Diffusion Dynamics of Energy-Efficient Innovations in the Residential Building Environment

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I. Abstract

The overall target of the Swiss Energy Policy is to reduce CO_2*-emissions and thereby to achieve the vision of an energy-efficient '2000 Watt per Capita Society'. A major instrument to contribute to the vision in the residential building sector is standards about energy-efficient building designs. However, new residual houses according to the energy-efficiency standard are not as often constructed as they ought to be. This short-term decision has a long-term consequence. In the paper, a preliminary System Dynamics model about the system 'residential building environment' will be presented with the purpose to explain the development of key variables of the building environment system. The analysis of possible policies put forward that a sound understanding of the decision process of potential building owners is necessary to create a beneficial system design which foster the diffusion of energy-efficient building designs. Furthermore, the paper should enable discussions about the model and methodological issues of the model creation process.*

Keywords: Sustainable Development, Energy-Efficiency, Building Environment, Diffusion, Innovation, Kyoto Protocol

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1. Introduction[2]

The overall target of the Swiss Energy Policy is to reduce CO_2-emissions and thereby to achieve the vision of an energy-efficient ‘2000 Watt per Capita Society’. A major instrument to accomplish the vision is the Minergie-Standard, a standard about energy-efficient building designs. However, new residual houses according to the energy-efficiency standard are not as often constructed as they ought to be in order to achieve the 2000 Watt society vision (Koschenz and Pfeiffer 2005). The research project ‘Diffusion dynamics of energy-efficient Buildings (DeeB)’aims at carving out reasons for the comparably low acceptance rate of energy-efficiency standards. For this purpose, a System Dynamics model about the system ‘building environment’ will be created with the purpose to explain the development of key variables of the building environment system, such as number of energy-efficient and traditional houses and sqm of living area in residual housing. The purpose of the paper is to show the results of a first modeling workshop and the status of the system dynamics modeling part of the research project. Ulli-Beer et al. provide a more comprehensive summary of the status of the ‘DeeB’ research project (Ulli-Beer et al. 2006). Furthermore, the paper should enable discussions about the model and methodological issues of the model creation process.

2. Context of the Problem

In the next chapters, relevant positions of the Swiss Environment Policy will be shown in order to elaborate the position of the Minergie measure. Then, the research project will be described for which the System Dynamics model will be built.

2.1 Environment and Energy Politics of Switzerland

The Swiss Constitution is the most basic institution anchoring environmental issues in Switzerland and the Swiss Society. The Swiss Government is bound to the mandate stated in the Constitution. Especially article 73 (sustainable development), article 74 (protection of the environment), and article 89 (energy politics) are relevant with regards to environment and energy politics. In addition, Switzerland signed the Kyoto Protocol in 1997 and committed itself to reduce emissions of climate affecting green houses gases. On the basis of the Kyoto Protocol, the Swiss Parliament passed a CO_2-Law implementing the emission reduction objective (BUWAL 1999). According to the CO_2-Law, the emission of CO_2 has to be reduced by 10 percent below the reference value of 1990 (Swiss Federal Assembly 1999) until the year 2010. The subfield of energy politics comprises concretizations of the high-level objectives of CO_2-emission reduction. Its content can be divided into the Energy Policy Vision of the 2000 Watt Society and the programs elaborated to compass the vision. In the following, the vision and the programs will be discussed separately.

The vision of a post-industrial 2000 Watt per capital Society[3] was developed by the council of the Swiss Federal Institute of Technology in the year 1998 (ETH Council 1998). Its main goal is to reduce the primary energy consumption to 2000 Watt per capita by means of technological innovations and to maintain or increase the actual standard of living simultaneously (Jochem et al. 2004; Spreng and Semadeni 2001). What the measure ‘2000 Watt’ signifies will be explained by a comparative example. Today’s global energy consumption is on average 2000 Watt per capita. The energy consumption figures, which

[2] The abbreviation ’ee’ stands for energy-efficiency or energy-efficient and is used throughout the paper.

[3] The 2000 Watt measure is the calculated average energy consumption for a period of one year per person. In physics, the unit ‘Watt’ signifies power and not energy consumption or work. If, in addition to absorbed power, time is considered, the energy consumption is obtained. I. e., 2000 Watt*Year/(Year*Person) would be the correct unit of measure for the energy consumption target. This is equivalent to 48 kWh/day, which is a more common notation for energy consumption.

depend highly on the technological level of the observed country, vary from 500 Watt in Ethiopia to more then 10.000 Watt in the United States. Unfortunately, a further increase in per capita energy consumption is expected (Novatlantis 2005; Spreng and Semadeni 2001). The per capita energy consumption in Switzerland is approximately 5100 Watt. In the year 1960, the consumption per Swiss inhabitant was around 2000 Watt which is the present objective of the vision. However, this does not indicate that the comfort and living standard has to be reduced to the situation in 1960. It rather implies a change in the consumption behavior towards a modern life style based on innovative technical solutions, new management concepts and societal innovations which improve the efficiency of energy utilization and which in turn reduce the total energy consumption (Spreng and Semadeni 2001). However, not only should there be a reduction of consumed energy; the consumption must also transform from fossil to non-fossil fuel resources. The actual energy consumption can be divided into two parts: energy obtained by usage of fossil and non-fossil fuel resources. In the year 2000, the average Swiss energy demand of 5100 Watt was generated by 2/3 fossil and 1/3 non-fossil fuel resources. The total consumption per capita should be reduced by the factor of 1.6 until the year 2050 whereas the fossil fuel consumption should be halved (cf. Figure 1).

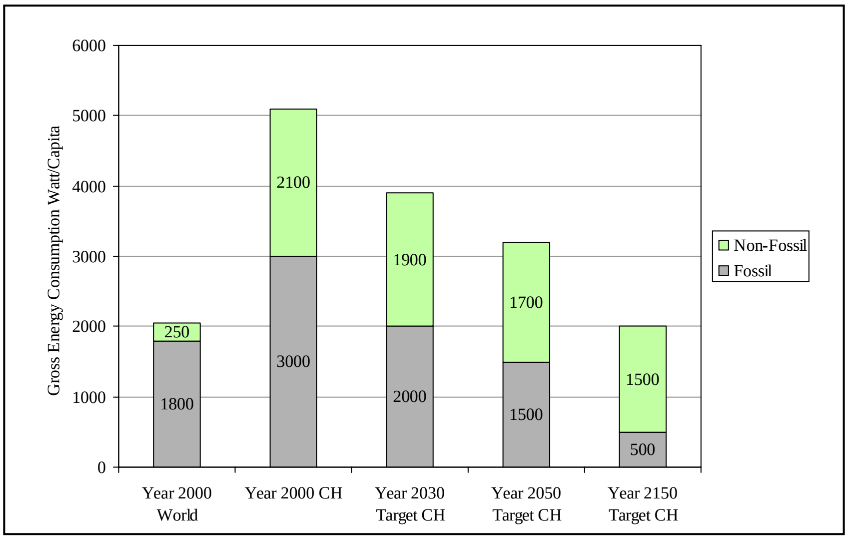

Figure 1: Development of the Swiss Gross Energy Consumption until the Year 2150 (Koschenz and Pfeiffer 2005). The consumption should be reduced from 5100 Watt to 2000 Watt what corresponds to a reduction of 60%.

In the long-term, the gross energy consumption, both fossil and renewable fuel, should be reduced from 5100 Watt to 2000 Watt with the fossil fuel part being 500 Watt, which is equivalent to the long-term objective producing maximal one ton of CO_2 per capita and year (Novatlantis 2005). Noteworthy is that approximately one-half of the 5100 Watt is used for the construction and maintenance of buildings (BFE 2005; Koschenz and Pfeiffer 2005; Spreng and Semadeni 2001). Hence, to reduce the energy consumption of the building environment is crucial to achieve the objectives of the 2000 Watt Society. Furthermore, the vision's long time horizon is mainly caused by the long renewal and refurbishment cycles in the building environment.

After the vision, the second part of the Swiss Energy Politics, the programs, will be discussed. The Swiss Energy Policy is transformed in 10-years lasting measure programs, which are based on the cooperation with the private sector and follows the subsidiary principle of federal interventions to achieve the 2000 Watt vision (Nauser 2005). The program lasting from 1991 until 2000 was named 'Energie2000', an investment program with the objective to increase the acceptance of energy-efficient technologies. Its budget added up to 560 Mio.

CHF (BFE 2005). The follow-up program of ’Energie2000’ is ’EnergieSchweiz’. Since the situation of CO_2 emissions has worsened due to strong increases in energy consumption, the government focuses its financial resources on improvements of innovative technologies and measures in four areas: transportation sector, industrial processes, energy-efficient building technologies, and renewable energies. Despite the current development in energy consumption, the government retains the '2000 Watt Society' as the strategic long-term objective (BFE 2001). The soft target of the program is the development of energy awareness in the Swiss Population. It is one prerequisite for voluntary actions, improvements in education, creation of new technologies and efficient energy utilization (BFE 2001). The measurable objective of the program is to reduce consumption of fossil fuels by 10 percent in the upcoming 10 years. Thereby, the Swiss Government tries to achieve the Swiss CO_2-Law reduction target of 10 percent until the year 2010 with 1990 as base value. ’EnergieSchweiz’ is therefore the main program for the Swiss Energy and Climate Policy. Its total budget is not pre-determined for the 10-year period. The budget allocation is negotiated on a yearly basis. For 2001, it added up to 75 Mio. CHF. In the years 2004 and 2005, it was reduced to 49 Mio. and 45 Mio. CHF, respectively (Nauser 2005).

The measures of the program ’EnergieSchweiz’ can be distinguished in three parts: (1) support of voluntary measures, (2) promotion measures for positive energy-related behavior, and (3) regulations regarding target values and specifications (BFE 2001; Nauser 2005).[4] The introduction of the Minergie-Standard is a measure which is located both in the first and second category. In other words, the acceptance and application of the Minergie-Standard occurs nowadays on a voluntary basis and can be funded by cantonal promotion programs. Other current measures of the ‘EnergieSchweiz’ program are the climate levy for gasoline and diesel as well as the CO_2-levy for combustibles. Both measures are parts of the third category (BUWAL 2005; Swiss Federal Assembly 1999).

