

# The Structure and Dynamics of the Residential Built Environment: What Mechanisms Determine the Development of the Building Stock?

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## I. Abstract

The residential built environment and the belonging values creation network consisting of several interdependent actors has not obtained much attention from the field of science. Even though much literature exists about the diffusion of innovations (e.g., Rogers 1995), the diffusion process of innovations in the residential building system is not fully understood. Hence, the enormous potential to reduce CO<sub>2</sub>-emissions cannot be captured. The authors try to elaborate the different processes in the built environment in order to provide policy interventions based on a simulation study. Based on this research project, we present interconnections between the different actors in the system. Thereby, we depict the inner structure of each important actor group by some detail. In the current version of the paper, some details about the architects and the production supply chain consisting of producer-supplier-technical firm is provided. For the other actors, empirical survey research is in the process of being executed, after the completion of which dedicated models can be presented, different policies tested and implications discussed.

## Keywords

Qualitative model, built environment, path dependency, organizational learning, action theory, theory development

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## 1. Introduction<sup>1</sup>

Meadows et al. reported in their famous study 'Limits of Growth' that global ecological constraints related to resource use and emissions would have significant influence on global developments in the twenty-first century (Meadows, Meadows et al. 1972). In an updated version of the study, they conclude that "humanity has already **overshot the limits of earth's support capacity**" (Meadows, Randers et al. 2004). Wackernagel et al. define an easy to comprehend measure, the ecological footprint, and compare it to the world carrying capacity. The ecological footprint is the average land area that is required to provide the resources and to assimilate the emissions of global society at a specified standard of living (Wackernagel, Schulz et al. 2002). Nowadays, humankind needs actually the equivalence of 1.2 earths to sustain their consumption at the actual level. Given this, the exigence to reduce emission is apparent (World Bank 2001). One possibility to reduce the pressure on the world ecological system is the significant reduction of CO<sub>2</sub>-emissions (UNFCCC 1997; IPCC 2007).

### 1.1 Issue Statement, Significance of the Topic, and Research Gap

As stated at another place (Groesser and Bruppacher 2007), the energy consumption of the Swiss residential built environment contributes to a large extent to the Swiss CO<sub>2</sub>-emissions. The Swiss government has committed itself to significantly reduce the CO<sub>2</sub>-emission to achieve the vision of a 2000 Watt per capita society. Experts state that the severe reduction of greenhouse gas and energy consumption is achievable with the existing technologies (Jochem 2004; Koschenz and Pfeiffer 2005; Jakob 2006). Figure 1 shows a scenario with a time frame of 130 years in which the total annual energy consumption of the residential buildings (per capita) is reduced from 1700 Watt to 720 Watt (Koschenz and Pfeiffer 2005). However, the reality shows that these assumptions are not nearly matched, i.e., only 11% of the new constructions are built according to energy efficient standards (CEPE 2004; Minergie 2004), and only a low percentage of all refurbishments are executed in an energetically improving manner (Ott, Jakob et al. 2006). Hence, the uptake of the energy efficient measures is not as large as it should be in order to achieve the objective of the Swiss government. An important part of the problem is that the introduction of innovative technologies for sustainable buildings is a complex process of creating new socio-technical configurations and gradually adapting technology design and emerging practices of use. This is far more than a pure focus on technology design, as is the case in most technology-related R&D programs (Rohracher 2005). The **literature review** puts forward that research about innovation diffusion in the **construction industry is still in its infancy** and requires further investigations (Egbu, Kaye et al. 1998; Sexton, Barrett et al. 2001). Even though some research has been carried out to understand the social structure of the construction industry, and how this enables the sharing of knowledge and the communication of new concepts between the various parties involved, **no integrated theory exists that describes the structure and behavior of the residential built environment**. Weber (2005) has created a first conceptual framework which considers different actor groups (suppliers, users, policy-makers) and different kinds of networks (innovation network,

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<sup>1</sup> Some of the work reported here was carried out while the author was working as a researcher with the Interfaculty Center for General Ecology in Berne, Switzerland, Europe. The project "Diffusion Dynamics of Energy-Efficient Buildings (DeeB)" was funded by the Swiss National Science Foundation (Project No. 405440-107211/1).

policy network, information network). He uses mainly the mechanisms of self-organization and evolution to conceptualize the transformation of a system.

