example, in Fig. 2.2, a positive causal relationship (marked with a "+") is postulated to exist between the *Birth Rate* and the *Population*, and a negative relationship (marked with a "–") is postulated to exist between *Death Rate* and *Population*. This means that a rise in the birth rate causes the population to grow and a rise of the death rate causes the population to shrink.

By coupling several variables and arrows in a feedback loop, an endogenous explanation of a system's causal structure is presented. Depending on the dominating polarity, a feedback loop is reinforcing (marked with "R" or "+") or balancing (marked with "B" or "–"). Reinforcing feedback loops strive for exponential growth, whereas balancing feedback loops converge towards a value. By combining reinforcing and balancing feedback loops as well as adding delay, any system can be sketched in a qualitative way.[12]

The example from population biology shown in Fig. 2.2 illustrates the use of CLDs: The higher the number of animals in the population is, the more births occur if fertility remains constant. This loop for itself would cause the population to grow

[11] This whole subsection is based on Sterman (2000, 137ff., p. 141).

[12] In the System Dynamics literature there is an interesting strain of research investigating system archetypes that aims to find the combinations of reinforcing and balancing feedback loops and delays that constitute the most fundamental (generic) building blocks that make up a larger system. See for example Senge (2006, pp. 389–400), Wolstenholme (2004) and the literature quoted therein.

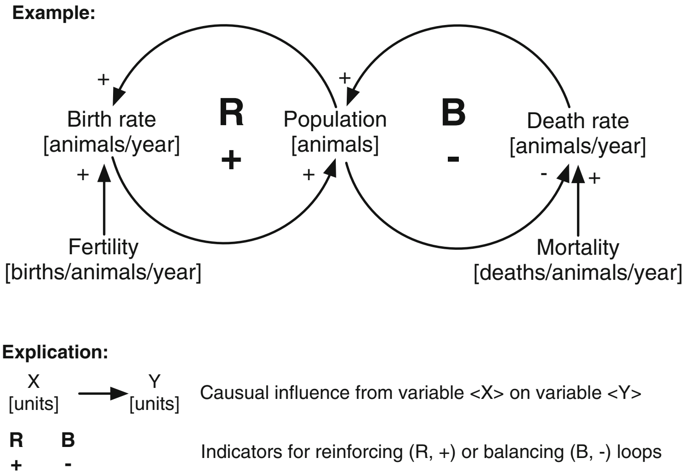

Fig. 2.2 Example of a causal loop diagram from population biology (*top*), including explanation of the symbols (*bottom*) (Sterman 2000, p. 138)

exponentially towards infinity; it is reinforcing (marked with "R"). However, there is a balancing feedback loop which prevents the system from growing exponentially (marked with "B"): Since a rise in the population also causes the death rate to grow, the population is again diminished.

While CLDs are valuable devices for the visualization of a system's feedback structure, they have problematic aspects too. As CLDs cannot provide the same rigor as SD simulation models, they risk oversimplifying an issue as well as remaining vague in important aspects, particularly with regard to distributions and numerical values. Yet, because SD simulation models often are very detailed, CLDs are useful devices for communicating the structures of a SD model.

2.3.6 Quantitative Modeling with System Dynamics

Causal loop diagrams are a useful tool to represent the main structure of causality which gives rise to dynamic complexity (see Chap. 6). Yet ultimately, they do not allow for too much precision, and they cannot be used to analyze the effects of multiple causalities. Quantitative simulation, in contrast, allows to understand how structures of causality produce a system's behavior. In System Dynamics, the use of stock-and-flow-diagrams is well established. These diagrams are a tool to visually represent the basic structure of System Dynamics models. In order to actually produce computer simulations using a computer simulation software (such as VENSIM), such stock-and-flow diagrams need to be specified with the equations and parameters. Figure 2.3 shows the graphic elements that are typically used in stock-and-flow diagrams. This example depicts the same model as introduced above (see Fig. 2.2).