2.2 Project about Diffusion Dynamics of Energy-Efficient Buildings

As described above, the diffusion of energy-efficient building technologies is a focal point for the Swiss Government. The Project ‘Diffusion of energy-efficient Buildings (DeeB)’ is funded by the Swiss Federal Research Fund as part of the Research Program SNP 54.[5] The project will be described in the following.

The project 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, 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 factors and contextual factors, thus explaining the diffusion of energy efficient buildings in a community (Kaufmann-Hayoz, Bruppacher, and Ulli-Beer 2005). The project team is hosted at the Interdisciplinary Center for General Ecology at the University of Berne, Switzerland.

3. Review of Existing System Dynamic Models for the Building Environment

A System Dynamics oriented literature review puts forward that less than a dozen articles are publicly available which cover the issue of house construction or urban development. Vennix provides a model which addresses how a housing association can maintain low cost housing

[4] Neuser provides an comprehensive overview of the specific measures in the ’EnergieSchweiz’ program (Nauser 2005).

[5] Cf. also http://www.nfp54.ch/e.cfm.

and at the same time guarantee its financial continuity (Vennix 1996). Eskinasi's and Rouwette's model concentrates on the effect of a building development programs on the social housing vs. commercial housing development (Eskinasi and Rouwette 2004). The purpose of their model is in line with Forrester's Urban Dynamics model (Forrester 1969). Hennekam and Sander extend Forrester's work and explicitly represent 40 urban sectors and their interconnections via spatial interactions (Hennekam and Sanders 2002). Hong-Minh et al. concentrate particularly on the determinants creating the demand for new private houses (Hong-Minh, Childerhouse, and Naim 2000). And finally, Lee and Choi explore the effects between recent Green Belt policies and the urban subsystem of Seoul (Lee and Choi 2004). To conclude, the literature review shows that several studies about the building environment have been conducted, either on the side of demand generation, or from the perspective of single actors, or to assess effects of a specific policy. However, a comprehensive representation of the system 'building environment' does not exist, which would enrich the understanding of all involved actors, such as home owners, architects, building firms, and official authorities.

4. A Preliminary Simulation Model

The preliminary model, which will be described and used for policy analysis, was created during a group model building session held at the end of a one week introductory class in System Dynamics at the University of Berne/Switzerland. The group consisted of 14 participants. The session lasted for five hours and the modeling team consisted of one facilitator, one modeler and one reflector. In the following, we will describe the resulting model in several steps according to the standard modeling process (Sterman 2000).

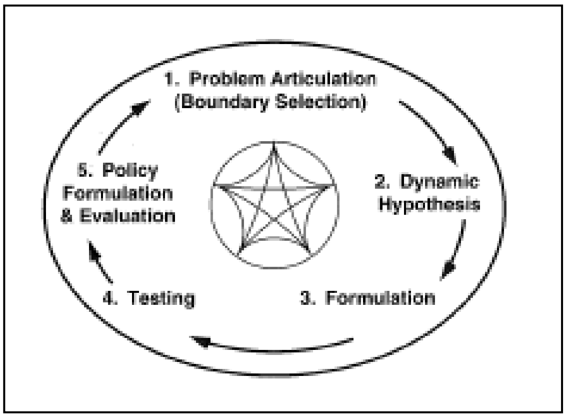

Figure 2: The Iterative Model Creation Process is a systematic way to articulate, formulate, test and evaluate the created model and leads to a sound dynamic hypothesis about the problem statement (Sterman 2000).

4.1 Problem Articulation and Boundary Selection

The first step in a model creation process is to formulate a problem statement and to define the model purpose. Since this System Dynamics model will be used in a scientific research project, we pose several research questions that have to be answered to achieve the goals of the project.

Problem Statement

Energy-efficient innovations for the residential building environment can significantly contribute to reduce the energy-consumption of the residential building stock (Groesser 2006; Koschenz and Pfeiffer 2005). However, the system 'Residential Building Environment' consists of several independent actors resulting in distributed decision making and is therefore highly complex and unintuitive in its behavior. In addition, the system exhibits a strong tendency toward policy resistance. The problem exists because the system reveals a distributed decision structure due to the supply chain organization leading to sustained suboptimal decision making. This phenomenon is well recognized and documented in the literature (Duggan 2004; Fiddaman and Peterson 2000; Milling 1999; Sterman 1989, 1992; Sterman and Fiddaman 1993). In other words, the system will most probably not cure or optimize itself because of the individual decision possibilities of the agents.

Model Purpose

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 residential building environments in a community. The second objective is to recommend a system design that fosters reinforcing processes towards a sustained diffusion of energy efficient innovations in the residential building environment within a community.

Research Questions for the Simulation Model

1. What is the physical structure of the residential building environment?
2. What are essential system variables that determine the rate of growth of the energy efficient and traditional building stock for residential buildings? (Main Research Question)
3. What are main forces that steer management processes[6] of relevant actors in the value creation chain of energy efficient buildings?
4. What are external conditions[7] and behavioral factors[8] that inhibit or facilitate the diffusion of energy efficient buildings?
5. How do these factors interact with each other?
6. What are possible intervention policies to foster the innovation adoption?

The elaborated preliminary model, presented in this paper, will not be extensive enough to answer the posed questions, but it provides first ideas about the structure and sectors of the system ‘building environment’.

Reference Modes as Dynamic Problem Definition

The reference mode is a graphical representation of the answers to the questions ‘What is the historical behavior of the key concepts and variables? What might their behavior be in the future?’ Furthermore, the reference mode defines the problem in a dynamical manner. It is the red thread needed to guide the model conceptualization and simulation development. However, criticism about the selected reference modes is appropriate. The question has to be raised, if the selected reference modes are adequate definitions of the problem being studied. Possible reference mode variables for the diffusion of energy-efficient innovations in the residential building environment are:

- number of energy-efficient and traditional residential houses,
- m^2 of energy-efficient and traditional residential area,
- Energy demand per capita and m^2 of residential area,
- Energy consumption for heating per capita and m^2,
- Energy consumption for warm water per capita and m^2.

[6] Such as strategic planning process, supply capacity and hiring decisions.
7 Such as technical and cost factors, technological innovations, public initiatives, and market conditions.
8 Such as planning, decision making, and routines.

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:

- Validation of the chosen variables by real data must be possible,
- Variables must represent the problem development, i.e., the root causes of the problem must be included,
- 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.

Figure 3 (left side) shows a possible development of the number of houses according to energy-efficient and traditional building standards. The number of traditional houses (blue graph, #1) increases in the time from 1970 until 2012. 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, #2) increases with an average slope of 40 houses per year after the 2024 because the required information and knowledge is available that foster the dissemination of the products.

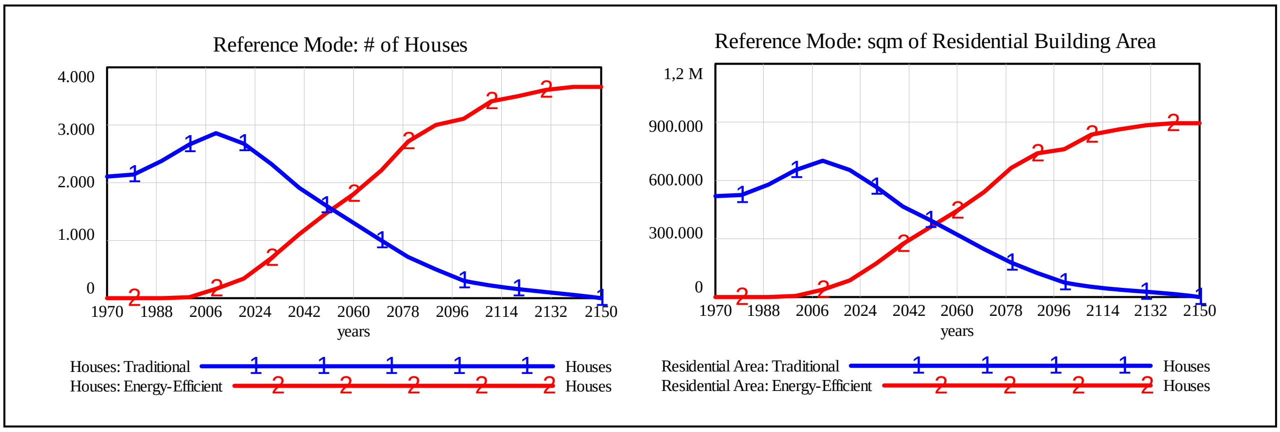

Figure 3: Expected Reference Modes for the Simulation. The reference mode diagrams for the variables '# of Houses' and 'sqm of residential building area' are supported by statistical data until the year 2000. Thereafter, the development is sketched according to the best information and considerations about the diffusion process.

Figure 3 (right side) depicts the reference mode 'sqm of residential building area' for the categories 'traditional' and 'energy-efficient'. The development of traditional residential area is according to the development of number of traditional houses. Until the year 2010, the sum of traditional living area (blue graph, #1) increases slightly and falls thereafter with a low slope due to building demolition. Energy-efficient living space (red graph, #2), on the other hand, increases strongly starting around 2004. The growth rate is further increased by the trend to more residential area per capita. The development is damped and stopped when the demand for residential area is satisfied. Considering the peak level at around the year 2010, it is improbable that the turning point will occur already in the year 2010. It could appear at a later point in time. Further analysis has to determine when this peak will most probably happen.

Both figures show typical graphs of a logistic function about the diffusion process indicating that the system structure has to be related to Bass's Diffusion Model (Bass 1969; Sterman 2000). Even though the graphs appear reasonable, further validation with statistical and non-statistical data is required to determine if the chosen variables are good choices as reference modes. However, there will always be a caveat regarding the reference mode because the model purpose is to model the diffusion process of an innovation that is about to occur. Two possibilities exist to cope with the problem: First, use of data about diffusion processes in another country, e.g., use the data from a country in which the energy-efficient building innovations have already occurred, or second, use data from a similar diffusion process within Switzerland that matches the diffusion process in the building environment as close as possible.

