1 Introduction

This document outlines the structure and details of the agent-based building stock model. The agent-based building stock model (ABBSM) simulates the dynamics of national building stocks and its energy- and climate-impact over time. The ABBSM follows a bottom-up methodology based on physical principals and technical fundamentals and on a simulation of decisions affecting change in the stock (new construction, refurbishment and replacement) based on micro-economic principles. The BSM thereby models scenarios for reducing GHG emissions and energy demand considering the conflicts and synergies between various strategies and technological solutions at a stock level.

This model description follows the ODD (Overview, Design concepts & Details) protocol [1,2]. The model is implemented in Python using the libraries Pandas [3], Numpy [4] and mesa [5].

2 Purpose

The model is designed to support the study of the development of building stocks in terms of their energy demand and GHG emissions and in particular how building owner´s decisions to retrofit the building envelope and replace heating systems under different policy interventions affects this development. It is developed for the residential building stock of Switzerland and calibrated to model the past development in the stock from 2000 to 2017.

3 Entities, state variables, and scales

The ABBSM includes two main types of model entities: buildings and the general model environment. Building agents combine the building properties including the individual building components. Even though the model simulates building owner decisions, they are not implemented as a separate agent, but are combined with the building agent. Therefore, the current model does not differentiate between different owner types nor buildings being owned by the same owner. Moreover, also attributes connected to the building location (e.g. availability of renewable energy sources) are tied to the building agent. The other model entity is the model environment, which holds data on the climatic, economic, technological and policy framework conditions.

3.1 Building

Building agents will be initialized based on the method to construct synthetic building stocks described in [6]. The method synthetically reconstructs a representative sample building stock, where each of the generated synthetic building is representative of a part of the stock. The parameters included make it possible to run building energy demand simulations using the same calculation engine developed in [6]. The building agents' properties are, therefore, defined based on the same structure, which was extended for the purpose to be used in the ABBSM (see Figure 1). Table 4 in the appendix gives a full overview and description of the different state variables.

Each building agent made up of different building components (such as roofs, walls, floors and windows), and HVAC systems (heating system, hot water system and ventilation system) and one to many dwellings. Each of the individual parts of the building agent is characterized according to Figure 1. The full building agent characterization includes building owner and building location specific properties (see Figure 1) such as the decision parameters of the decision model used as well as building specific framework conditions such as the availability of which energy resources are available for a building (e.g. is it possible to use a ground-source heat pump). Accordingly, the heating system choice of a building will be constrained according to this criterion. In case of the grid-bound energy sources (e.g. gas and district heating), these properties might be changed over the model period as certain the grid may be extended or shrunk.

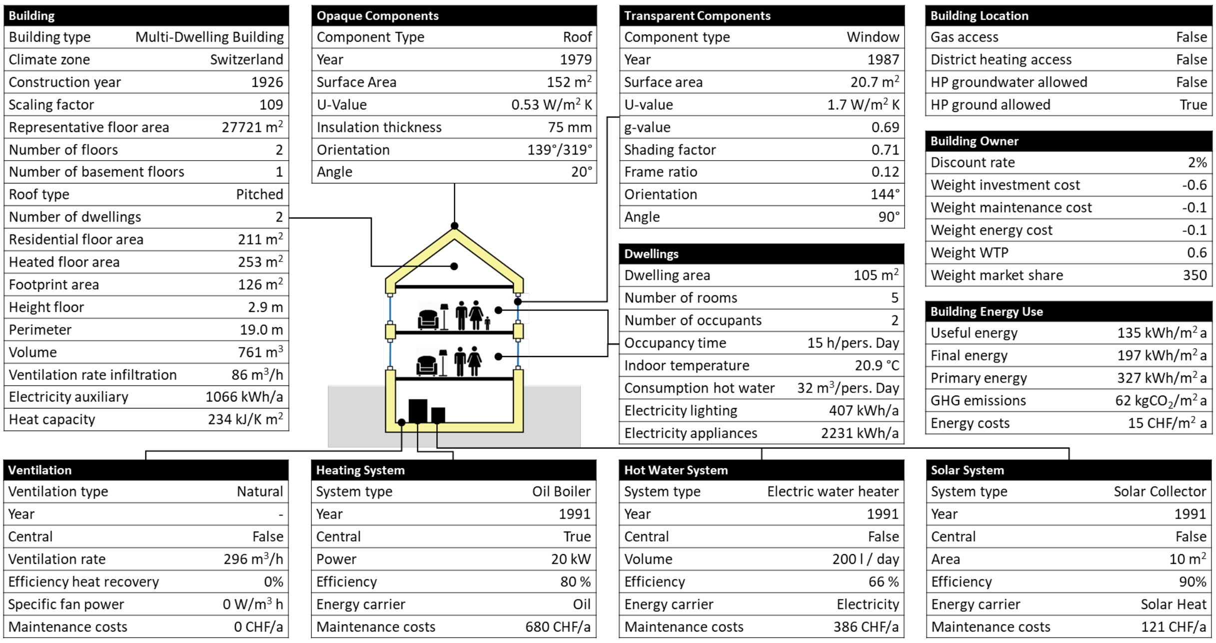

Figure 1 Example representation of building agent including its building components, systems and usage. Adapted from [6]

3.2 Model environment

The model environment holds all other climatic, economic, technological and policy framework data needed to run the simulation and is shown in Figure 2. This includes climate data to run the energy calculation, economic and technological characteristics of the technologies modeled (e.g. costs, efficiencies and lifetimes of technologies), energy prices including the development of prices over the modeling period, policy framework data such as building standard, subsidies and restrictions on the availability of technologies as well as other scenario drivers such as population and material and labour cost development. Table 5 in the appendix gives a full overview and description of the different state variables.

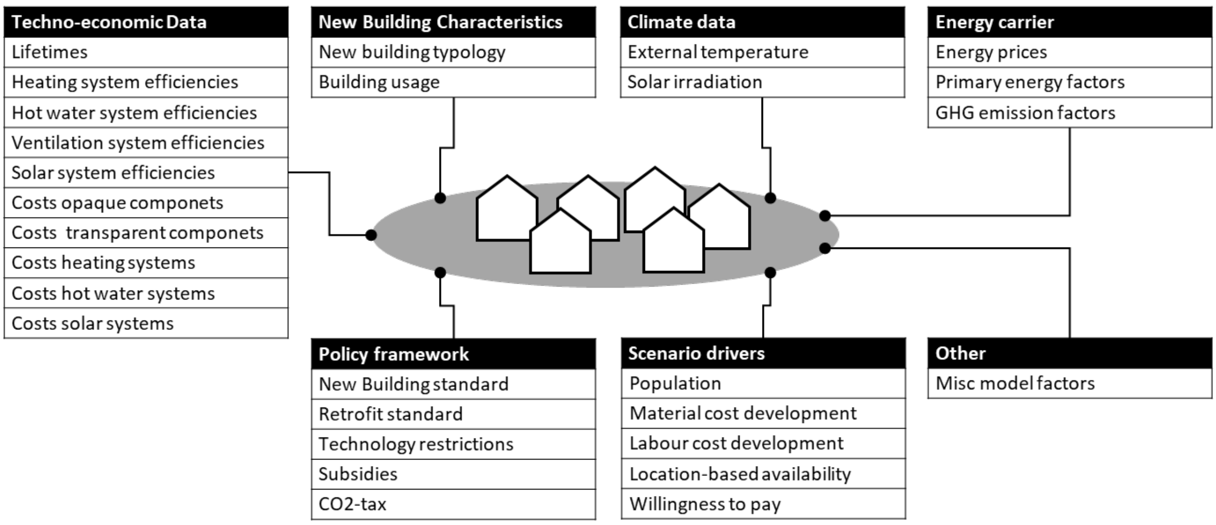

Figure 2 Description of data included in the model environment agent

3.3 Scales

The model uses a time step of one year, while the energy demand calculation is done on a monthly basis. The geographical scale of the model encompasses the borders of Switzerland.

4 Process overview and scheduling

This section gives an overview over the model process and scheduling. A more detailed description of the initialization process as well as the different submodels are given in section 6 and 8 respectively. Figure 3 gives an overview over the model process and steps.

The model is initialized by first loading all input data and defining the initial state of the model environment. Then the initial building stock is initialized based on the method to generate synthetic building stocks [6] by generating 50´000 building agents. The generation of the synthetic building stock follows three steps:

1. Building stock initialization: A representative sample of 50’000 synthetic building agents is created that has the same structured in terms of type, building period, number of dwellings, number of floors according to structural data of the real building stock.
2. Building characterization: Each of the building agents is further characterized according to the attributes required for building stock energy modelling such as building geometry and energy relevant parameters (e.g., original U-values) as well as other state variables of the building agent (e.g. location, technology availability, etc.).
3. Updating building characteristics: Update attributes of building agents to take into account previous retrofit and reinstatement measures carried out before the model start year, to represent the current state of the building (e.g., in terms of current U -values).

Following the initialization of the synthetic building stock, the model forecasts the stock dynamics based on the processes of demolition, new construction ,retrofit and replacement with a discrete timesteps of one year. It starts by updating the model environment based on input data. The process of an individual time step involves three main steps:

1. Update model environment: Update the model environment based on input data
2. Update existing buildings: loop over all building agents existing at the beginning of the timestep and update their scaling factor as well as upgrade buildings with components or systems in need of refurbishment or replacement.
3. Generate new buildings: Add new building agents based on calculated demand and loop over them to characterize the different building and component characteristics as well as define heating system.

Each of these steps is carried out is carried out one after another. In the remainder of this section, an overview of the two main steps 2 and 3 is given.