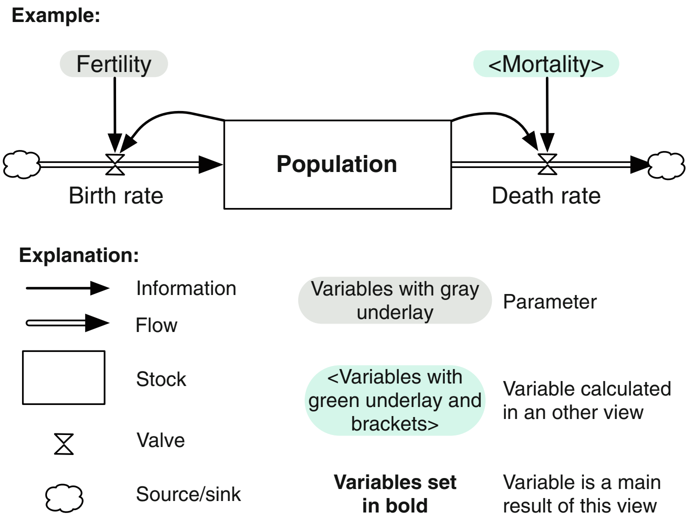

Fig. 2.3 Example of a stock-and-flow diagram from population biology, based on Sterman (2000)

Note that stocks can only be changed by in- or outflows. The rate of flow is controlled by valves. Valves can either be constants or a function of other variables. By recursively making stocks, flows and auxiliary variables dependent from each other, feedback loops of any complexity can be simulated. However, in order to yield a computable simulation model, the equations need to be specified. For example, the POPULATION was modeled as a stock here. Mathematically, all accumulation processes follow the same structure. The value of a stock is defined as an integral of the in- and outflows plus the initial stock. Equation 2.1 shows how the POPULATION stock is calculated in this example.

$$\text{Population}_t = \int_{t_o}^{t} [\text{Birth rate} - \text{Death rate}]ds + \text{Population}_{t_o} \tag{2.1}$$

Further, the BIRTH RATE is calculated according to Eq. 2.2, as a function of the current state of the population and a parameter.

$$\text{Birth rate}_t = \text{Population}_t * \text{Fertility}_t \tag{2.2}$$

With these building blocks any kind of system can be represented: Instead of calculating a population of animals, any other countable variable can be substituted. Such variables can be *persons*, *energy-efficient buildings*, the *share of building owners which invest into energy-efficiency*, and so on.

I used a computer simulation program called *VENSIM*[13] was used. VENSIM is particularly well suited because it allows to graphically sketch the model by relying on the stock-and-flow diagrams.[14]

VENSIM allows to replicate a model structure for several instances by using subscripts. Imagine, for example, that the small population model above should be used to simulate the population dynamics of three different countries. While it would be possible to create that model structure three times, it is unnecessarily tedious. Instead, VENSIM allows to use the same model structure to track different instances by giving each instance a subscript value. Internally, VENSIM then calculates the model structure for each instance.[15]

Conventions for the Presentation of Model Structures

When I present model structures, I generally show the stock-and-flow-diagram of the sector, I explain how the important variables are calculated, and I provide the equation. I generally rely on the following conventions:

- I indicate subscripts by stating the subscripts in the variable name. For example, the variable ATTRACTIVENESS OF ENERGY- EFFICIENT HOUSINGS BY TENANT is subscripted by tenant types.
- I shorten variable names by inserting square brackets where adequate. For example, the variable CONSTRUCTION COST COMPONENT OF THE RENT FOR PAINTJOB HOUSING may be abbreviated as CONSTRUCTION COST COMPONENT [...]
- I write all equations without time indices to facilitate readability.

I frequently use the terms "endogenous" and "exogenous". An endogenous variable is a variable which is part of a loop. In the example in Fig. 2.3, the BIRTH RATE is an endogenous variable, because it is calculated as a function of the system itself. In contrast, the variable FERTILITY is exogenous, because it remains unchanged regardless of the state of the system.

2.3.7 Model Testing and Validation

In order to assure the quality of a simulation model, model testing needs to be conducted. In the System Dynamics literature, a large array of tests have been described (Barlas 1996; Sterman 2000; Schwaninger and Groesser 2009). As a model passes

[13] Specifically, VENSIM®DSS for Windows Version 5.9 was used, running on current versions of Windows XP, emulated by *Parallels®Desktop 5 for Apple Macintosh*, executed on current versions of Mac OS X 10.6 (Processor: 2.3 GhZ Intel Core i5). See http://www.vensim.com, http://www.parallels.com and http://www.apple.com for further information on the software used.

[14] *PowerSim* (www.powersim.com), *Stella/iThink* (http://www.iseesystems.com) and similar software might be just as adequate.

[15] See http://www.vensim.com/subscript.html, accessed 28 June 2011, for a more detailed explanation.

a test, it can be considered to be more valid than before. If a model fails a test, it needs to be adapted so that it becomes better and eventually passes the test. In fact, model testing closely mirrors the evolutionary process: Just as species become adapted to their environment, a model must become increasingly adapted to the available information. Adaptation of a model can be seen to correspond to natural variation and model testing can be seen to correspond to natural selection. As the model is iteratively tested, adapted and tested again, it gradually evolves and becomes better adapted to the available information.