Time Horizon

The determination of time horizon and reference mode is intertwined and subject to an iterative process. The issue of time horizon selection puts forward the questions about:

- How far back in the past lie the roots of the problem?, and
- What is the reactivity of the system, and thus, when can intended effects be seen?
- How far into the future should we consider to avoid unintended effects of your policy intervention?

We employ the following criteria for the selection of the time horizon:

- Availability of data for key reference variables,
- Roots of the problem lie in the historical time period,
- Time horizon is corresponding to the time frame indicated in the problem formulation (short- vs. mid- vs. long-term) (see also the time horizon of the 2000 Watt Society in (Koschenz and Pfeiffer 2005),
- Consideration of the characteristics of the problem context. In the building environment, it is important to consider the long lasting building stock structure leading, e.g., to long-term renovation or demolition cycles.

For the simulation model, we chose the time horizon from 1970 until 2150. Our decision was guided by the aforementioned criteria.

4.2 Dynamic Hypotheses

The modeling step 'dynamics hypotheses' comprises the development of a theory about the dynamics characterizing the problem in terms of underlying feedback and stock and flow structure of the system (Sterman 2000). The dynamic hypotheses and the system structure will be developed according to the following steps: model boundary chart, definition of model variables and discussion of assumptions, subsystem diagram, formulation of causal loop diagrams and finally, representation of the system structure as stock and flow diagrams.

Model Boundary Chart

The model boundary chart in Figure 4 shows the endogenously modeled variables in the simulation model (yellow area), the variables being used as exogenous inputs (green area) and variables that are not considered for the formulation of the simulation model (framed by the blue oval). The description of relevant variables is provided below.

Definitions of Model Variables and Discussion of Assumptions

House Building Population

The house building population consists of entities that all want to build houses. In the simulation, an exogenous driven value is used to represent the goal quantity of people who want to build and own houses. It is rather unnatural and methodologically artificial to use a fixed exogenous value for a dynamic value such as population. Apart from the fact that the model is a first sketch and has to be elaborated in certain dimensions, a basic rationale is behind this choice of modeling. According to the available statistical data from the year 1980 until 2004, the house building population has an arithmetic average of 14803 [persons] with a standard deviation of 330 [persons]. This indicates very weak population dynamics and results in a relatively stable population size. The development of the male and female population matches each other almost perfectly with an average difference of approximately 580 [persons]. Noteworthy is that the time series data (1980 - 2004) shows an increasing trend for foreign inhabitants and a declining trend for the native inhabitants what could have significant influences on social trends of family size and inhabited residential area.

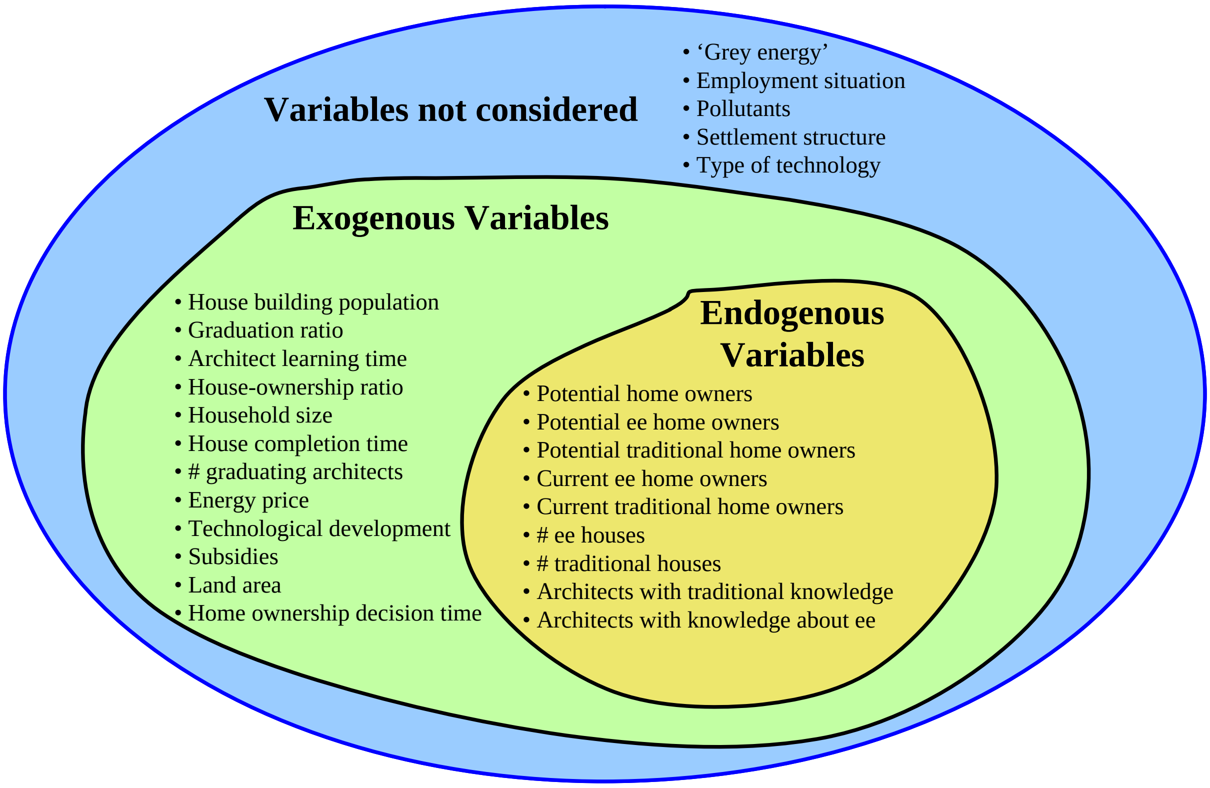

Figure 4: Model Boundary Chart. It shows the variables included and excluded in the simulation model. Emphasis is laid especially on the endogenous and exogenous variables that describe and explain the dynamic development of the problem being studied.

Potential Home Owners

The variable 'potential home owners' represents the amount of people who can possibly and who want to build a home. It is assumed that the term home refers to single family houses. In the model, we discuss only the development of home ownership of single-family houses and do not concentrate on ownership of multi-family houses or on leasing of either single or multi family houses. The potential home owners are differentiated in potential traditional and ee home owners. The first want to build a house according to the traditional energy standard. Or more precisely, they do not want to or cannot build an energy-efficient building. The second group is the potential ee-home owners.

Decision for ee-Fraction

The decision for ee-fraction is a highly-aggregated variable embodying factors important to the potential home owner's decision about an energy-efficient or a traditional home design. It is a key variable because it strongly determines the path the potential home owner will take due to, e.g., irreversible investment costs in building material and social capital. Possible hidden factors could be classified in several clusters: psychological, context, social, technological and political factors (Groesser 2006). In order to accelerate adaptation of energy-efficient technologies, it is essential to understand the hidden factors indicating a need for further disaggregation.

Current Home Owners

People who currently inhabit and own a single-family house are named 'current home owners'. The definition comprises only private home owners inhabit their home. Institutional investors are not included in the definition. In the simulation model, two groups of home owners are differentiated: traditional and energy-efficient home owners. But, what is the distinctive feature between traditional and energy-efficient houses? A first possibility is when the building design complies with existing energy-efficiency standards, e.g., Minergie® or Minergie-P®. Problematic is the fact that not all houses which comply with the aforementioned standards actually have the label, because an additional bureaucratic process is required to obtain the label. Consequently, not all houses complying with the standards have been registered and labeled as energy-efficient houses. This problem of 'complying with the standard, but not officially labeled as complying' becomes more important because the dark figure grows daily (Groesser 2005). A second possibility would be to define a threshold in energy-consumption, measured in MJ/(m^2*a). According to this definition, a house would be energy-efficient when its average energy-consumption figure would be lower than this threshold. Certainly, the threshold ought to evolve dynamically over time corresponding to enhancements in energy-efficient technologies.

Transition to Energy-Efficient Home Owners

In case a home owner has built his house the traditional way, one possibility to change the characteristic of the house is to refurbish it with energy-saving components. Transition to a energy-efficient home owner represent the result of the refurbishment, i.e., in case houses are upgraded and comply to the energy-efficiency standard, the home owners then belong to the class of energy-efficient home owners. This formulation shows only one side of the medallion. The second, more intuitive side is that the decision process of the traditional home owner to obtain an ee-house is modeled which, in turn, causes the transition of the house type from traditional to energy-efficient. For this formulation alternative, more decision variables would be required. Further research has to determine if a disaggregation is required since refurbishment is not part of the current research project, however, important in the near future.

Physical Structure of House Environment in Construction

The physical structure of house environment in construction captures the physical creation process of houses once it has started. The preceding process of house planning and multi-party negotiations are not considered. In case the house is completed, it changes its affiliations and no longer belongs to this category. Again, a differentiation between traditional and energy-efficient houses is drawn. While houses are in construction, an inhabitation is not possible. The aggregation level of houses has been chosen because more valid data is available from statistics. Other possible aggregation levels would have been: number of apartments or m^2 of residential area. The first measure can also be derived from statistics and will probably incorporate in a future version of the model. The m^2-measure would be derived from the number of apartments and buildings with an average value of residential area for each apartment size. Thus, by this estimation impreciseness would be added and model accuracy would be reduced. However, if an estimation of the development of the energy-consumption per residential area (MJ/m^2*a) is intended, this would be a reasonable calculation method.

Completed Houses

Completed houses are physical building structures either according to energy-efficient or traditional standards. In the model, only completed houses can be inhabited by home owners. The affiliation of the houses to certain classes is determined by the decision at the beginning and can only be changed by severe refurbishment. Small refurbishment projects cannot change energy consumption of the house and, therefore, are not considered.