Despite this attempt, no approach incorporates the distributed decision making system with several independent actors in the building market. The players in the construction market are subject to the short-term oriented success dilemma and therefore exhibit resistance to new practices that are not in their portfolio of competence. This results in policy resistance of actors towards new innovations as well as decision and execution delays in the distributed decision system which is not explored. The construction system is bound to the trajectory it has been encountered in the last decades. Consequently, the system is locked in its old structure (Liebowitz and Margolis 1995).

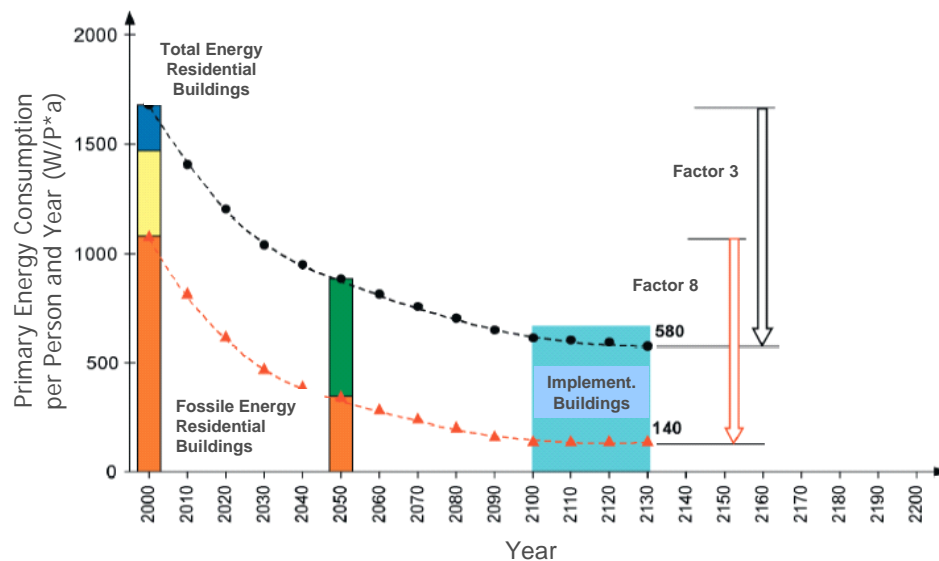


Figure 1: Intended Reduction of the Energy Consumption of the Swiss Residential Built Environment (Koschenz and Pfeiffer 2005) (the color code is not important in this instance).

## 1.2 Background, Context and Definitions

### Background: A Project-Based Case Study

The research about diffusion of energy efficient building innovations is a focal point for the Swiss ministry of Energy. The project ‘Diffusion of energy efficient Buildings (DeeB)’ is funded by the Swiss National Science Foundation (SNSF) as part of the National Research Program (NRP) 54.<sup>2</sup> It aims at analyzing and accelerating managerial and organizational adaptation processes that foster the diffusion of pioneering energy efficient technologies in the building sector. Psychological, managerial, sociological and economic theories as well as the results of empirical investigations about antecedents of behavior choices will be synthesized into a simulation model for a middle-sized Swiss city. The model will shed light on dynamic interactions between behavioral and contextual factors, thus explaining the diffusion of energy efficient buildings in a community (Kaufmann-Hayoz, Bruppacher et al. 2005). The project team is hosted at the Interdisciplinary Center for General Ecology at the University of Berne, Switzerland. After having

<sup>2</sup> Cf. also <http://www.nfp54.ch/e.cfm>.  
Groesser, Stefan N. et al.

shown the issue statement and the research project in which the following work, among others (e.g., Groesser 2006; Ulli-Beer, Bruppacher et al. 2006; Groesser and Bruppacher 2007), is done, we will concentrate on the development of the dynamic hypotheses.