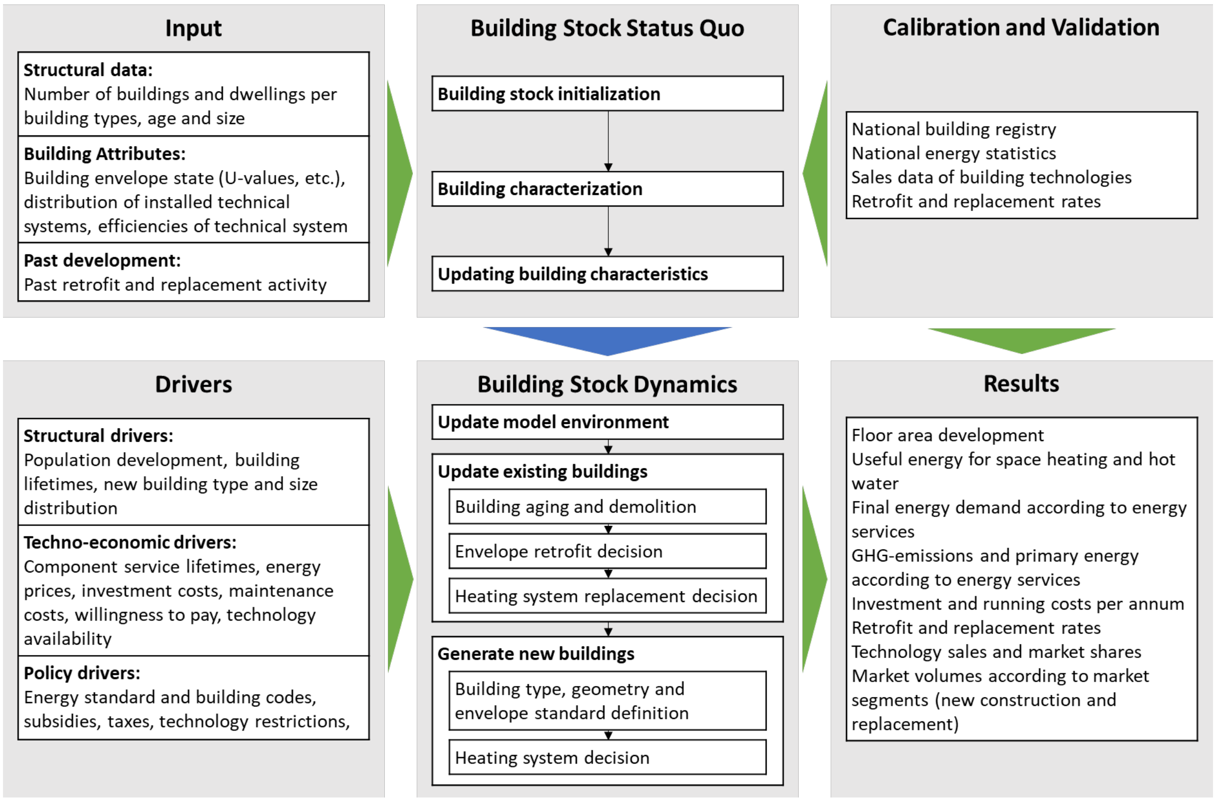

Figure 3 Process overview over building stock dynamics

4.1 Update existing buildings agents

The model loops over all buildings existing at the beginning of the time step and addresses each building one after another. First, the building and its components are aged by one year. Based on the new building age, the scaling factor and the representative floor area are adjusted to take into account demolition. Thereby, the share of the buildings represented by a given building agent is decreased to account for demolished buildings (see section 8.2.2.1).

After the scaling factor and the representative floor area are adjusted, the model checks, if any of the building envelope components have reached the end of their assigned lifetime and need to be refurbished. If this is the case, the retrofit decision is triggered. The retrofit decision model (see section 8.2.2.3) simulates the building owners' decision whether to only reinstate a certain component or to implement an energy efficiency retrofit measure (e.g. add insulation). The model decides based on an application of the general decision model (see section 5.1.4) from a choice set of a reinstatement-only option as well as three different retrofit options with different energy efficiency standards. The choice model calculates a choice probability for each option that takes into account the refurbishment costs and the possible reduction in energy costs of the building in case of the retrofit options. Based on the probability the choice is carried out stochastically. After the choice has been made, the model then updates the useful and final energy demand of the building to take into account the new state of the envelope.

If none of the building envelope components need refurbishment or they have been refurbished through the retrofit decision model, the model moves on to the heating system and checks if it has reached the end of its assigned lifetime and needs replacement. If the heating system needs replacement, the replacement decision is triggered. Moreover, the heating system is always replaced as a whole including hot water system and (if applicable) the solar system. The model decides based on an application of the general decision model (see section 5.1.4) from a choice set of all possible technologies. This choice set is first broken down to all feasible options (i.e. options not applicable for a given building agent are excluded) and then further broken down to a small consideration set based on the market share of the different technologies in the choice set. The model then calculates a choice probability for each remaining option in the choice set. This choice probability is calculated based on the utility of each option and takes into account the investment costs and energy costs of the different options. Based on the probability the choice is carried out stochastically. After the decision has been made the final energy demand of the building is updated to take into account the new heating system properties.

After the heating system has been replaced if need be, the building´s energy costs, primary energy and GHG emissions are updated to take into account the changed building properties as well as any changes in the energy prices. This process is repeated for each building.

4.2 Add new building agents

After the existing building agents have been updated, the model adds new building agents based on the demand for new construction. For this purpose, the model first calculates the need for new construction in terms of new dwellings based on the population development (see section 8.2.3). Based on the total number of dwellings needed, the number of new building agents to represent these new dwellings are calculated based on the average scaling factor in the model. For each new agent to be generated a new building agent is initialized and further characterized.

To further characterize the new building agents the model loops over all new building agents and characterize different building and component characteristics as well as defines the heating system. First, the building type, size (in terms of number of dwellings, and number of floors and average dwelling area) is defined by sampling from input distributions. Afterwards the building´s dwellings are generated based on the number of dwellings in the building and the average dwelling area. All dwellings in the building are assumed to be the same size, however, parameters such as number of occupants, occupancy time, indoor temperature and hot water demand are sampled randomly from input distributions.

To further characterize the building, the heated floor area is first estimated based on the total residential floor area from all dwellings in the building. Based on the total heated floor area and the number of floors, the building geometry in terms of surface area of walls, windows, roof and floor is defined based on a shoebox model (see section 8.2.3.1). For each of the components the energy standard is then defined based on the currently defined building standard. Moreover, the ventilation in terms of type, ventilation rate and, if applicable specific fan power and heat recovery are also defined by sampling from input distributions. Based on this the initial heat demand of the building can be estimated.

Once the building is defined to that level, the heating system decision model for new buildings is triggered to decide which heating system is installed in the building (see section 8.2.3.4). The model decides based on an application of the general decision model (see section 5.1.4) from a choice set of all possible technologies. This choice set is first broken down to all feasible options (i.e. options not applicable for a given building agent are excluded) and then further broken down to a small consideration set based on the market share of the different technologies in the choice set. The model then calculates a choice probability for each remaining option in the choice set. This choice probability is calculated based on the utility of each option and takes into account the investment costs and energy costs of the different options. Based on the probability the choice is carried out stochastically. After the decision has been made the final energy demand of the building is defined based on the chosen heating system properties.

After the heating system has been defined, the building´s energy costs, primary energy and GHG emissions are calculated to finalize the generation of the new building agent. This process is repeated for each new building.

5 Design concepts

5.1 Basic principles

Core to the ABBSM is the modelling of the retrofit and heating system decision through a decision model. For this purpose, different concepts and theoretical background were used to develop the general decision model applied in this model. The different concepts are briefly outlined in the following subsections as well as in the main paper, following a detailed description of the developed general decision model.

5.1.1 Decision process

To structure and operationalize the decision-making process of building owners and conceive a model for building agents decision making on retrofit and heating systems, different theories and methods were combined. Mainly the structure of the model is based on two theories: (1) the theory on strategic decision making developed by [7], and (2) the theory on the diffusion of innovation developed by [8], which are briefly summarized below.

The model for strategic decision-making developed by [7] structures decision processes into three distinct steps:

1. Identification:
   The identification step consists of two routines: decision recognition, during which problems, opportunities, and crises are recognized, and diagnosis, during which the cause-effect relationships of these stimuli are closer examined for the decision situation.
2. Development:
   The development step comprises of the search mechanism by which one or more solutions for the problem, opportunity or crisis at hand are developed. It consists of two alternative approaches to develop these solutions, namely the search routine, which looks for available, readymade solutions to the problem, and the design routine, which is used to develop custom-made or modifies ready-made solutions.
3. Selection:
   The selection step is the last step of the decision process during which the selection is made. It consist of three routines: (1) Screen routine, during which available options are screened and feasible options selected, (2) Evaluation-choice routine, during which the remaining choices are evaluated and the preferred solution selected, and (3) Authorization routine, during which formal approval for a decision is granted (only applies to cases where the decision-make needs to get formal authorization, e.g. in a company).

The theory of on the diffusion of innovation developed by [8] structures the adoption processes of innovations into five different stages:

1. Knowledge stage:
   In the knowledge stage, the decision-maker is made aware of the innovation and how it functions.
2. Persuasion stage:
   During the persuasion stage the decision-maker makes up his mind about the innovation and forms either a positive or negative attitude towards the innovation.

3. Decision stage:
   In the decision stage, the decision-maker either chooses to adopt or reject the innovation.
4. Implementation stage:
   In this stage the innovation is implemented and put into use.
5. Confirmation stage:
   During the confirmation stage, the decision-maker evaluates the decision made and either reinforces or weakens his attitude towards the innovation if exposed to conflicting messages.

Rogers further specifies that previous practice as well as a felt need/problem are both prior conditions for the implementation of the innovation adoption process [8].