Active Architects
Architects in Switzerland are distinguished between ones that offer only traditional building layouts and ones that offer building layouts in compliance with traditional and energy-efficient standards. The difference between both types of architects being competencies and knowledge about how the requirements are met in order to create layouts that comply with energy efficient standards.

Elaboration of Single Hypotheses
In the System Dynamics model, some hypotheses are integrated which we want to make more explicit and subject to further research and validation by means of literature, expert judgment and empirical data.

H1: The sum of persons about energy-efficient innovations has a positive influence on the decision for ee-fraction of potential home owners

Hypothesis H1 is well supported by scientific literature about diffusion of innovations. Sterman formulates a diffusion model in System Dynamics syntax (Sterman 2000) based on Bass's theory of innovation diffusion (Bass 1969) and elaborates several versions. Hypothesis H1 can be supported by the effect known as 'word of mouth (WOM) effect' in the first diffusion phase. However, once the market demand is going to be satisfied, the word of mouth effect is compensated by the effect of market saturation. H1 is, therefore, only valid if the market is not saturated. Stated differently, H1 is too coarse and needs further detailing.

H2: The probability to decide for an energy-efficient house has a positive influence on the house conversion rate from tradition houses to energy-efficient houses

The probability to decide for an energy-efficient house is operationalized by the variable 'decision for ee-fraction' and is formulated to aggregately represent the decision process of a future home owner and is valid for the decision to build a new home. Hypothesis H2 implicitly assumes that the factors influencing the decisions of future home owners are also valid for current owners of traditional houses with respect to the refurbishment of their traditional house to an energy-efficient house. H2 proposes an indirect causal relationship between the variable 'decision for ee-fraction' and 'house conversion rate'. Bond et al. support the reasoning with the theory about social interdependency in decision making among probands (Bond and Smith 1996).

H3: The higher the demand for traditional houses, the lower will be the intention of architects for further education

Hypothesis H3 implicitly assumes an interaction between the market forces of supply and demand. The higher the demand for traditional houses, the higher will be the expected profit of architects who offer this kind of service and therefore further learning as means to acquire knowledge about energy-efficient building designs does not seem to be necessary to stay in business. The current representation of the causal effect needs further disaggregation in order to obtain reliably testable and relationships that can be validated. But the basic rationale seems plausible.

H4: The higher is the variable ‘decision for ee-fraction’, the higher will be the graduation rate of architects with an education in ee

Hypothesis H4 proposes a relationship which influences the capacity of the supply side of the market. If an indicator of the demand side, the variable ‘decision for ee-fraction’, increases in value then architects in education will be more willing to change their course of study in order to graduate with latest knowledge about energy-efficient building technologies to meet the higher demand that is assumed to exist then. H4 has to be validated in expert interviews, because we expect that literature will not provide further information about the issue.

Preliminary Sector Diagram

By means of the subsystem diagram, the variables of the simulation model are divided in several subgroups and are graphically represented in an aggregated and coarse manner. Three sectors could be identified for the discussed simulation model: Building owner sector, physical building sector, and architect sector.

The building owner sector comprises the different types and states of ownership. The other sectors are connected via the decisions of the home owners for traditional or energy-efficient home designs and via the quantities of different home owners. The development of the building owners quantities correspond to the development of the house structure quantities indicating a tight relationship between both sectors. The sector ‘physical building traces the changes of the physical building stocks for both traditional and energy-efficient houses. The connections to other sectors is created by, first, the number of architects resulting in the offered architect capacity, and second, by decision of future home owners about the types of buildings. The last sector concerns the architects. Their decisions about first education (first graduation) and second education (further learning) is represented. Links are created by the potential home owners’ decisions. Figure 6 shows the sectors, the main variables for each sector and the connections between them.

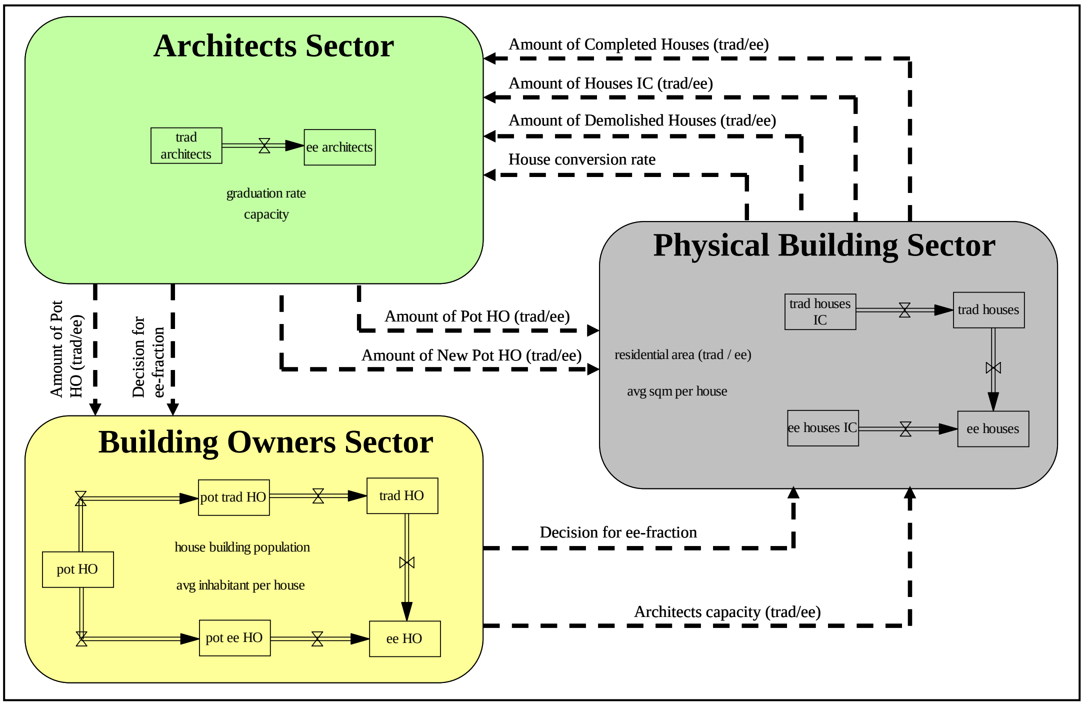

Figure 5: Sector Diagram consists of Architect Subsystem, Building Owner Subsystem, and Physical Building Subsystem. The major interconnections represent information dissemination processes especially between the building owner and architect as well as between the building owner and the physical building sector.

A further elaborated model could also include sectors of the industry which comprises supply of materials, labor, education demand, and financial comparison between different building designs. Moreover, sectors about technology and the support system could be included, i.e., actors which have a supportive influence on the diffusion of energy-efficient technologies in the building environment.

Feedback Loops

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 simulation will be explained, because the explanation of approximately 200 feedback loops of this relatively small model is not feasible. Several feedback loops can be identified which drive or balance the system. Loops L1 until L3 are positive feedback loops fostering the diffusion process, whereas loops L4 until L8 are negative feedback loops which lead to balancing or dampening tendencies of the system.

L1: Word of Mouth Effect by Potential ee Home Owners (Figure 6)

The word of mouth effect is a phenomenon that fosters diffusion processes. People with knowledge about a new technology pass it to people who do not have this knowledge (Bass 1969; Sterman 2000). In the building environment, the total amount of persons convinced about energy-efficiency has a positive influence on the decision of potential home owners to build an energy-efficient house. As a result, more potential home owners become potential energy-efficient home owners. Consequently, the sum of persons convinced to energy-efficiency will further increase leading to a reinforcing process which is controlled by the balancing mechanism L4 ‘Everybody has a house’.

L2: Market Pull for ee Architects (Figure 6)

The feedback loop ‘market pull for ee architects’ represents the effect the decision for energy-efficient houses has on the supply of architects with special knowledge about energy-efficiency. In more detail: An indicator of the market demand for energy-efficient houses, represented by the potential ee home owners and indicated by the decision for ee-fraction, has an effect on the amount of architects graduating with special knowledge about energy-efficient designs. Production management literature coins the aforementioned mechanism effect market pull effect (De Toni, Caputo, and Vinelli 1988; Kimura and Terada 1981). The more of these architects are available, the higher is the supply and capacity to build energy-efficient houses. Given the ceteris paribus condition, the number of potential energy-efficient home owners will increase leading to a higher amount of convinced people and finally will result in an increase of the decision fraction of ee.

L3: Word of Mouth Effect by Current ee Home Owners (Figure 6)

The first reinforcing loop is created by the word of mouth effect of potential ee home owners. Also people, who already live in an ee-house, tell their acquaintances about their experience and thus contributing to the word of mouth effect, which will lead to new potential ee home owners and in turn to a higher number of current home owners of ee-buildings. Since the causal chain is similar to the aforementioned feedback loop L1, it will not be explained in detail. But why do we distinguish between the word of mouth of potential ee home owners on the one hand and current ee home owners on the other hand? We expect the feedback loops to have different strengths, e.g., that the word of mouth effect created by current ee home owners is more powerful because the people currently living in energy-efficient houses are either convinced by experience that their house choice was right or act in a way to be consistent with their choice made and to avoid dissonant behavior (Stroebe, Jonas, and Hewstone 2001). However, this stronger effect of current ee-home owners might contribute to the total word of mouth effect with a delay until the home owners actually inhabit the building.

L4: Everybody Has a House (Figure 6)

The negative loop 'Everybody has a house' captures the fact that the finite house building population will be satisfied, amongst others, by the word of mouth effects and limit the diffusion process once the whole population is either owner of an energy-efficient home or in the phase of building such a home. Starting with many people without own houses, more potential home owners exist and resulting in a higher number of new potential owners of ee-houses. In turn, they will increase the amount of ee-home owners and therefore the total number of enrolled and current home owners. Consequently, the number of people without houses will be reduced. The more positive feedback cycles foster the spread of information and experience about energy-efficient building technologies, the faster will the number of people without houses be reduced, and the more rapid will L4 stabilize the system at it upper value.