### **Context: Residential Built Environment**

The residential built environment comprises of all buildings in Switzerland which have accommodations with their purpose providing living space. Hence, administration or commercial buildings, storage space, school buildings, gymnasiums, etc. are not part of the residential building environment (BFS 2005). The residential built environment is defined by the physical structure and not the type of ownership.

### **Definition: Theory and a Dynamic Theory**

The definition of the term theory is an endeavor of philosophy of science that cannot result in a single and valid definition. The definition we use in this paper is a definition that is used both in natural sciences and in social sciences. It says that “theory should explain phenomena, identifying causal mechanisms and processes which, although they cannot be observed directly, can be seen in their effect.” (Marshall 1998, p. 666). In our paper, we will also refer to dynamic theory and dynamic hypotheses. The dynamical aspect stems from the over time behavior of the causal interplay between the elementary structures (Serman 2000). We will also use the term hypotheses and dynamic hypotheses, which is understood as proposition of a theory or dynamic theory, respectively – the difference compared to a theory is the lower level of certainty and confidence in the validity.

### **Definition: Mechanism**

In the philosophy of science much work has been done to address the issue of explanations as mechanisms (Machamer, Darden et al. 2000; Glennan 2002; Olaya 2004; Tabery 2004). Machamer et al. define a mechanism as follows: “Mechanisms are sought to explain how a phenomenon comes about or how some significant process works. ... To give a description of a mechanism for a phenomenon is to explain that phenomenon, i.e., to explain how it was produced. ... Mechanism descriptions show how possibly, or how actually things work (Machamer, Darden et al. 2000, pp. 2&3&21). Olaya concludes that System Dynamics modeling may be one of the best ways to depict this kind of explanations (Olaya 2004).

## 2. Research Strategy – Objective, Question, and Design

In the following chapter, the research objectives and research question for this study will be elaborated. Thereafter the research design will be described.

### Research Objective

The overall goal of the research project is to understand, describe and explain the process of innovation diffusion in the residential built environment in Switzerland; more specifically, in a middle-sized and representative region of Switzerland. The two objective of this paper are:

I.

The first objective is to analyze what **feedback mechanisms contribute to the diffusion** of technological energy efficiency innovations in the residential building environment in Switzerland.

II.

The second objective is to elaborate and indicate the **relative importance** of the different **mechanisms**.

For the analysis, as well as for the overall research project, we consider only innovations that take effect in the area of action of the relevant actor. These actors are architects, private building owners, institutional building owners, producers of energy efficient technologies, suppliers and technical firms that install these devices. It is not intended to concentrate on one specific innovation; it is rather the superordinate concept of energy efficiency.

As for the mechanisms, we especially concentrate on such that either **foster or hinder the diffusion processes and of the innovations**. By the utilization of multiple research methods, it is intended to approach the research object from several directions and, therefore, obtain a more holistic perspective.

### Research Questions for the Simulation Model

The paper concentrates on answering the following research questions:

- What are the essential system variables that explain the dynamic development of the total building stock?
- What is the overall dynamic macro behavior of the diffusion process in the distributed decision system ‘residential built environment’ given actors’ decision rules?
- What are main forces that steer management processes<sup>3</sup> of relevant actors in the value creation chain of energy efficient buildings?

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<sup>3</sup> Such as strategic planning process, supply capacity and hiring decisions.  
Grosser, Stefan N. et al.

## Research Method

In order to develop a dynamic hypothesis of innovation diffusion and to answer the research questions about the **development of the residential building stock over time**, several research methods have to be employed and integrated. In order to achieve the research objectives, a computational modeling approach is required (Dörner 1980; Dörner 1993). For the **multi-agent feedback situation** in the residential built environment, two computational **simulation approaches** are of relevance: System Dynamics modeling, and agent-based modeling. The fundamentals for the System Dynamics approach are documented in great detail (Richardson and Pugh 1981; Roberts, Andersen et al. 1981; Meadows and Robinson 1985; Coyle 1996; Sterman 2000). Agent-based modeling is one of the latest developed computational simulation approaches and is yet not embodied in the social sciences on a wide basis. Seminal work about agent-based modeling is provided by Holland (1995), Axelrod (Axelrod 1997; Axelrod 2005; Axelrod and Tesfatsion 2005), and Epstein (Epstein and Axtell 1996; Epstein 1999). Current research about simulation approaches explores the differences of both approaches in detail and distills their areas of application (Scholl 2001; Schieritz and Milling 2003; Borshchev and Filippov 2004; Rahmandad 2004; Schieritz 2004; Gilbert and Troitzsch 2005).