5.1.2 Bounded rationality

The model applies the concept of bounded rationality [9] when modelling technology adoption decisions, taking into account not just technological and economic attributes but also situational and individual aspects in the decision process. Therefore, human decision making is characterized by heuristics and biases to simplify the task. In the case of building owners' decision to renovate and select heating system, research suggest, that one such heuristic lies in reducing the number of options that are considered. For example, results from [10] suggest, that in the case of heating system substitution decisions, building owners often do not even consider any or only a few alternatives when replacing their existing system. Such behaviour is consistent with findings in other studies, suggesting a two-stage decision process [11,12]. Namely, a first screening stage in which the alternatives to be considered are collected based on simple rules, followed by the actual evaluation of the selected alternatives. This process is also consistent with ABM´s model making use of social interaction between agents to model diffusion through contagion or imitation effects such as [13].

5.1.3 Discrete choice model

The model applies a discrete choice model (DCM), which is based on micro-economic utility theory, when modelling decisions on technology adoption such as the heating system choice of building owners, specifically for the selection process. Discrete choice models are widely used within research to examine how decision makers such as households, firms and consumers make their choices [14]. They have found application in many different areas such as marketing, transportation, housing and also energy research [14]. The DCM method applied is a Multinominal Logit (MNL) model, which is the most commonly applied discrete choice model [14]. The MNL model calculates the probability of a decision maker making a certain choice based on a utility function and the assumption of independence from irrelevant alternatives [14]. This means that the choice probability depends on the observed part of the utility (i.e. what can be observed and measured by the researcher/model).

5.1.4 General decision model

The general decision model applied is built up on the general model of the strategic decision process [7] and the theory of innovation [8] in combination with a discrete choice model as well as applying the principle of bounded rationality similar to [15]. It is structured based on the three steps of the model for strategic decision making process of [7](see Figure 4):

1. **Identification:**
   The building agent identifies the need for decision. This decision may be for a new heating system in case of a new building or the need to replace a heating system in an existing building). Different triggers result in a different choice set and a different evaluation process later on.
2. **Development:**
   During the development step, the building agent searches for choice alternatives and a

consideration choice set is constructed based on a universal choice set tacking into account technological and policy restriction as well as the concept of bounded rationality.

3. **Selection:**
   In the third step, the building agent evaluates each option in the choice set in detail and assesses their utility in order to finally decide which option to choose.

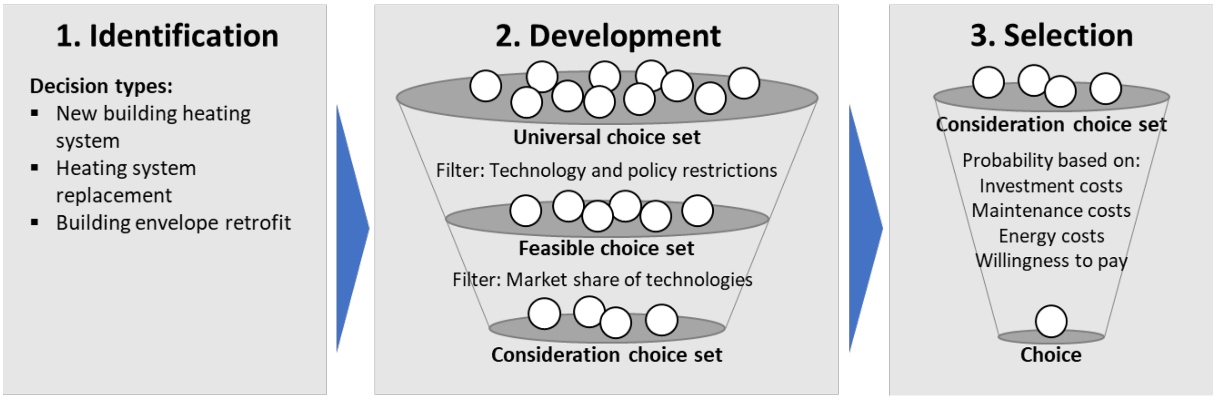

Figure 4 Overview over general decision model

5.1.4.1 Identification

During the identification stage, the building agent identifies the need for a decision process. This decision process can be triggered by different circumstances, which then also determine the choices process later. The model differentiates between three different decision frames/types:

1. **New building heating system:**
   The decision process to invest into a heating system for a new building is triggered by a new building agent being generated.
2. **Heating system replacement:**
   The decision process to replace an existing heating system is triggered by that system reaching the end of its assigned lifetime and having to be replaced.
3. **Building envelope retrofit:**
   The decision process to reinstate or retrofit a building component is triggered by that component reaching the end of its assigned lifetime and having to be retrofitted or reinstated.

5.1.4.2 Development

Once a decision process has been triggered, the choice set the building agent chooses from is defined. For a given building and decision process, the choice set is constructed based on a universal choice set encompassing all possible options for a given decision process. This choice set is first narrowed down to a feasible choice set and then to the consideration choice set, which includes all options considered by the building agent in the next stage of the decision process, section (see Figure 4).

- **Universal Choice Set**
  The universal choice set covers all theoretically available choices, which are included in the model. It is the same for all building agents and across the model period as it includes all possible options for a given decision.
- **Feasible Choice Set**
  The feasible choice set is adapted from the universal choice set for each building individually for a given decision process. Options that are technically unfeasible or not available for a building agent are excluded from the feasible choice set. Therefore, it only includes options, which are feasible for a certain building agent to apply. For example, heating systems, which are

unavailable (e.g. in case buildings not connected to the gas or district heating grid) are excluded from the feasible choice set).

- **Consideration Choice Set**
  The feasible choice set is then further narrowed down to the consideration choice set for a given decision. The consideration set includes the options the building agent considers in detail in the specific decision. The consideration set, therefore, excludes options that are feasible but are not actually considered by the building agent. Therefore, it considers the bounded rationality of decision makers and their inability or unwillingness to screen all possible options in their decision making. E.g. a building owner replacing his heating system may not check for other options than simply replacing the system with the same type that he has already installed.

The consideration choice set is formed based on the feasible choice set by selecting a certain number of options to be considered by the building agent. For this purpose, first the choice set size has to be defined. The choice set size is defined for each decision based on a gamma distribution (see equation (1)) based on [16].

$$p(n, \alpha, \theta) = \frac{1}{\Gamma(\alpha)\theta^{\alpha}} e^{-\frac{n}{\theta}} n^{\alpha-1} \tag{1}$$

n *number of choices in the choice set*
α *shape parameter*
θ *scale parameter*

The choice set composition is then chosen by weighted randomly sampling of the feasible choice set. The weights are defined for each choice set based on the market shares of the technologies of the different options. However, in the heating system replacement decision, the currently installed system is always included in the consideration choice set. The exception is in case such an option is no longer available to the building agent (e.g. in case of a ban of fossil fuel heating systems). The probability that other options will be included in the consideration choice set is then defined based on equation (2).

$$P_{ni} = \frac{e^{\sum w_{mn} MS_{mi}}}{\sum_{j}^{S} e^{\sum w_{mn} MS_{mj}}} \tag{2}$$

P_{ni}: *Probability of option i being included in consideration choice set of decision maker n*
w_{mn}: *Weight of technology m for decision maker n*
MS_{mi}: *Market share of technology m which is part of option i*

5.1.4.3 Selection

To model the selection process, the model applies a Multinominal Logit (MNL) discrete choice model. The MNL model calculates the probability of a decision maker making a certain choice based on the calculated utility of each option under consideration.

The utility of a certain option is calculated based on a utility function. The model applies a utility function based on an assessment of the total costs of the option, taking into account investment, maintenance and energy costs (see equation (3)). To make investment costs comparable to recurring costs such as energy or maintenance costs, the investment costs are converted to equivalent annual costs. In order to be able to use the same utility function regardless of building size the costs are converted to specific cost per m^2 floor area. Subsidies for different technologies and retrofit options are consider as a reduction in the investment costs. The effects of CO_2 tax are accounted for by changes in the energy price which together with the energy demand affects the energy costs of each of the options. In addition to the cost factors, the utility function includes a willingness to pay factor, which is calculated based on a percentage of the equivalent annual investment costs and reflects additional attributes of a technology not covered by the other factors (e.g. increased comfort through new windows). See section 8.3.2 for a more detailed description on how the individual elements of the utility function are calculated.

$$V_i = \beta_{AC} EAC_{I,i} + \beta_{MC} C_{M,i} + \beta_{EC} C_{E,i} + \beta_{WTP} WTP_i \tag{3}$$

V_i: *Utility of option i*
$EAC_{I,i}$: *Specific equivalent annual investment costs of option i in CHF/year m^2*
$C_{M,i}$: *Specific operation and maintenance costs of option i in CHF/year m^2*
$C_{E,i}$: *Specific energy costs of option i in CHF/year m^2*
WTP_i: *Willingness to pay for option i*
β_n *Weighting factor for decision criteria n*

The choice probability of an option i out of the choice set S can then be calculated based on equation (4). The model then randomly selects one option out of the consideration choice set based on the calculated probabilities for each option in the set.

$$P_i = \frac{e^{V_i}}{\sum_j^S e^{V_j}} \tag{4}$$

5.2 Emergence

The model studies the emergence of retrofit and heating system installation and replacement behaviour in the residential building stock resulting from agents' decisions. These decisions are influenced by costs, availability, energy prices as well as policy measures affecting these aspects. Emerging results are the retrofit, and replacement/installation behaviour of agents as well as the resulting market shares of technologies as well as energy demand and GHG emissions of the stock.

5.3 Adaptation

Agents adapt their behaviour (i.e. their decisions) in response to changes in the environment (i.e. changes in energy prices, policy framework, etc.) as well as changes in their own states (e.g. previous decisions to retrofit may affect later decisions on heating system replacement). The underlying decision logic and heuristics (e.g. decision criteria and weighing factors) do, however, not change.