L5: EE House Building Slows Down the Diffusion Process (Figure 7)

L5 describes the effect that ee-house construction requires architects with knowledge about energy-efficiency leading to a smaller future construction rate of energy-efficient houses because the architects supply is reduced by occupations. This loop could slow down the diffusion process when not enough architects with knowledge about energy-efficiency are available. L5 indicates that the number of architects with special knowledge is a bottle-neck variable which needs further attention. However, since the occupation of the architects is rather short (short time delay), this feedback loop is considered to have only insignificant influences.

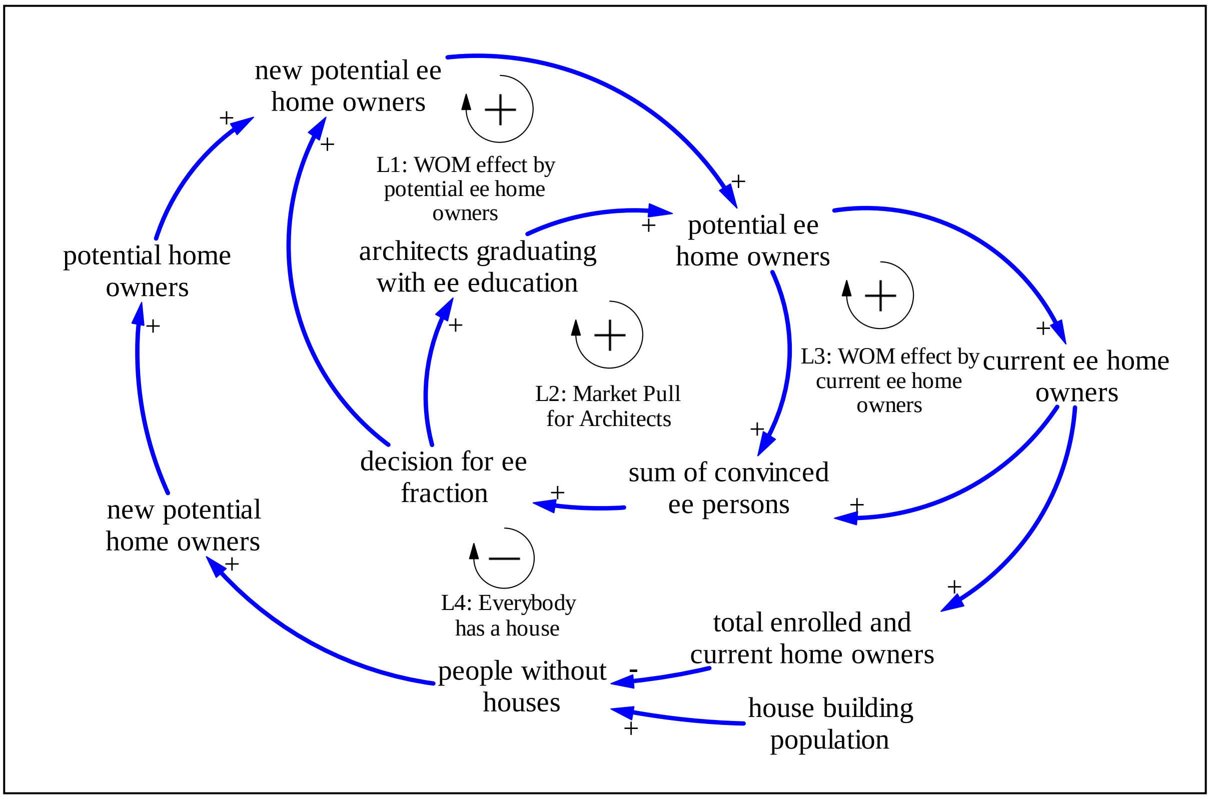

Figure 6: Feedback Loop Diagram about potential and actual home owner dynamics. The reinforcing loops, which are driven by word of mouth and market pull effects, lead to a strong positive development of the number of current ee-home owners. These three loops are controlled by the powerful balancing loops representing the limitation to this growth process by the satisfaction of the house building population.

L6: EE Architect Capacity Clear the ee-Demand (Figure 7)
Loop L6 depicts the reduction of the demand for energy-efficient houses by the transition of architects from traditional to the energy-efficient branch, e.g., by further education. The balancing process comes into play when the ee-architects exploit the demand for ee-houses. The rationale is that more architects with knowledge about energy-efficiency will increase the number of built energy-efficient houses. The more of such houses exist, the lower will be the demand for energy-efficient houses relative to the demand for traditional houses, given a fixed number of the total building population. Thus, architects having a traditional education will be more resistant to change their competence portfolio and will rather remain in the architect branch they are currently in. In other words, the ee-architects construct houses and fulfill the demands of the population willing to build according to ee-standards. This leads to a perceived market saturation effect of the potential ee-house owners. Hence, traditional architects delay their decision to enlarge their product portfolio by energy-efficient designs, because they want to serve the potential traditional home owners. This mechanism works against the WOM-effect, but is comparably weak.

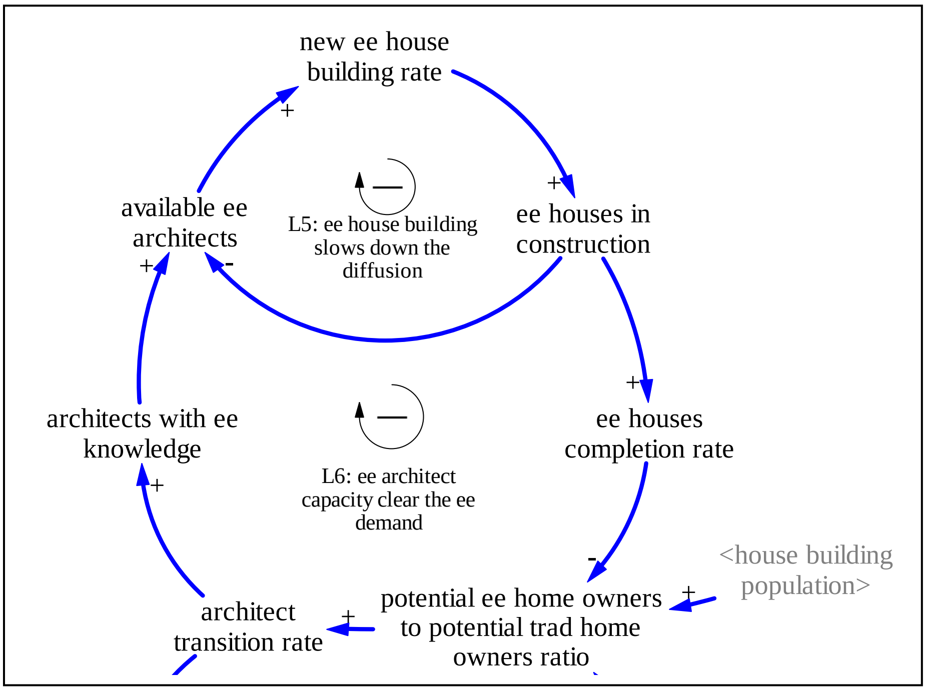

Figure 7: Feedback Loops L5 and L6 are both balancing loops. They represent both the effect the house construction has on, first, the number of available ee-architects, and second, the motivation for traditional architects to become ee-architects.

L7: Traditional Architect Capacity Clear the Traditional Demand (Figure 8)
Loop L7 is similar to loop L6. It represents the fact that the reduction of the demand for traditional houses will increase the number of architects who want to expand their business and want to offer energy-efficient building designs as well. Just like L6, the strength of the feedback loops is weak compared to L1 to L3.

L8: Traditional House Building Exhausts the ee-Architects Capacity (Figure 8)
The loop L8 is similar to the loop L5. It describes the effect that traditional house construction requires architects with knowledge about traditional building design leading to a smaller future construction rate of traditional houses because the required architect supply is reduced. This loop hinders the diffusion of traditional buildings and thus fosters indirectly the diffusion of energy-efficient buildings. Again like L5, the effect of this loop is considered weak compared to L1 to L3.

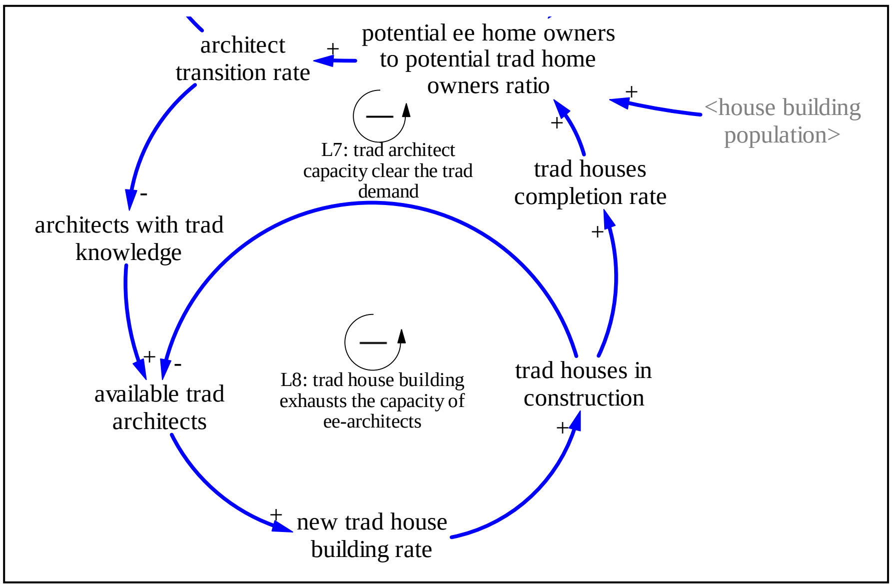

Figure 8: Feedback Loops L7 and L8 are both balancing loops. They represent the effect the house construction has on the number of available ee-architects, and the motivation for traditional architects become ee-architects.

Stock and Flow Diagrams

The formulation of the simulation model as stock and flow diagrams will be provided in the appendix. We assume the detailed diagrams are self evident and refrain from describing them. Table 1 shows the values of the parameter used in the model.