The main conclusions are that **System Dynamics modeling is most appropriate** and beneficial when the modeled reality can be **highly aggregated** and the research is concentrated on the **feedback mechanisms** in the system. A disadvantage is that the aggregated entities lose their heterogeneity. **The agent-based modeling** approach, on the other hand, is appropriate when the **spatial interactions of individuals and their characteristics are of importance**. A drawback for scientific purposes is that the explanatory power is considerably low compared to System Dynamics modeling, because the formulation of the agent-based model is considered to be a black box whereas the System Dynamics model is transparent or a white-box model (Pidd 1998). Because of the **higher explanatory power of a System Dynamics model** and its ability to fulfill requirements formulated in the research objectives, the System Dynamics modeling approach will be chosen.

## Data Sources

For the development of the qualitative model, we use several data sources that provide us with relevant information. The overall design of the study is positioned as a **case study**. A region and city in the middle land of Switzerland is object to the study. The city was elected mainly because of two reasons that are valid selection criteria (Yin 2002): (1) access to important stakeholders within the administration, and (2) the characteristics of the city are typical of a middle-sized Swiss city. Other goods companies do first experiment with their goods in this city.

Four kinds of information sources will be used: (1) review of existing **literature**, (2) **explorative interviews** with major stakeholders based on the cognitive mapping approach, (3) model building in **focus expert groups** of the region of the case study city, and (4) different **research reports**. By using these sources, we try to obtain a more comprehensive picture of the structure and behavior in the residential built environment.

### 3. Basics Properties about the Simulation Study

#### Model Purpose

(1) The model will shed light on **dynamic interactions between behavioral factors and contextual factors**, and thus, first, **explaining** the diffusion of energy efficient innovations in the social-technical system “residential built environments” in a specific region. (2) The model shall enable to derive **recommendations** about a **policy interventions** and **system design** that foster reinforcing processes towards a sustained diffusion of energy efficient innovations in the residential built environment. The model explicitly considers the time span from 1970 until 2100.

#### Reference Modes

The time series data is on an aggregate country level. For the final version of the simulation study, it is intended to validate the model with data about the specific case study region. For the reference mode, the question has to be raised, if the selected reference modes are adequate definitions of the problem being studied. For this paper, the main objective is to **understand and to influence the diffusion of the innovations in the socio-technical system of the residential built environment**. Figure 1 shows one possible reference mode for the diffusion of energy efficient houses; it corresponds to a classical logistic curve.

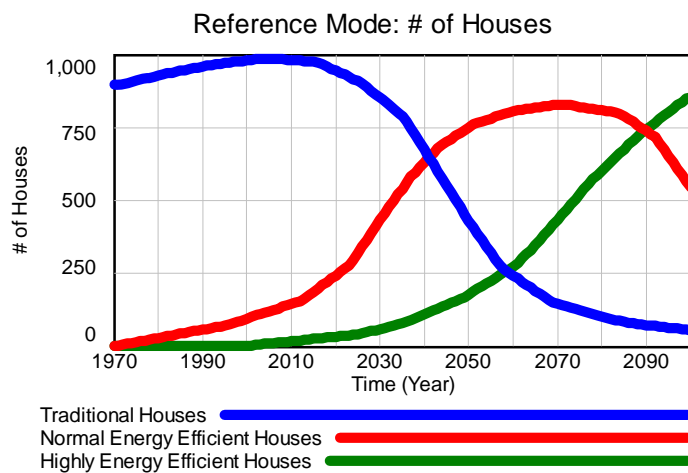


Figure 1: New houses per month (different ee qualities)