5.4 Objectives

Building agents do not have an objective per se.

5.5 Learning

Learning is taking into account implicitly by adaptation of cost factors and efficiency of HVAC technologies over the modelling period but is not modelled explicitly.

5.6 Prediction

Agents can predict what investment and maintenance costs building retrofits and different heating system options have and how these options may affect the energy demand of the building including what energy costs result from that.

5.7 Sensing

Building agents can sense energy prices and technology costs as well as availability of technologies. Moreover, when defining the consideration choice set, building agents have full knowledge of the market share of technologies and fill their consideration choice set based on these shares (see section 5.1.4.2).

5.8 Interaction

Building agents do not interact directly with each other, but they have an indirect interaction through the collective adoption behaviour of heating systems. The resulting market share of technologies affects the decision of agents in the next time step as they compose their consideration choice set based on the market share of the previous time step. Otherwise building agents decide autonomously from each other.

5.9 Stochasticity

The model uses stochastic method at different stages in the model, both in the initialization as well as during the dynamic behaviour.

Initialization:

- The structure of initial stock is based on a random sample from data on the structure of the stock in terms of building types, building periods, number of floors, number of dwellings, dwelling sizes, etc.
- Other building properties are also sampled randomly based on input distributions of the different attributes according to step 2 of the synthetic building stock method.
- Step 3 of the synthetic building stock method defines the current age and the remaining lifetime of different building components, which is also sampled from a lifetime distribution for each building component.
- The initial availability of heating system technologies is assigned randomly to the initial building agents based on the defined share in the input data.

Stock dynamics:

- Each timestep the location-based availability of certain heating systems (e.g. access to gas grid) is updated based on the input data. Depending on whether the availability increases or decreases, a random sample of buildings with or without access have the respective state variable updated.
- The lifetime of components of each building agent is sampled randomly from component lifetime distributions, this lifetime defines the timing of replacement/retrofit decisions.
- Additional restriction of the availability of certain technologies in addition to the location based (e.g. restrictions based on policy) are applied only to a share of buildings based on input data. If the restriction applies to a certain building is chosen randomly based on the input distribution.
- When constructing the consideration choice set for the heating system replacement and new construction decisions, the heating system technologies included in the choice set are sampled randomly based on the market share of the different technologies.
- The choice of retrofit/heating system option is done randomly based on the calculated probability, which in turn is based on the utility of each of the options in the choice set.

5.10 Collectives

This model does not consider collective behaviour of agents.

5.11 Observation

The model output records the structural changes in the building stock (number of buildings, dwellings, floor area, etc), energy demand according to energy services, GHG-emissions and primary energy, investment and running costs, technology sales/installations, market volumes according to market segments (retrofit/new construction). In addition, also a detailed output of selected state variables per building agent is recorded for the initial and end state of the model as well as selected years in between.

6 Initialization

The initialization of the model is done in two steps. First, the model environment is set up and, second, the initial building agents are generated. The model environment is set up by loading the input data and setting the initial state of energy prices, costs, and other frame work parameters included in the model environment. After the model environment is initialized, the initial state of the building stock of 50´000 building agents is generated through the methodology to generate synthetic building stocks according to [6], see Figure 5. The method is structured into three steps:

1. Building stock initialization: The synthetic building stock is initialized by creating a representative sample of 50’000 synthetic building agents based on input data describing the structure of the stock in terms of type, age, typology, size, etc. The individual created building agents in the sample are taken to be representative for a part of the stock and are assigned a scaling factor.
2. Building characterization: Each of the building agents further characterized according to the attributes needed for building stock energy modeling, such as the building geometry, energy relevant parameters (e.g. original U-values), as well as other state variables of the building agent (e.g. location, technology availability, etc.) sampling from distributions of archetypical data on building attributes and/or sample data.
3. Updating building characteristics: Update attributes of building agents to take into account previous retrofit and reinstatement measures carried out before the model start year, to represent the current state of the building (e.g., in terms of current U -values).

A detailed description of the implemented procedure is given in section 8.1.2.

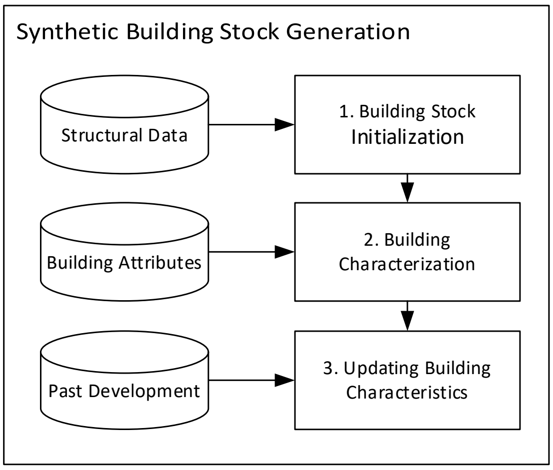

Figure 5 Process for the synthetic building stock generation for the use in the BSM (adapted from [6]*)*

7 Input data

Table 1 Description of input data and data sources

Aspect	Attribute	Unit	Differentiated according to	Distribution	Source
Initial Building Stock Structure	Number of Buildings	#	Building type, construction period, number of floors class, number of dwellings class, heating system type, hot water system type	-	[17]
	Number of Dwellings	#	Building type, construction period, dwelling Size class, number of rooms class	-	[17]
Building Geometry	Share Roof Type Pitched	%	Building type, construction period	-	[18]
	Share Buildings with Basement	%	Building type, construction period	-	[18]
	Room Height	m	Building type, construction period	Lognormal	[18]
	Height Between Floors	m	Building type, construction period	Normal	[18]
	Share One Side Attached	%	Building type, construction period	-	[18]
	Share Two Sides Attached	%	Building type, construction period	-	[18]
	Plan Depth	-	Building type, construction period	Lognormal	[18]
	Window To Wall Ratio	%	Building type, construction period	Normal	[18]
	Window Frame Ratio	%	-	Normal	[18–20]
	Window Shading Factor	%	-	Normal	[18–20]
	Ventilation Rate Infiltration	m^3/m^2h	Building type, construction period	Normal	[21,22]
	Internal Heat Capacity Building	$kJ/K\,m^2$	-	Normal	[19,20]
	Building Orientation	°	-	Uniform	-
Building Envelope	U-Value	W/m^2K	Building type, construction period, building component type	Normal	[18,21–23]
	g-Value Window	-	Building type, construction period	Normal	[18,21,22]
	Lifetime	year	Building type, building component type, renovation period	Weibull	[24,25]
	Share Energy Efficiency Refurbishment	%	Building type, building component type, renovation period	-	[26]
	Insulation Thickness after Refurbishment	mm	Building type, building component type, renovation period	Normal	[18,21–23]
	U-Value Window after Refurbishment		Building type, renovation period	Normal	[18,21–23]

	g-Value Window after Refurbishment	-	Building type, renovation period	Normal	[18,21–23]
HVAC Systems	Share Mechanical Ventilation with Heat Recovery	%	-	-	[18]
	Ventilation Rate	m^3/m^2h	Building type, construction period, ventilation type	Normal	[21,22]
	Lifetime	year	Building type, building component type, renovation period	Weibull	[24,25]
	Efficiency Space Heating	%	Heating system type, year of installation	Normal	[18,22,27–29]
	Efficiency Hot Water	%	Hot water system type, year of installation	Normal	[18,22,27–29]
	Efficiency Heat Recovery	%	Ventilation type, year of installation	Normal	[18,30]
	Specific Fan Power	$W/(m^3/h)$	Ventilation type, year of installation	Normal	[18,30]
Building Usage	Number of Occupants	#	Dwelling size class	Binominal	[17,31]
	Occupancy Time	h/persons day	-	Normal	[19,20,30]
	Indoor Temperature	°C	-	Normal	[19,20,30]
	Consumption Hot Water	l/persons day	-	Normal	[19,20,30]
	Electricity Appliances	W/m^2 year	Number of rooms class	Normal	[30,32]
	Lighting Power	W/m^2 year	Number of rooms class	Normal	[30,32]
	Lighting Full Load Hours	h/year	Occupancy time	Normal	[30,32]
	Electricity Auxiliary Building Services	W/m^2 year	Building type	Normal	[30,32]
Decision Model	Choice Set Size		Decision type	Gamma	
	Discount Rate	%		-	
	Decision Weighting Factors		Decision criteria	-	
Drivers	Population	million persons	Year	-	[33]
	Share Mechanical Ventilation with Heat Recovery	%	-	-	[18]
	Labour Cost Development	%	Year	-	[34,35]
	Material Cost Development	%	Building component, year	-	[36]
	Subsidies	%	Building component, decision type, year	-	[37–40]

	Willingness To Pay	%	Building component, decision type, year	-	
	Heating System Availability	%	Heating system type, building type, year	-	[41–44]
	Renewable Energy Requirement	%	Building type, project type, year	-	[45–61]
Building Stock Developme nt	New Building Type	%	Year	-	[31]
	New Building Characteristics	%	Building type, year, number of floors class, number of dwellings class	-	[31]
	New Dwelling Characteristics	%	Building type, year, dwelling Size class, number of rooms class	-	[31]
New Building Standard	U-Value	W/m 2 K	Building type, year, building component type	Normal	[62–64].
	g-Value Window	-	Building type, year, building component type	Normal	[18,21,22]
	Ventilation Rate Infiltration	m^3/m^2h	Building type, year, building component type	Normal	[18,21,22]
Retrofit Standard	Insulation Thickness	mm	Building type, year, building component type, retrofit standard	Normal	[18,21–23]
	U-Value Window	W/m 2 K	Building type, year, building component type, retrofit standard	Normal	[18,21–23]
	g-Value Window	-	Building type, year, building component type, retrofit standard	Normal	[18,21,22]
	Ventilation Rate Infiltration	m^3/m^2h	Building type, year	Normal	[18,21,22]
Energy Carrier	Energy Price	CHF/kWh	Energy carrier, year	-	[28,65]
	CO2 tax	CHF/kWh	Energy carrier, year	-	[66]
	GHG Factor	$kgCO_2/kWh$	Energy carrier, year	-	[67]
	PE total Factor	kWh/kWh	Energy carrier, year	-	[67]
	PE non-renewable Factor	kWh/kWh	Energy carrier, year	-	[67]
	PE renewable Factor	kWh/kWh	Energy carrier, year	-	[67]
Costs Opaque Components	Material Costs	CHF/m2	Building component type, insulation thickness	-	[21,22,68,69].
	Labour Costs	CHF/m2	Building component type, insulation thickness	-	[21,22,68,69].
	Additional Costs	CHF/m2	Building component type, insulation thickness	-	[21,22,68,69].
	Maintenance Costs	CHF/m2 year	Building component type, insulation thickness	-	[21,22,68,69].
Costs Transparent	Material Costs	CHF/m2	Building component type, U-value	-	[21,22,68,69].