Generally, model tests can be categorized as *contextual*, *structural* or *behavioral* tests. Contextual model tests address questions as to whether the boundaries are adequate or whether the purpose of the model has been clarified sufficiently. Structural model tests address questions as to whether the model structure corresponds with the relevant knowledge of the system. Finally, behavioral model tests investigate whether the model behavior adequately reproduces the observed behaviors (Sterman 2000; Schwaninger and Groesser 2009). I will further elaborate on model testing in Sect. 7.9 and Appendix C.

2.4 Discussion and Conclusions

In a summary of critiques of System Dynamics, Jackson (2003, pp. 78–82), states the following criticism:

> To those working in specific disciplines and trained in the scientific method, system dynamics seem to jump to building their models without doing their homework. They simply ignore existing theories in the field they are exploring. At other times, if insufficient data are known about an area of concern, they remain prepared to plough on, building their models without bothering to collect all the relevant data that others would regard as essential. Judgement rather than proper scientific research is used to fill in the gaps. (Jackson 2003, p. 79)

The criticism by Jackson, above, boils down to the following basic demands: Modeling requires substantial empirical grounding, a broad knowledge of existing theories in the field of study, and a clear distinction between knowledge and assumptions. That seems all very reasonable, and I absolutely agree with such demands. However, given the fact that research is a process that often needs to start from scratch, a "chicken-or-egg" situation may arise. On the one hand, data collection without a model may be difficult or inefficient. On the other hand, having a model without empirical grounding is obviously not very useful either. I think that Jackson (2003) misses an important point, namely that data-collection and modeling are two mutually dependent operations. Only with a model do we know what kind of data matters, and only a model which is grounded in data matters. Further, I agree with Sterman (2000) who argues that it is preferable to include into the model causal relevant relationships rather than ignoring such relationships on grounds of uncertain or missing data. By including probable causes into the model, even when well-established knowledge is missing, System Dynamicists follow a pragmatic approach. By acknowledging a potentially relevant cause, further empirical research may be motivated, either by the original modeler, by subsequent researchers, or by model users. An important pre-condition, however, is that each relationship needs to be justified by a discussion of the reasons of including it and by the plausibility of the relationship. Yet ultimately, it is best and most convenient if System Dynamicists can draw on a well-developed literature and on comprehensive data sets.

Ultimately, System Dynamics simulation models are best characterized as empirically grounded, theoretical constructs. In particular, they transcend the simple divide between "qualitative" and "quantitative" approaches. In any model, numerical data from surveys or observations can be integrated with insights generated from "qualitative" research. In order to arrive at useful model structures, any source of information may be relied upon. Non-numerical empirical research methods (often called "qualitative" research methods) can provide a whole range of contributions to computer-assisted theory building with System Dynamics: Information gained from interviews or workshops can help to understand the model context or inform the conceptualization of the model structure. In fact, the System Dynamics literature has developed *group model building* as a method for building models together with practitioners (Vennix 1996; Andersen and Richardson 1997a,b).

A key difference between econometrics and computer-assisted theory building with System Dynamics is that econometrics is about *observation* while System Dynamics is about *representation*. No respectable scientist would approve of "inventing" the data used for the estimation of econometric models. Such an approach would rightfully be classified as fraud. Computer-assisted theory building with System Dynamics works the other way round: In order to build a model of observed reality, model structures must be combined in a way that reproduces observed reality reasonably well and that is useful for the investigation of the issue under study.

Casual observation indicates that empirical data collection in the social sciences is generally not guided by a formal model, at least in the social sciences I know. Instead, a whole 'academic industry' is occupied with relentless testing of hypotheses. Yet, hardly any effort is made to build causal, formal, explicit and dynamic models. Instead, verbal theories are used to deduct hypotheses for empirical testing. In contrast, 'theory building with System Dynamics' would offer the social sciences an approach to guide empirical research and to integrate its results into a formal model.

The research design of my study is perhaps best explained with a metaphor. According to this metaphor, most academic research aims to produce a small, specific, and well-made puzzle-piece. In contrast, my research design aims to put together a picture from the pieces that are currently available.

Reflecting on the research process of my study, I think that there is reason to have confidence in the structure of my model. This is because I could draw on a broad and extensive literature, and because my interviews helped me a lot to describe the structure of the diffusion process. In contrast, the operationalization phase proofed very challenging for several reasons. First, the built environment is incredibly complex, and only for some aspects data and information were found. In addition, obtaining yearly data often proved impossible. I therefore think that the model behavior should be treated as a first, serious approach. Yet further research almost certainly will improve the behavioral validity of the model.

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