No.	Parameter Name	Value	Unit
1	House Building Population	13287-14582 (var.) (1970-2004)	Person
2	Decision Time for House Building Population	25	Year
3	Initial Traditional Houses in Construction	20	House
4	Initial Potential House Owners	100	Person
5	Initial Traditional Houses	2099	House
6	Initial ee-Houses	0	House
7	Inital Potential ee-House Owners	0	Person
8	Avg. Inhabitants per House	2	Dmnl
9	Initial ee-Houses in Construction	0	House
10	House Completion Time	2	Year
11	Demolishing Time Traditional Houses	60	Year
12	Demolishing Time ee-Houses	80	Year
13	Conversion Decision Time	1	Year
14	Architects Learning Time	1	Year
15	Architects Work Life Time	35	Year
16	Initial Traditional Architects	30	Person
17	Initial ee-Architects	0	Person
18	Graduating Architects	5	Person/Year
19	Normal Graduation Ratio	0.1	Dmnl
20	Architect Capacity	2.75	Person/Year
21	Normal Architects Switching Ratio	0.25	Dmnl
22	Start of EE-Movement	1998	Year
23	Decision Time 'Building Type'	3	Year

Table 1: Parameter Values of the Simulation Model. The parameter values with the grey background color are values that are validated by statistical data. The other values have to be validated in further expert interviews or by other means.

4.3 Formulation of a Simulation Model

In the phase 'formulation of a simulation model', the specification of structure and decision rules, estimation of parameters, behavioral relationships and initial conditions, as well as the test for consistency with the purpose and boundary has to be addressed (Sterman 2000). The stock and flow diagrams have been created with this step already in mind. Therefore, this sub-step is already completed. Since real values were only partially available for the specific region of Switzerland, the missing data was reasonably estimated. The purpose of the simulation model is consistent with the stated purpose. The most crucial values in the simulation model are up to now the number of traditional and energy-efficient houses, and also the number of home owners in both classes. The other variables are supportive. The stated model purpose is to shed light on dynamic interactions between behavioral factors and contextual factors, and thus explaining the diffusion of energy efficient innovations in the residential building environment in a community. The model boundary of the simulation model is considered to be too narrow in the current state. As we have pointed out in Chapter 4.2, several other sectors have relevant influences on the diffusion of energy-efficient buildings and need to be included in an elaborated version of the model.

4.4 Model Validation

The validation of System Dynamics models has two important aspects: structure and behavior validation (Barlas 1996). Structure validation is about warranting that the model's internal structure is a sufficiently accurate description of the real system, with respect to the model purpose and issue of interest. Structure validation can be differentiated in several direct and indirect structure tests respectively (Barlas 1996; Sterman 2000). Behavior validation means that the output behavior of the model reproduces closely enough the dynamic behavior of the real system under study.

In the validation process, different structure validity tests were carried out (e.g., dimensional consistency tests, direct extreme-condition tests, stress tests, behavior sensitivity tests) (Coyle 1996; Roberts et al. 1981; Sterman 2000). The model was improved continuously in the course of validation. The validation, however, can be improved significantly once more specific data about the reference mode is available. As pointed out previously, it is possible that the data selection and data management could be prohibitively high. Further research about available data and its selection and gathering is required.

4.5 Standard Runs, Policy Formulation and Evaluations

Standard Simulation Run

Figure 9 shows the development of some key variables of the system. Traditional houses (blue line, #1) show an increasing tendency that peaks at the year 2008 followed by a decreasing trend. The market powers, especially the word of mouth effect (L1, L3) and supply of ee-architects (L2), foster energy-efficient instead of traditional building designs, but these effects are only active when a large enough pioneer group exists. Time is required for the group to evolve, thus, explaining the time delay before the traditional houses number decreases. The amount of energy-efficient houses (red graph, #2) increases around the year 1997 due to the formal establishment of an energy-efficiency association. The growth rate peaks at the inflection point around 2045 and thereafter reveals a diminishing growth because of the market saturation process. L4 is active and weakens the L1 to L3. The growth rate of the energy-efficient houses will be equal to the demolition rate of tradition houses, after the house building population has been satisfied. This leads to a slow transition from the traditional building stock to energy-efficient houses.

A differing development can be seen for the number of traditional architects (grey line, #4) and energy-efficient architects (black line, #5). The changes in the traditional architect quantity lags behind the changes in the house quantities because the traditional architects are only willing to change or graduate with an ee-education when the demand for traditional houses shrinks. In addition, the retirement of traditional architects reduces the number of traditional architects. In case of the ee-architects, the variable concurs with the number of ee-houses because ee-houses can only be built when ee-architects are available. The higher market demand for ee-houses, driven by the WOM-effects (L1 and L3), pulls the graduating architects towards an ee-education (L2). Hence, the number of ee-architects grows steeply. A saturation effect occurs around the 2090 when the number of retiring architects equals the graduation architects resulting in a dynamic equilibrium.
The green graph (#3) shows the development of the total enrolled and current home owners indicating a goal seeking behavior towards the goal ‘total building population’. This graph relativises the considerably fast spread of energy-efficient houses because the demand for houses is nearly satisfied at the end of the simulation. A further spread of energy-efficient houses can only occur when traditional houses are demolished which have a life time of 50 to 100 years. However, at the year 2150 only a few traditional houses still exist indicating that the residential building system changed from a traditional-oriented building stock towards an energy-efficient one. However, the assumption that technology has not advanced during the time duration of 180 years is unrealistic and has to be relaxed in a further version of the model.

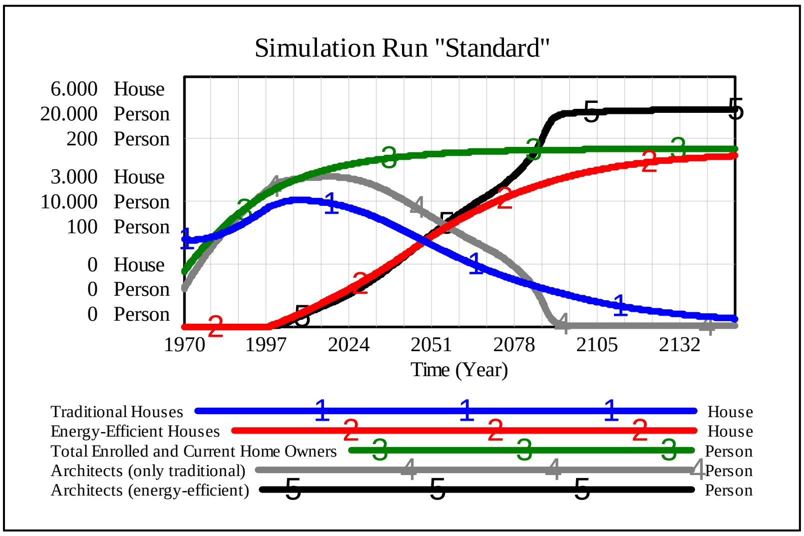

Figure 9: Development of # of Houses, and # of Architects, and Total Enrolled and Current Home Owners. The system behavior reveals a long-term diffusion process due to long cycle time of the building stock.

Figure 10 shows the development of the decision for ee-fraction (blue line, #1). To remember, this variable represents the main driver for the decision to build an energy-efficient house or not. The more the value tends toward the value 1.0 [dmnl], the greater is the amount of potential building owners who will decide to build an ee-house. In the current model, the combined word of mouth effects of ee-convinced persons and current ee-home owners is the only factor that influences the decision process. Thus, the growth of the sum of the convinced persons directly affects the decision about energy-efficiency and subsequently leads to a stronger word of mouth effect. The goal seeking growth behavior of the decision for ee-fraction is solely caused by the increasing ee-population (red line, #2).

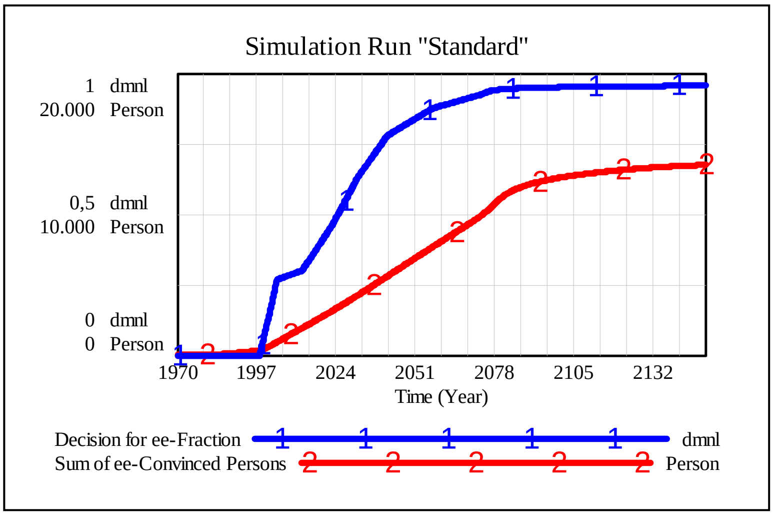

Figure 10: Development of Decision for ee-Fraction. The variable represents the decision of potential home owners for energy-efficient buildings. The sum of ee-convinced persons is the antecedents variable for the development of the ee-decision variable.

The variable 'decision for ee-fraction' seems to be a highly important leverage point of the system. Thus, additional factors that influence potential home owners' decision about energy-efficiency have to be included, because they do not only decide due to the word of mouth effects, but also due to financial restrictions, objective feasibility and so forth (Groesser 2006). Figure 11 shows the mathematical formulation of the decision for ee-function.

$$f_1 = f((EF(x_1, x_2), x_3 ..., x_n) = EF(pot\_ee + cur\_ee) * N\_Dec\_ee;$$

with: $f_1 = \text{decision for ee-fraction}$

$EF(x_1, x_2) = \text{effect of convinced persons on decision for ee fraction}$

$pot\_ee = \text{potential ee home owners}$

$cur\_ee = \text{current ee home owners}$

$N\_Dec\_ee = \text{normal decision fraction for ee}$

Figure 11: Formulation of the decision function of potential home owners for an energy-efficient home. Currently, the sum of ee-convinced persons is the argument for the decision function.