Figure 1 shows a possible development of the number of houses according to normal energy efficient, traditional, and highly energy efficient building standards. The number of traditional houses (blue graph) increases in the time from 1970 until 2010. Energy efficient building designs do not exist, or are not known widely or not accepted. However, the number of traditional houses does not further increase after knowledge about energy efficient building designs has disseminated through the society and new buildings are constructed according to the energy efficient building standards. The number of energy efficient houses (red graph) increases with an average slope of 40 houses per year after the 2024 because the re-

quired information and knowledge is available that foster the dissemination of the products. The technology advances and so the building technologies become outdated. The red graph does not decrease until the year 2070. Thereafter, it is substituted by a more measure for energy efficiency.

### Other possible Reference Modes

- Sqm of energy efficient and traditional residential area,
- Energy demand per capita and sqm of residential area,
- Energy consumption for heating per capita sqm,
- Energy consumption for heating per capita and sqm.
- Energy consumption for warm water per capita an m3.

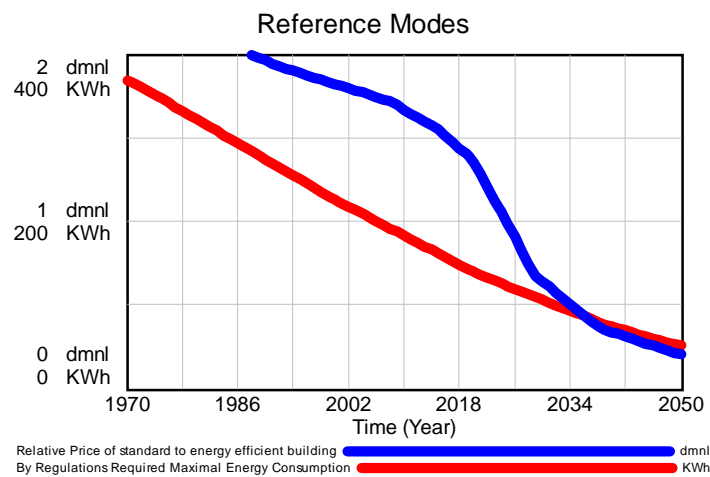


Figure 2: Relatives price of ee-technologies and requires legal energy standard

The variables chosen for the reference mode are first ideas and need further improvement and validation. Especially the following criteria will be used to determine if the selected variables have the potential for key reference variables: (1) validation of the chosen variables by real data must be possible; (2) variables must represent the problem development, i.e., the root causes of the problem must be included. Furthermore, the development of the variable must not be biased by any other development/trend occurring at the same time horizon, or the trends must be detachable.

### Model Boundary Chart

What variables create the dynamics of the explanandum? What variables have to be endogenously explained in the simulation model? What variables lie outside the model boundary? We address these questions with a model boundary chart (Figure 3). The description and definition of the variables is provided in the Appendix I (see also Groesser 2006).