Components	Labour Costs	CHF/m2	Building component type, U-value	-	[21,22,68,69].
	Additional Costs	CHF/m2	Building component type, U-value	-	[21,22,68,69].
	Maintenance Costs	CHF/m2 year	Building component type, U-value	-	[21,22,68,69].
Costs Heating Systems	Material Costs	CHF/kW	Heating system type, heating power	-	[22,70].
	Labour Costs	CHF/kW	Heating system type, heating power	-	[22,70].
	Additional Costs	CHF/kW	Heating system type, heating power	-	[22,70].
	Maintenance Costs	CHF/kW year	Heating system type, heating power	-	[22,70].
Costs Hot Water Systems	Material Costs	CHF/l	Hot water system type, hot water demand	-	[22,70].
	Labour Costs	CHF/l	Hot water system type, hot water demand	-	[22,70].
	Additional Costs	CHF/l	Hot water system type, hot water demand	-	[22,70].
	Maintenance Costs	CHF/l year	Hot water system type, hot water demand	-	[22,70].
Costs Solar Systems	Material Costs	CHF/m2	Collector area	-	[22,70].
	Labour Costs	CHF/m2	Collector area	-	[22,70].
	Additional Costs	CHF/m2	Collector area	-	[22,70].
	Maintenance Costs	CHF/m2 year	Collector area	-	[22,70].
Climate Data	Solar Irradiation	kWh/m^2 month	Month, orientation	-	[71]
	External Temperature	°C	Month	-	[71]
	Minimum External Temperature	°C		-	[71]
Other	Heat Capacity Water	Wh/m3 K		-	[19,20]
	Heat Capacity Air	Wh/m3 K		-	[19,20]
	Average Heat per Person	W/person		-	[19,20]

8 Submodels

The following section describes the different submodels in more detailed. The section is structured based on the model workflow. The first section (8.1) describes the initialization procedure used to implement the initial synthetic building agents. Afterwards, in section 8.2, the modelled building stock dynamics are described in greater detail including a description of the different implementations of the decision model. The last section (8.3) describes the energy and cost assessment models used for the decision model as well as to assess the energy and GHG emission impact of the modelled building stock.

8.1 Initialization

8.1.1 Initialize model environment

The model environment is initialized by loading the input data from the input files. Based on the input data the initial state of different framework parameters such as energy prices, costs, climate data, etc. are defined.

8.1.2 Generate initial building agents

The initial state of the building stock is generated through the methodology to generate synthetic building stocks according to [6], see Figure 6. The method is structured into three steps:

1. Building stock initialization: The synthetic building stock is initialized by creating a representative sample of buildings based in structural data, describing the stock in terms of type, age, typology, size, etc. The individual created buildings in the sample are taken to be representative for a part of the stock.
2. Building characterization: Individual, synthetically created buildings are further characterized according to the attributes needed for building stock energy modeling, such as the building geometry, energy relevant parameters (e.g. original U-values), etc. sampling from distributions of archetypical data on building attributes and or sample data.
3. Updating building characteristics: The current state of the synthetic buildings is updated with regards to past retrofit measures, e.g. in terms of current U-value.

8.1.2.1 Building stock initialization

The synthetic building stock is initialized using input data on the structure and make-up of the building (and dwelling) stock from the 2000 census of Switzerland [17]. The census data holds information on the number of buildings according to building type, building period, number of floors and number of dwellings as well as the number of dwellings per building type, building period, size class and number of rooms. The input data from is used to generate a representative sample of 50´000 buildings. The number of buildings represented by each synthetically created building agent in the sample is then defined based on the ratio between the number of building agents and the number of buildings in the input data per building type and building period.

Once the sample is generated, the different attributes that are defined by a class in the census data, e.g. number of floors (e.g., 10+ floors), number of dwellings (e.g., 6–9 dwellings) and the construction period (e.g., 1920–1944) are randomly interpolated for each record in the sample. For open-ended classes (e.g., 10+ dwellings), which are not delimited on both sides, an exponential distribution is assumed to define the attribute.

In a next step the dwelling attributes (e.g. size and number of rooms) are added to the sample, by sampling from the input data on the structure of the dwelling stock. Contrary to the approach in [6], the dwellings are not first generated independently and then assigned to a building, but in this case the dwellings assigned to a building are chosen to be all the same size. Similar to the building attributes, also the class attributes of dwellings are interpolated.

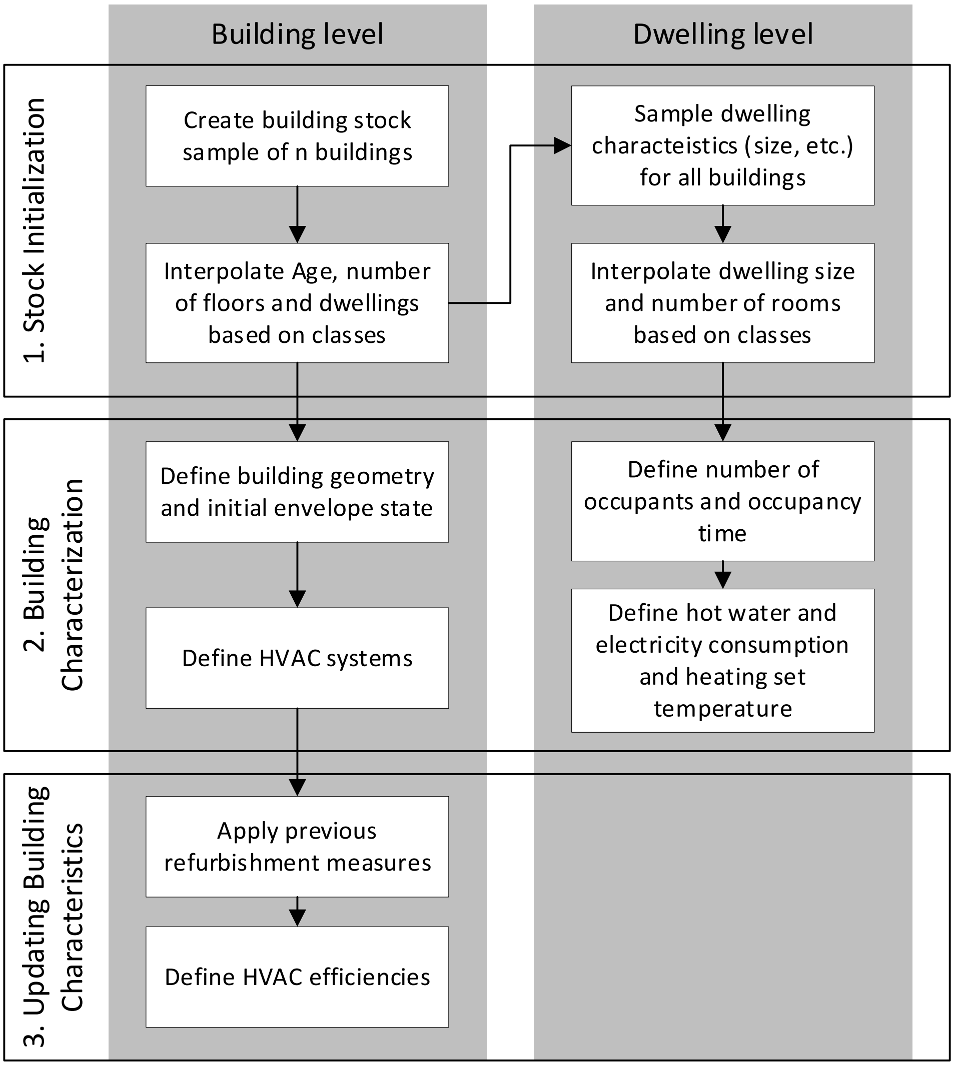

Figure 6 *Flow chart describing the process for generating a the initial building agents (adapted from* [6]*)*

8.1.2.2 Building characterization

The step building characterization step further characterizes the initialized stock of building agents by defining all further building attributes required for the ABBSM.

First, the total floor area, building geometry and building envelope are further characterized. The total residential floor area is calculated by summing up the dwelling area of all dwellings in the building. From that the heated floor area is calculated by applying a factor of 1.38 for single-dwelling buildings and 1.3 for multi-dwelling buildings based on [72]. After the floor area has been defined, additional building attributes are chosen randomly based on Monte Carlo sampling from input distributions according to the building type and thereby assigning whether the building agents have a basement, which roof type (pitched or flat), attachment (freestanding, one-sided or two-sided), window to wall ratio of the façade, average floor height, plan depth of the building as well as what main building orientation they have. Based on this the building geometry (i.e. the surface areas and orientation of all building envelope components) can be generated according to shoe box model described in section 8.2.3.1. The (initial) energy efficiency standard of the different building components (U-value and g-value for windows) is then selected by again sampling from distributions defined in the input data, depending on the building type, construction year and component type.