Sensitivity Runs as Parameter Policy Runs

The objective of policy experiments is to improve or optimize the system behavior according to some set of objective variables or objective functions. Coyle distinguishes policy into its structure and its parameters within the structure (Coyle 1996). Not changing the aforementioned, we argue that in an early stage of the modeling the objective of a policy experiment is not to optimize the system behavior, it is rather to understand the system better and detect structural inaccuracies as well as get a more intuitive grasp about the system behavior under different structural parameter sets. Table 2 provides an overview about the parameter policy runs.

For all three policy runs, sensitivity analyses have been used to explore the effects of parameter changes on the system behavior. Monte Carlo simulations have been employed to conduct the sensitivity analyses.[9] Monte Carlo simulations are stochastic techniques, i.e., they

[9] Basic parameters: n=500 runs; noise seed 1234, intervention parameter is distributed according to a random uniform distribution with values within the interval indicated in table 2.

are based on the use of random numbers and probability statistics to investigate the behavior of the modeled system with different parameters values.

No.	Policy Name	Randomized Variable	Lower Bound	Upper Bound
P1	Architects with ee-Knowledge Flood the Market	normal graduation ratio	0 [dmnl]	0.9 [dmnl]
P2	Supply of Further Education for Architects	architect switching ratio	0 [dmnl]	0.9 [dmnl]
P3	Influence the Decision of Potential Home Owners towards Energy-Efficient Homes	normal decision for ee	0 [dmnl]	0.25 [dmnl]

Table 2: Parameter Policy Runs. The three different policy runs give an indication about the model behavior. The randomized uniformly distributed variables take values in reasonably bounds.

The interpretation of the sensitivity graphs will be provided upfront. The simulation results are displayed in the graphs as confidence bounds. These are computed at each point in time by ordering and sampling all the simulation runs. Thus, for example, for a confidence bound at 50, one-quarter of the runs will have a value larger than the top of the confidence bound and one-quarter will have a value lower than the bottom. The color code (yellow, green, blue, and grey) corresponds to the confidence different bounds (50%, 75%, 95%, and 100%). In the following, three policy runs are analyzed and their results will be compared with each other.

P1: Architects with EE-Knowledge Flood the Market (Variable: normal graduation ratio)
The first policy run analyzes the effects changes in the education support system, e.g., financial support for universities for the supply of education courses about energy-efficiency in the building environment, has on the graduation rate of architects. The first variable 'Architects with traditional knowledge' (Figure 12, left side) shows relatively sensitive behavior to changes of the parameter values from 0.0 [dmnl] to 0.9 [dmnl]. After the initiation of the energy-efficiency topic, the normal graduation ratio has significant influence on the system. The lower the normal graduation rate, indicating that people do not graduate with knowledge about energy-efficiency, the more architects are available to construct houses according to the traditional standard. Because the word of mouth effect is rather low and people are not convinced to build ee-houses a demand for traditional houses exist. Thus, the feedback loops L1 and L2 are reduced in their strength resulting in fewer ee-houses.
When the parameter has values $p > 0.1$ [dmnl], the number of architects with traditional knowledge decreases rapidly due to a large decision for ee-fraction that is driven by L1 and L3. In addition, the decision for ee-fraction leads to a faster transfer of the traditional architects to the ee-cohort. The result on the ee-houses is a relatively strong inclination between $2015 < t < 2050$. The behavior of the ee-house development is considered robust because three-quarters of the random draws create an envelope with a maximal width of 900 entities.

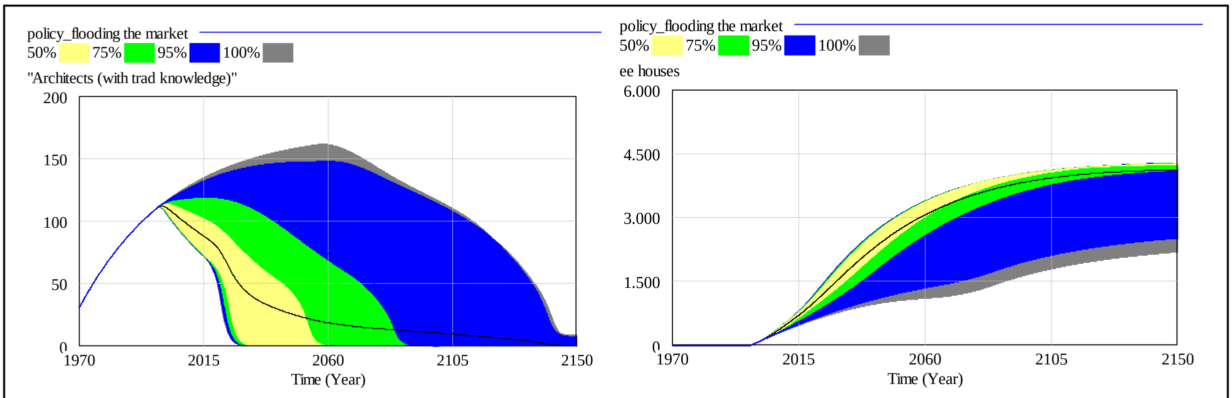

Figure 12: Analysis of the Policy Run 'Architects with ee-Knowledge Flood the Market'. For $p < 0.1$ [dmnl], the system shows highly sensitive behavior. The behavior is for $p > 0.1$ [dmnl] much more robust.

P2: Supply of Further Education for Architects (Variable: architect switching ratio)
The second policy run analyzes, again, the effect of changes in the education support system. This time, however, not the first education, in other words, the education in the university, but the further education of already graduated architects is financially supported and enabled by the federal government. The effects are shown in Figure 13 and indicate almost no changes when varying the randomized parameter inputs. Where does this robustness of the system come from?
Figure 13 (left side) shows that the variable ‘architects with traditional knowledge’ is non-sensitive to variations in the normal switching ratio until t > 2070. This is because the ratio of potential traditional home owners to energy-efficient home owners is quite small leading to transition effect of nearly 0. In other words, the architects stick to their business and try to satisfy the demand for traditional houses. Then, L7 becomes active and dampens graduation of traditional architects because the market demand is perceived to saturate. Hence, graduating architects decide for an ee-education. The remaining traditional architects serve the still existing demand for traditional houses. At the same time, the demand for ee-houses increases because of the word of mouth effect. Hence, the ratio between potential energy-efficient and traditional home owners increases. Consequently, the first architects leave the traditional architecture market and move towards energy-efficient building designs by further education. This development starts at t = 2070. Depending on the value of the normal switching ratio, the architects switch more rapidly (for p > 0.1 [dmnl]) or more slowly (for p < 0.1 [dmnl]). In either case, the effect of switching architects does not influence the development of the ee-building stock because the limiting variable in the development of the ee-building stock is not the number of ee-architects; it is the number of potential ee-home owners.

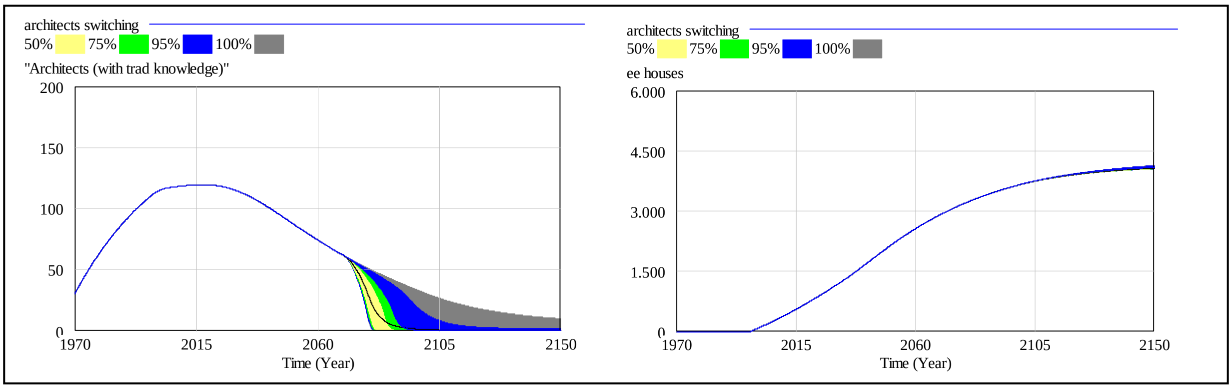

Figure 13: Analysis of the Policy Run ‘Supply Further Education of Architects’. The switching of architects occurs when the future market is considered to be the energy-efficient building market. This happens at t > 2070. However, the switching of architects does not have an influence on the ee-building stock because the bottleneck variable is the potential ee-home owners.

P3: Influence the Decision of Potential Home Owners towards Energy-Efficient Homes (Variable: normal decision fraction for ee)
The last policy run analyzes the effect of changes in the building owner decision system. By these changes, the effects of further decision factors on the system behavior are explored. Figure 14 (left side) shows that the number of traditional architects is highly sensitive to the normal decision fraction because it drives the decision for ee-fraction which leads to a higher value number of potential ee-home owners. The more home owners are interested in ee, the stronger is the motivation for traditional architects to become ee-architects. If the normal decision for ee-fraction is smaller than the standard value, the architects will switch more slowly due to the inverse mechanism just described. Consequently, the number of traditional architects indicates a strong dependency on the normal decision for ee-fraction.

The variable ‘ee-houses’ is also influenced by randomized changes in the variable ‘normal decision for ee-fraction’, because the bottleneck variable ‘potential ee-home owners’ is indirectly influenced by it. Hence, higher values than the standard value lead to a steeper growth of the potential ee-home owner stock that, in turn, will result in more ee-houses. For parameters smaller than the standard value, the opposite is true. Both cases are depicted by Figure 14 (right side).