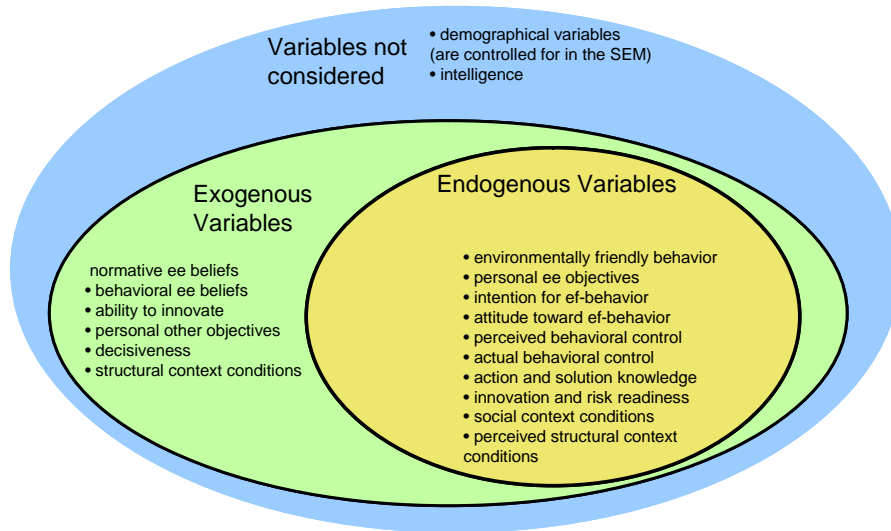


Figure 3: Model Boundary Chart for the

**Subsector Diagram**

The following subsector diagram represents the overall dynamic hypotheses. The cause map (Bryson, Ackermann et al. 2004) was created by merging the concepts.

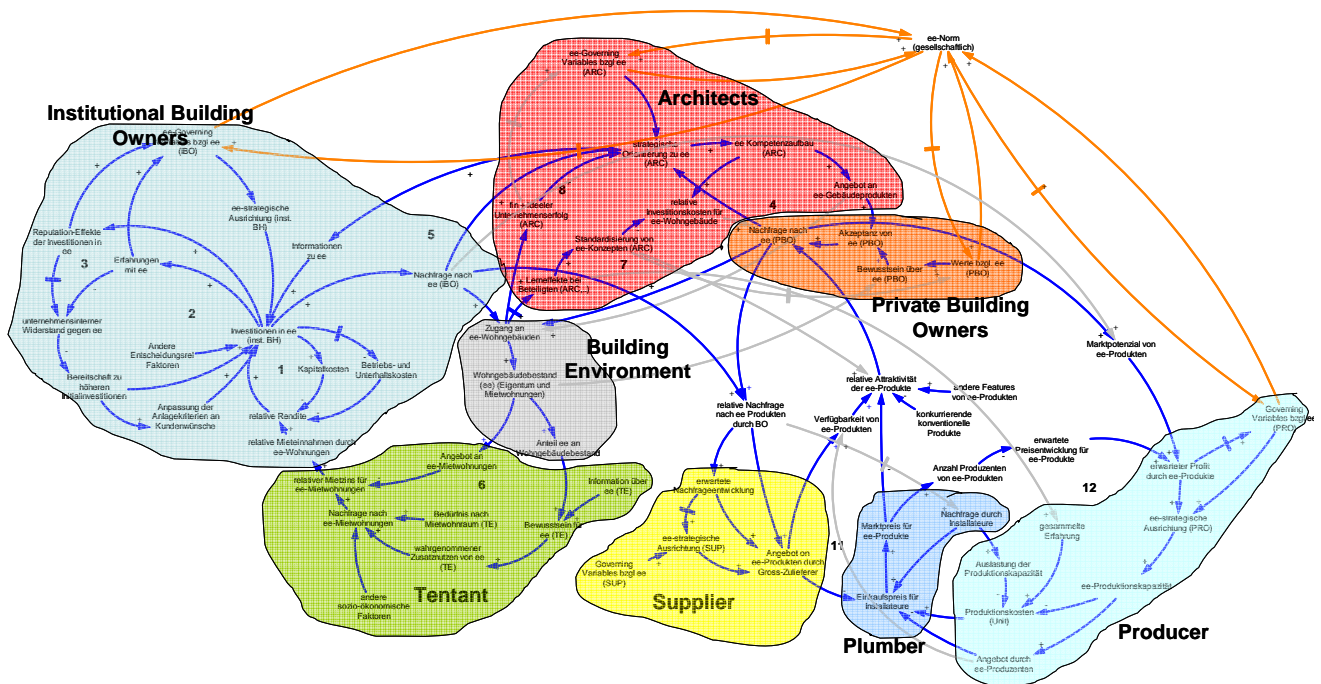


Figure 4: Dynamic Hypotheses about the residential building environment

## 4. Dynamic Hypotheses about the Built Environment

In the following, the overall dynamic hypotheses that have been created during the research project will be shown. As has been described elsewhere (Ulli-Beer, Bruppacher et al. 2006; Müller, Ulli-Beer et al. 2007), the residential built environment consists of several independent actors whose actions and perceptions are indirectly interlinked.