Second, the HVAC systems installed in the building are characterized. The heating and hot water system type of the building agents are sampled from the census data based on the building type and building period. The attributes included in the census include the energy carrier for space heating and hot water as well as the heating type (central/decentral). Based on this information are mapped to the system type definitions used in the model (see Table 6 in the appendix) and the heating and hot water systems of the building agents defined. This involves the definition of solar collectors as an additional system rather than a heating/hot water system on their own, differentiating between central and decentral systems using the same energy carrier (decentral electric heaters compared to central electric heating), differentiation of different heat pump types as well as some data cleaning to account for implausible combinations (e.g. decentral heating system using district heating). The efficiency of the systems is only defined in the next step (see section 8.1.2.3), once the year of installation of the system has been defined. The share of residential building agents equipped with mechanical ventilation systems is estimated based on the input data, while the rest is assumed to be naturally ventilated (the majority of residential buildings in Switzerland). The ventilation rate is then defined from input distributions based on the building type, construction year, and the ventilation type. Furthermore, the ventilation rate is differentiated between infiltration and natural/mechanical ventilation depending on the system type.

Third, the dwellings of the building agents are further characterized in terms of the number of occupants, the average occupancy time per day, indoor set temperature, the hot water consumption as well as electricity use for lighting and appliances. Each of these attributes are sampled from input distributions individually for every dwelling in the building.

Lastly, the initial availability of heating systems of the building agents is defined based on the shares defined in the initial state of the model environment. This is involves randomly selecting buildings and adjusting the availability for gas, district heating as well as ground/water and water/water heat pumps. Building agents who have such a system installed based on the characterization procedure described above have this system always set as available.

8.1.2.3 Updating building characteristics

The last step in the initialization procedure updates some building attributes (heating system efficiencies, U-values, etc.) to account for retrofit and replacement measures that have been carried out before the model start year.

Based on the method developed by [6], first the year of the last intervention for each component and system is defined based on (repeated) sampling from the building component lifetime distribution and updating the year of the last intervention starting with the construction year until the year of the next intervention surpasses the start year. The year of the last intervention may be the year of construction in case of new buildings, but older buildings may have undergone already one or more renovation cycles. The difference between the model start year and the year of the last intervention defines the current age of the component, while the difference between the last sampled lifetime and the current age is taken as the remaining lifetime of the component modelling the stock dynamics later on (see section 8.2.2).

After the year of the last intervention has been defined, how the building component was altered is assessed. In the case of building envelope components, the model assesses whether or not the last intervention was an energy efficacy retrofit (and therefore had an effect on the efficiency of the component) or a simple reinstatement of the component, based on probabilities defined in the input data. However, in case the year of the last intervention was the same as the year of construction there has been no retrofit either. If there has been a retrofit measure implemented, the model updates the U-value of the component (and the g-value in case of windows) based on the defined insulation thicknesses and window standards per renovation period and component in the input data. In the case of the different HVAC systems, the year of the last intervention is taken as the year of installation based on which the technical characteristics of the system are defined. For the heating, hot water and, the solar systems this is the system efficiency, while for mechanical ventilation systems the specific fan power and (if applicable) the heat recovery efficiency is defined.

8.2 Building stock dynamics

Each timestep of the model is carried out in three distinct steps: (1) update the model environment (2) updating all existing building agents and (3) adding new building agents through new construction.

8.2.1 Update model environment

Each time step starts by updating the model environment. This involves the adjustment of framework parameters such as energy prices, cost factors, new building and retrofit standards technology efficiencies, as well as the availability of technologies based on input data. Moreover, the location-based availability of grid-bound energy systems (i.e. gas and district heating) of buildings is updated. Meaning, the availability of gas and district heating for randomly selected buildings is adjusted depending on whether the grid is extended or shrunk according to the input data.

8.2.2 Update building agents

The model loops over all buildings existing at the beginning of the time step and addresses each building one after another. The routine has four main processes that are carried out:

1. Demolition: Account for demolition of existing buildings by adjusting the scaling factor and representative floor area of each agent.
2. Building components ageing: Age building components by one year and assess whether they have reached the end of their lifetime.
3. Building envelope retrofit: Retrofit decision for building envelope components that have reached the end of their lifetime.
4. Heating system replacement: Replacement decision in case the heating system has reached the end of its lifetime.

8.2.2.1 Demolition

Demolition of existing buildings is modelled by adjusting the scaling factor and representative floor area of the building agent. As each agent represents a number of buildings in the stock based on the scaling factor, the model adjusts this factor to simulate demolition rather than simply removing agents from the model. This allows demolition to be modelled more distributed across all building agents.

The adjustment of the scaling factor (and representative floor area) is done based on a survival function. The model uses a the survival function of the loglogistic distribution (see equation (5)) , which was fitted based on data from [73]. The resulting distribution has a scale parameter of alpha 175 and a shape parameter of 3.4.

$$S(t,\alpha,\beta) = 1 - \frac{1}{1+\frac{t}{\alpha}^{-\beta}} \tag{5}$$

S	*Survival probability of the building*
t	*life time of the building*
α	*scale parameter*
β	*shape parameter*

Based on the survival function the scaling factor is adjusted according to equation (6) each timestep based on the change in the survival probability compared to the previous timestep.

$$f_{S,t} = f_{S,t-1} * \frac{S(t)}{S(t-1)} \tag{6}$$

$f_{S,t}$ *Scaling factor of the building agent at time t*

8.2.2.2 Building component ageing

In addition to the age of the whole building agent, also each building component of the building ages individually until it reaches the end of its assigned lifetime. At this point it will need to be reinstated, replaced or retrofitted, depending on the component. The lifetime of each component is assigned stochastically based on an input distribution. For this purpose the model uses Weibull distributions (see equation (7)) for each of the components, which are fitted based on data from [24,25]. The lifetime is assigned when a building agent is generated and each time a component is replaced or reinstated/retrofitted the age is set to 0 and a new lifetime is assigned.

$$\begin{gathered} F(t,k,\lambda) = 1 - e^{-\left(\frac{t}{\lambda}\right)^k} \\ f(t,k,\lambda) = \frac{k}{\lambda}\left(\frac{t}{\lambda}\right)^{k-1} e^{-\left(\frac{t}{\lambda}\right)^k} \end{gathered} \tag{7}$$

F *Cumulative density function of the Weibull distribution*
t *lifetime of the building component*
λ *scale parameter*
k *shape parameter*

8.2.2.3 Building envelope retrofit

The building envelope retrofit decision processes is shown in Figure 7, it is an application of the general decision model outlined in section 5.1.4. It is structured into three steps (1) identification, (2) development and (3) selection and is carried out for each building in every time step.

At the start of the identification step, all envelope components being aged one year and in case a component is at the end of its lifetime it will need refurbishment in that time step. If no component needs refurbishment, the process stops here, and the model moves on. If there is one or more component needing refurbishment then the development step is started.

In the next step, development, the choice set is defined. For all components that need refurbishment in this time step, the choice set consists of a reinstatement option as well as up to three energy efficiency retrofit option ranging from a minimal, medium to an ambitious option. The actual efficiency level (e.g. U-value of new window) of the different options, is defined as am exogeneous model input and changes over the model period. Each option in the developed consideration choice set is then evaluated according to its investment and energy costs (see section 8.3.2).

In the last step, selection, the utility of each option and - based on the calculated utilities - the choice probability for the different options in question is calculated based on the discrete choice model described in 5.1.4.3. Based on the calculated probability a random choice is made from the choice set and the building updated accordingly, which ends the decision process.

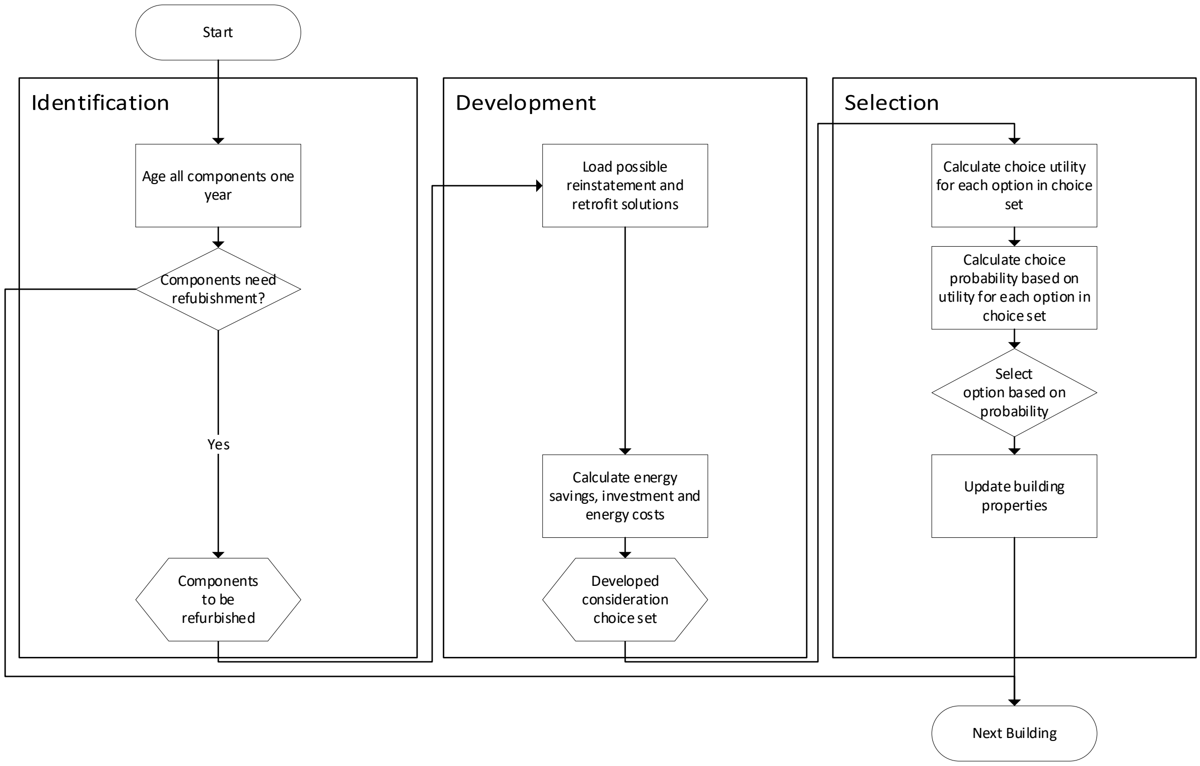

Figure 7 Flow diagram of building envelope retrofit decision model

8.2.2.4 Heating system replacement

The heating system replacement decision process is shown in Figure 8, it is also an application of the general decision model outlined in section 5.1.4 and is carried out for each building in every time step.