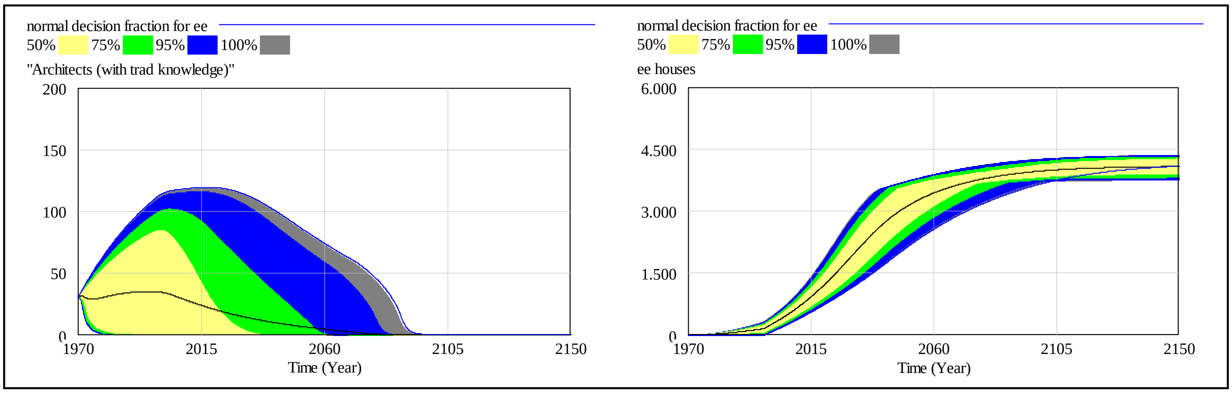

Figure 14: Analysis of the Policy Run ‘Influence of the Decision of Potential Home Owners’. Traditional architects and ee-houses exhibit sensitive behavior to changes in the normal decision fraction for ee because both variables depend on the variable ‘potential ee-home owners’ which is steered by decision for ee-fraction.

Comparison of the Policy Runs and First Insights Derived from the Model

A comparison of the simulation runs indicates beneficial and less beneficial intervention points for the federal government with the objective to increase the diffusion and adoption of the innovation. In order to evaluate the different policy runs, e.g., policy A is more effective than policy B, an objective has do be defined. In our case, the model purpose is to explain innovation diffusion and to derive a system design that fosters this diffusion process. Hence, the objective is that the ee-building stock reaches a value as high as possible and in a time period as short as possible. The variable ‘ee-houses’ is a highly and reasonable representative of the system development.

Given this objective of the system, the important policy graphs are the graphs on the right side in the Figures 12, 13, and 14 (‘ee-houses’). The graphs on the left represent an anteceding variable for the ee-houses and are not considered for the evaluation of the policies.

The first policy P1 (‘Architects with ee-knowledge flood the market’) influences the parameter ‘normal graduation ratio’ as control level. The system behavior is improved when value $p > 0.1$ [dmnl] because this leads to a higher graduation rate of ee-architects by which the market demand can be more satisfied. On the other hand, values of $p < 0.1$ [dmnl] reduce the number of ee-houses substantially. The maximal width of the envelop E_{P1} of policy P1 is about 2800 [houses]. P1 manipulates the control variable ‘normal graduation ratio’ to which the system is highly sensitive. The results of the policy exhibit the highest degree of uncertainty if compared with the other policy runs.

The second policy ‘Supply of Further Education for Architects’ (P2) influences the variable ‘architect switching ratio’ within reasonable bounds. As Figure 13 (right graph) shows, the behavior is not influenced by the uniformly randomized changes in the control lever. The development of ee-houses is highly robust. Policy P2 is therefore dispensable and should not be considered as improvement strategy.

Policy P3 (‘Influence the Decision of Potential Home Owners towards Energy-Efficient Homes’) is the most promising improvement strategy because it increases the number ee-houses even higher than P1 and avoids strong downside movements, simultaneously. The maximal width of the envelope E_{P3} of policy P3 is about 2000 [houses] which is about 30% less than P1. However, it is not clear which measure will have guaranteed influences on the variable 'normal decision for ee-fraction'. This indicates a requirement to elaborate the decision function (Figure 11) and include additional mechanisms of decision making.

4.6 Feedback Loop Management

Positive feedback loops are motors for growth or collapse of a system. They push towards exponential growth or decay and thrive towards disequilibrium. Feedback loop management intends to regulate them by actively managing different loops in favor of the system specified by a system objective. In the existing model, three positive feedback loops are controlled by five balancing loops. Hence, the controlling potential rather outweighs the reinforcing forces in number. However, not all feedback loops have the same influence on the system's behavior in strength and time. Table 3 shows a first feedback loop strength analysis. L3 is the strongest reinforcing feedback loop of the system. Moreover, loops L1, L2, and L3 are active when people have ee-houses or are convinced to construct ee-houses, and the population without own houses is sufficiently large. Later in the simulation, the population without own houses decreases (cf. Figure 9, consider that the population without own houses is the total population less the total enrolled and current home owners [line #3]). Thereby, the strongest balancing loop L4 is activated and weakens the three mentioned positive loops. From a management perspective, the diffusion process should occur as fast as possible. The limit to growth is determined by natural resources, i.e., by humans without own houses, and cannot be changed. If all humans in the considered region have fulfilled their demand for an own house, the diffusion process will stop. To foster the diffusion process, measures have to be introduced that enable the loops L1 to L3 to work, i.e., people have to be convinced to build ee-houses. One possibility is to introduce a timely determined advertisement program and subsidies to enable the reinforcement of the system.

No.	Feedback Loop	Polarity	Strength
L1	Word of Mouth Effect by Potential ee Home Owners	Reinforcing	2
L2	Market Pull for ee Architects	Reinforcing	2
L3	Word of Mouth Effect by Current ee Home Owners	Reinforcing	3
L4	Everybody Has a House	Balancing	3
L5	EE House Building Slows Down the Diffusion	Balancing	1
L6	EE Architect Capacity Clear the EE Demand	Balancing	1
L7	Traditional Architect Capacity Clear the Trad Demand	Balancing	1
L8	Traditional Architect Capacity Hinders the Diffusion of Trad Houses	Balancing	1

Table 3: Feedback Loop Management. L1, L2, and L3 are active leading to a diffusion of the innovation. L4 successfully controls them in the last quarter of the simulation time frame. Loops L5 to L8 are rather weak. Management activities should be concentrated on the first three positive loops.

5. Conclusions and Further Research

The overall target of the Swiss Energy Policy is to reduce CO_2-emissions and thereby to achieve the vision of an energy-efficient '2000 Watt per Capita Society'. Major instruments to contribute to the vision in the residential building sector are the standards about energy-efficient building designs. However, new residential houses according to energy-efficiency standards are not as often constructed as they ought to be. In order to investigate the problem, a preliminary System Dynamics model was created. With Coyle, we share the view that the main aim of System Dynamics is to develop system policies which improve the dynamic behavior of a system (Coyle 1996). However, the stage of the model is considered to be preliminary and therefore this goal is not achievable with the existing model. Our intention was rather to gain first insights about the diffusion of innovations in the residential building environment. Key insights drawn from the model formulation and analysis are: (1) The most important variable to enable a fast transition to an energy-efficient building stock is the potential ee-home owners. The demand side is the bottleneck for the diffusion process. The supply side anticipates the future market volume and demand. Throughout all simulation runs the demand side was the limiting factor for a successful diffusion. (2) The decision for ee-fraction is a high leverage point in the system as shown by policy P3. Changes in this variable can lead to significant improvements of the system behavior. Up to now, the function constituting the decision for ee-fraction is rather a black-box. This indicates a further research demand to comprehend the diffusion mechanisms better. (3) Most important mechanisms active to foster the diffusion of innovation process are the word of mouth effect, market pull effect and market saturation effect.

Further Research

As mentioned previously, the model is a preliminary version and needs more elaboration. Important questions that have to be addressed in the further research process are:

- Transition process of the legal requirements about energy-efficient building standards, e.g., SIA-Standard to Minergie-Standard,
- More precise definition of the limit between energy-efficient and non-energy-efficient buildings,
- Disaggregating the variable ‘decision for ee-fraction’, e.g., by utilization of additional scientific theories (e.g., theory of planned behavior (Ajzen 1991), or diffusion theory (Rogers 1995)),
- Inclusion of additional variables to improve model accuracy guided by psychological, managerial, economical theories as well as current legislation (SFOE 2002), empirical investigation about antecedents variables (Kaufmann-Hayoz, Bruppacher, and Ulli-Beer 2005),
- Further elaboration of the physical building structure, e.g., single-, double-, and multiple-family buildings, connection between buildings and owners, and consideration of the lessee-owners relation, vacant and occupied buildings or apartments,
- Additional parameter estimation and data analysis are required to improve the fit between model behavior and actual data,
- Validation and elaboration of the model with system experts and by means of real data,
- Investigation of the population dynamics, especially the increasing trend of foreign inhabitants and the effects of the trend on other trends and variables such as the inhabitants per house development or the inhabited residential area. Also the social trend to smaller families and the higher motivation to home ownership instead of home leasing has to be researched about in more details,
- Answer to the questions under which conditions a market pull effect occurs, e.g., if the market pull is determined by the system structure, and if the market pull effect can be intentionally altered in a market push effect,
- Improvement of the objective function for a ‘good’ or intended system behavior,
- Elaboration and inclusion of the house building support system, e.g., supplier and producer of building material.

The inclusion of further theory is an important step to (1) increase model accuracy and validity and (2) to foster the success of policy initiatives, because initiatives, such as the

Swiss energy program by the Swiss Federal Office of Energy, aiming at the diffusion of energy efficient buildings depend not only on technological innovations and fair market conditions (external opportunities) but also on adequate knowledge, decision rules, management, and networking (behavioral variables) of the various actors involved in the value creation chain of energy-efficient buildings (e.g., investors, architects, building crafts, producers, political authorities). The completed model will allow analyzing and demonstrating effects of policies on the variables of interest, such as energy consumption of the building stock, or decisions of future home owners about energy-efficient building designs depending on external legal requirements.

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