Later, an overview of actors will be provided that are active in the residential built system and their most important interdependencies. The purpose of the figure is to provide a general impression about the complexity of the situation.

In this paper, we want to present the most important sector, i.e., the sector about the private building owners; not all, since these are still hypotheses that are at the moment tested via an extended survey research. It is likely that the hypotheses have to be reformulated in the next step of iteration. That is also the reason, why we do not provide a preliminary stock and flow simulation model in this version of the paper. However, we will present the simulation model at the conference, since the survey research and the adjustment processes are completed by then.

### Feedback Loops as Dynamic Hypothesis

A feedback loop consists of variables connected by arrows denoting the causal influences among the variables (Sterman 2000). In the following, only the most relevant feedback loops incorporated in the model will be explained.

### Active Mechanisms

- Psychology of examples of success and failure
- Information diffusion mechanisms
- Learning by experimentation
- Standardization
- Learning about new frameworks
- Consensus building
- Technological interdependencies
- Economies of scale and scope
- Organizational interdependencies
- Learning from good practices
- Double loop learning in organizations

## 5. Possible Policies

In this chapter, the results of the base and several policy runs will be provided analyzed and hope it works, since the result of method strongly depends on the clarity of the problem statement.

- Environmental levy
- Environmental basis Punishment
- Information and campaign

## 5. Results and Discussion

### Results

- Economical, psychological and sociological mechanisms are active
- Most influential mechanisms comprise **several groups of actors** → time delays
- Mechanisms with **strong** impacted on diffusion: learning from good practices, economies of scale and scope, official standardization
- Mechanisms active at the **beginning** of the diffusion: learning by experimentation, information diffusion mechanisms (social learning, WOM)
- Mechanisms active at **intermediate** stages of the diffusion: learning from good practices, internal standardization
- Mechanisms active at **later** stages of the diffusion: official standardization, learning about new frameworks
- Our approach is conceptual; however, it builds on best possible validation strategies (case study, expert group, interviews, and official statistics).

### Discussion

- Limitations of the model, variables not considered
- Discussion about validity of the model, generalizability
- Limitation of energy efficiency: only at the consumption side, not the production side (primary)
- Limitations of actors: not the decision behavior of the policy maker → policy runs, scenarios
- Limitations of mechanisms: no speculative supply and demand, spatial effects are not considered, only new constructions
- Limitations of time scope: time horizon 1970 until 2100

### **Reflection**

- only mechanisms that are active or that are imaginable are captured → (group) subjectivity
- views of relevant actors are considered → holistic?

## **6. Conclusion and Next Steps**

### **Conclusion**

The residential built environment and the belonging values creation network consisting of several interdependent actors has not obtained much attention from the field of science. Even though much literature exists about the diffusion of innovations (e.g., Rogers 1995), the diffusion process of innovations in the residential building system is not fully understood. Hence, the enormous potential to reduce CO<sub>2</sub>-emissions cannot be captured. The authors try to elaborate the different processes in the built environment in order to provide policy interventions based on a simulation study. Based on this research project, we present interconnections between the different actors in the system. Thereby, we depict the inner structure of each important actor group by some detail. In the current version of the paper, some details about the architects and the production supply chain consisting of producer-supplier-technical firm is provided. For the other actors, empirical survey research is in the process of being executed, after the completion of which dedicated models can be presented, different policies tested and implications discussed.

### **Next Steps**

- Elaboration of the hypotheses as quantitative hypotheses
- Validation of the simulation model with the system expert group
- Support of validation via a CATI-survey

### Connection of other Work to Literature

Sector „Private Building Owner“ will be modeled in detail in Groesser et al. 2007, Decisions in the Planning Process of the Residential Building Environment → basic contents will be used for this research. Development of Norm will be elaborated in Groesser et al. 2007, Development of Societal Norms → basic mechanisms will be utilized in this model.

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