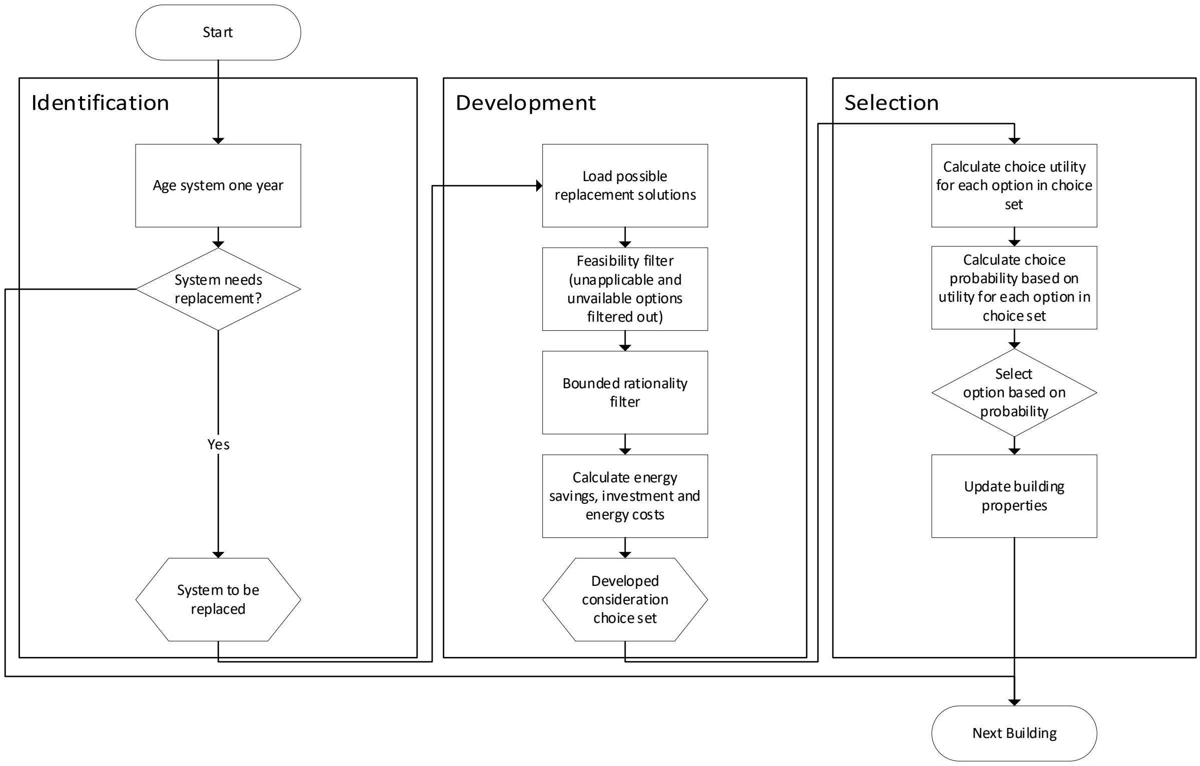

Figure 8 Flow diagram of building heating systems replacement decision model

At the start of the identification step, the heating system is aged one year and in case it is at the end of its lifetime it will need to be replaced in that time step. If it has not reached the end of its lifetime, the process stops here, and the model moves on, otherwise the heating system replacement decision is triggered. The heating system replacement always includes also the hot water system as well as the solar system (if installed already) in the decision as these systems are connected.

In the next step, development, the choice set is defined based on which system has be replaced. The universal choice consists of all possible combination of technologies available (see Table 6 in Appendix for a list of technologies). Based on different feasibility filters, the feasible choice set is defined, excluding options that are not available for this building (see Table 2). Based on the resulting feasible choice set, the consideration set is generated, by randomly drawing a number of options based on the market share of the option (see section 5.1.4.2). Lastly, each option in the developed consideration choice set is then evaluated according to its investment, maintenance and energy costs (see section 8.3.2).

In the last step, selection, the utility of each option and - based on the calculated utilities - the choice probability for the different options in question is calculated based on the discrete choice model described in 5.1.4.3. Based on the calculated probability a random choice is made from the choice set and the building updated accordingly, which ends the decision process.

8.2.3 New construction

The amount of new buildings and dwellings being added each time step is calculated based on the population development. First, the number of new dwellings to be added is estimated for each time step according to equation (8). The equation is calibrated based on the observed population development and growth in the newly constructed dwellings between 2000 and 2016, see Figure 9.

Table 2 List of the applied technological and policy filters for heating system replacement decisions

Filter	Description
Technological feasibility	Location-based filter of unavailable heating system options (e.g. gas, district heating, but also ground and water source heat pumps)
	Technical feasibility of certain options due to minimum or maximum power thresholds
	Exclude decentral heating options if the building has already a central heating system
	Building agents with district heating only consider options that include district heating (i.e. no disconnection from heating grid)
	Building agents with solar collectors only consider options that include solar collector
Policy	Exclude options that are restricted due to policy intervention (e.g. ban of fossil heating systems)

$$\Delta n_{d,t} = a + b \cdot \Delta n_{p,t} \tag{8}$$

$\Delta n_{d,t}$	*number of dwellings added in time step t*
$\Delta n_{p,t}$	*population growth from time step t-1 to t*
a,b	*calibrated factors*

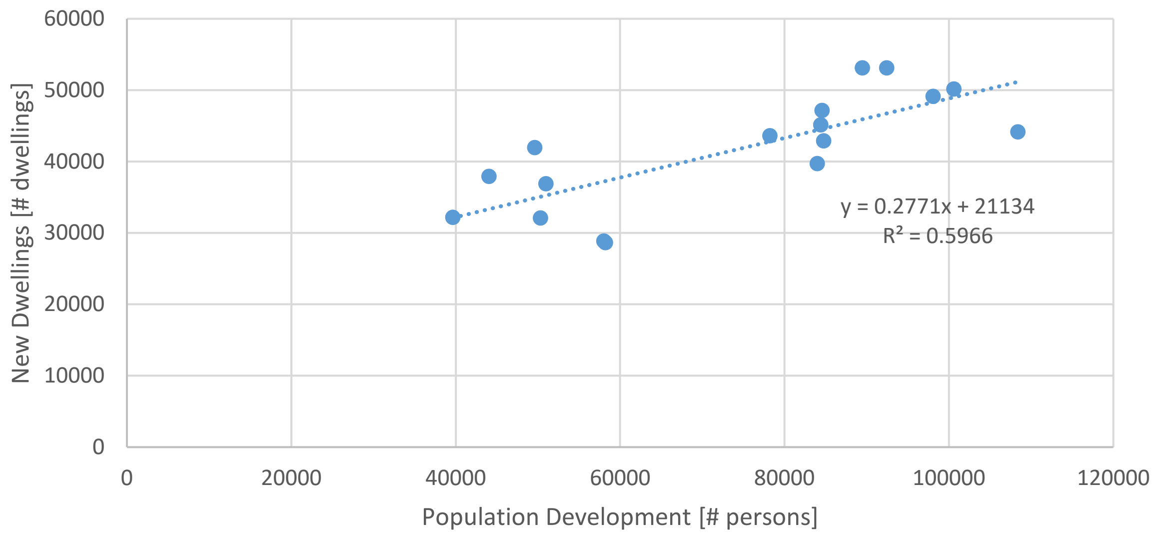

Figure 9 Correlation between population development and new dwelling growth according to [33,74]

Based on the number of dwellings to be added the number of building agents is calculated to have a similar average scaling factor than the rest of the stock. Each building agent as well as its dwelling(s) are then further characterized in terms of building type, number of floors, number of dwellings, number of rooms and dwelling size by randomly choosing from input distributions based on input data.

8.2.3.1 Building geometry

Once the building type and size of a new building agent has been defined, the total floor area and building geometry (walls, roof, floor and windows) are calculated. The total residential floor area is calculated by summing up all the dwelling area in the building. From that the heated floor area is calculated by applying a factor of 1.38 for single-dwelling buildings and 1.3 for multi-dwelling buildings based on [72].

Based on the calculated floor area, the building geometry is defined by constructing a shoebox model (Figure 10) based on these steps:

1. Additional building criteria are chosen randomly from input distributions based on the building type assigning whether the building has a basement, and which roof type (pitched or flat) it has, attachment (freestanding, one-sided or two-sided), window to wall ratio of the façade, average floor height, plan depth of the building as well as a main building orientation.
2. The footprint area (A_{floor}) is calculated by dividing the heated floor area with the number of floors. Depending of wheatear, the building was assigned to have a basement or not, the floor is classified as being towards the ground or unheated.
3. Based on the floor area the roof area (A_{roof}) can be calculated depending on the assigned roof type. In case of a flat roof the roof area is the same as the floor area. If the roof is pitched, then first a roof angle is assigned based on an input distribution with a mean angle of 30°. Based on the roof angle the total roof area can be calculated.
4. The building length can be calculated by dividing the floor area by the assigned plan depth. Based on these measurements the total perimeter of the building can be calculated.
5. The total façade area can then be calculated based on the building perimeter, number of floors, and floor height of the building.

6. The total façade area is reduced depending on whether the building was defined to be attached on one-side or two.
7. The resulting total façade area is subdivided between opaque wall area (A_{Wall}) and window area (A_{Window}) using the assigned to window-to-wall ratio.
8. All components are oriented depending on the main building orientation, with walls and windows being subdivided into two to four sub components (depending on level of attachment), which are angled in different directions.

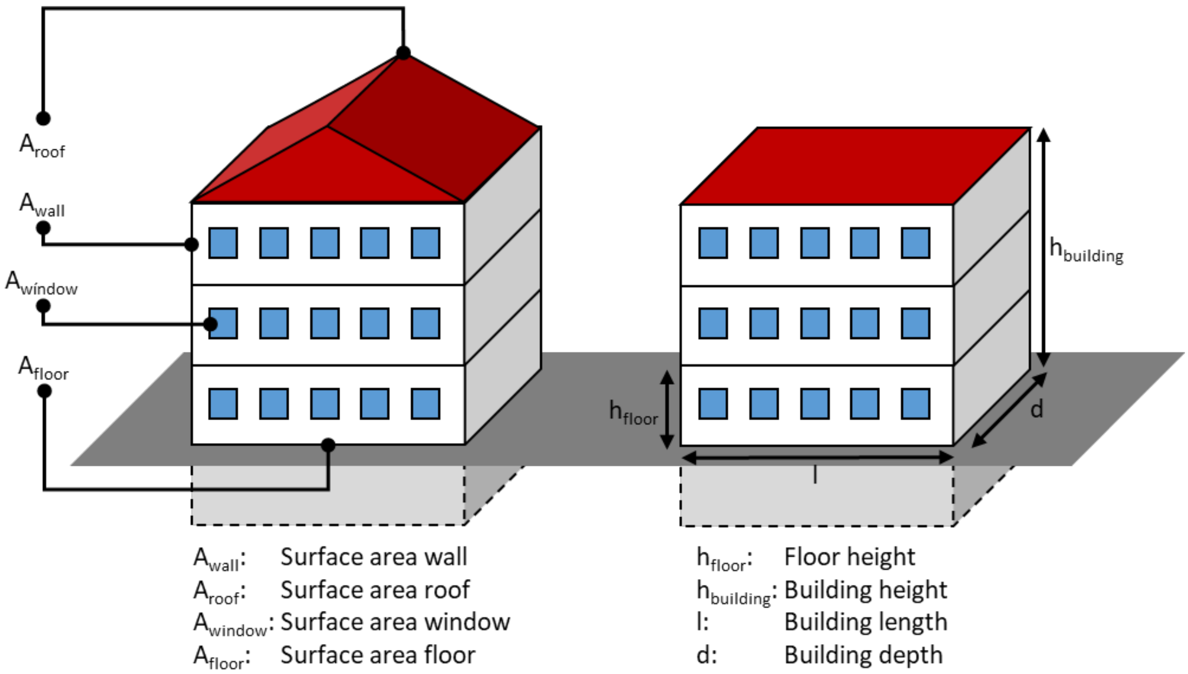

Figure 10 Building geometry generated according to the shoe box model for buildings with a pitched roofs (left) and flat roofs (right)

8.2.3.2 Envelope standard

Once the building geometry has been created, the standard of the building envelope is defined based on the new construction standard. The new construction standard is defined exogenously and is included in the input data that is loaded to the model environment. Based on the input data the U-value (and g-value of windows) of the different components is defined based on input distributions. In addition to the U-values, the heat capacity of the building is defined as well to account for the thermal mass in the building.

8.2.3.3 Ventilation system

The type of ventilation of the new building agent is defined based on exogenously defined shares of new buildings with mechanical ventilation systems based on the input data. Based on these shares, the type of ventilation is randomly assigned, while the rest is assumed to be naturally ventilated. The ventilation rate is then defined from input distributions based on the building type, year, and the ventilation type. Furthermore, the ventilation rate is differentiated between infiltration and natural/mechanical ventilation depending on the system type.

8.2.3.4 Heating system

After the building geometry and envelope standard are defined, the heating systems of the buildings are chosen based on process is shown in Figure 11, it is also an application of the general decision model outlined in section 5.1.4 and is carried out for each new building. The identification step is therefore simple for this process in that it is carried out for each new building.

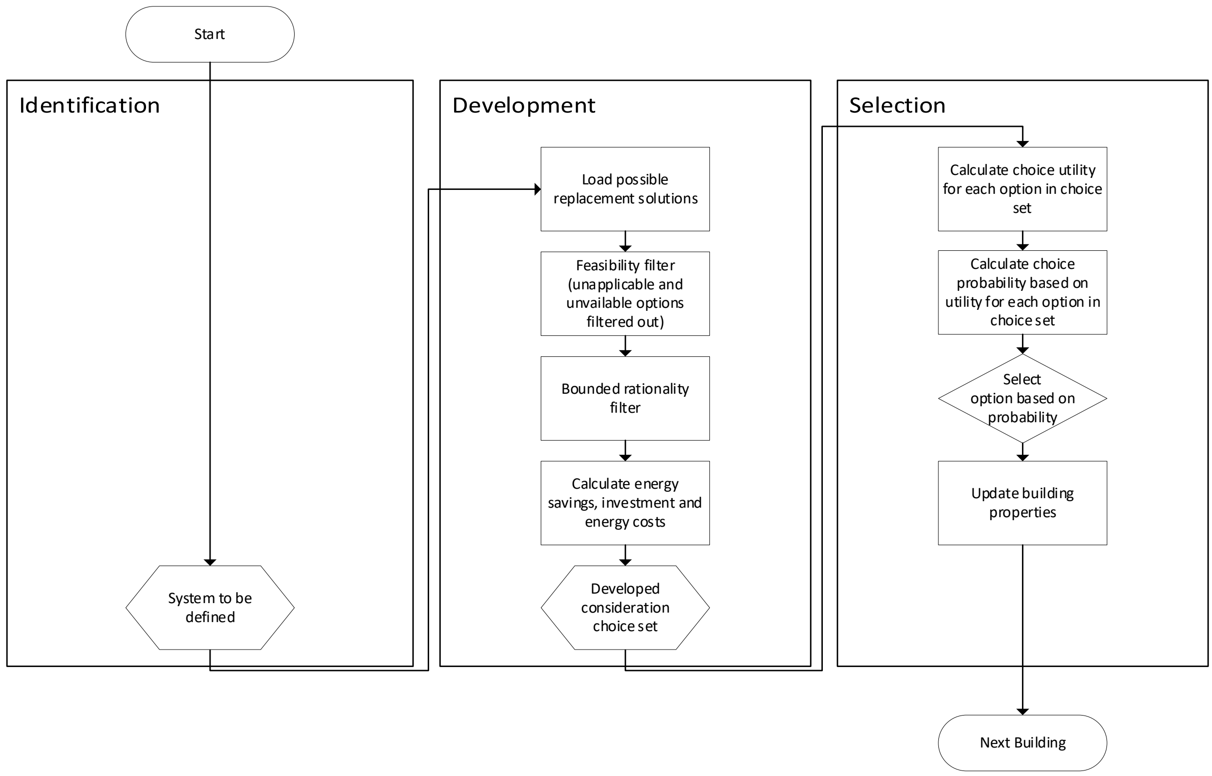

Figure 11 Flow diagram of new building heating systems decision model

In the development step, the choice set is defined. The universal choice consists of all possible alternatives of different combinations of heating systems (see Table 6 in Appendix for a list of technologies). From this universal choice set, the feasible choice set is defined based on different feasibility filters (see Table 3), excluding options that are not available for this building (e.g. building has no access to district heating or are not available due to policy restrictions). Based on this choice set, the consideration set is generated, by randomly drawing a number of options based on the market share of the option (see section 5.1.4.2). Lastly, each option in the developed consideration choice set is then evaluated according to its investment and resulting energy costs.

Table 3 List of the applied technological and policy filters for the new building heating system decision

Filter	Description
Technological feasibility	Location-based filter of unavailable heating system options (e.g. gas, district heating, but also ground and water source heat pumps)
	Technical feasibility of certain options due to minimum or maximum power thresholds
Policy	Exclude options that are restricted due to policy intervention (e.g. ban of fossil heating systems)
	Exclude options that do not meet the new construction standard (e.g. RES requirements)

In the last step, selection, the utility of each option and - based on the calculated utilities - the choice probability for the different options in question is calculated based on the discrete choice model described in 5.1.4.3. Based on the calculated probability a random choice is made from the choice set and the heating system of the building agent is defined accordingly, which ends the decision process.

After this, the initial state of the new building agent in terms of energy demand, primary energy, GHG-emissions and energy costs is defined accordingly.

8.3 Assessment models

8.3.1 Energy and impact assessment

The model has an integrated energy and impact assessment model which is used to model the energy demand of the building agents as well as to assess the effect of retrofit and replacement measures in the applications of the decision model. The overall energy calculation is based on a hierarchical structure according to Figure 12, calculating the energy demand according to different system boundaries (useful, final, primary energy and GHG emissions). The model differentiates the calculated energy demand and GHG emissions for different energy services (i.e. space heating, hot water, ventilation, appliances, lighting and auxiliary building services (e.g. pumps, etc.)).

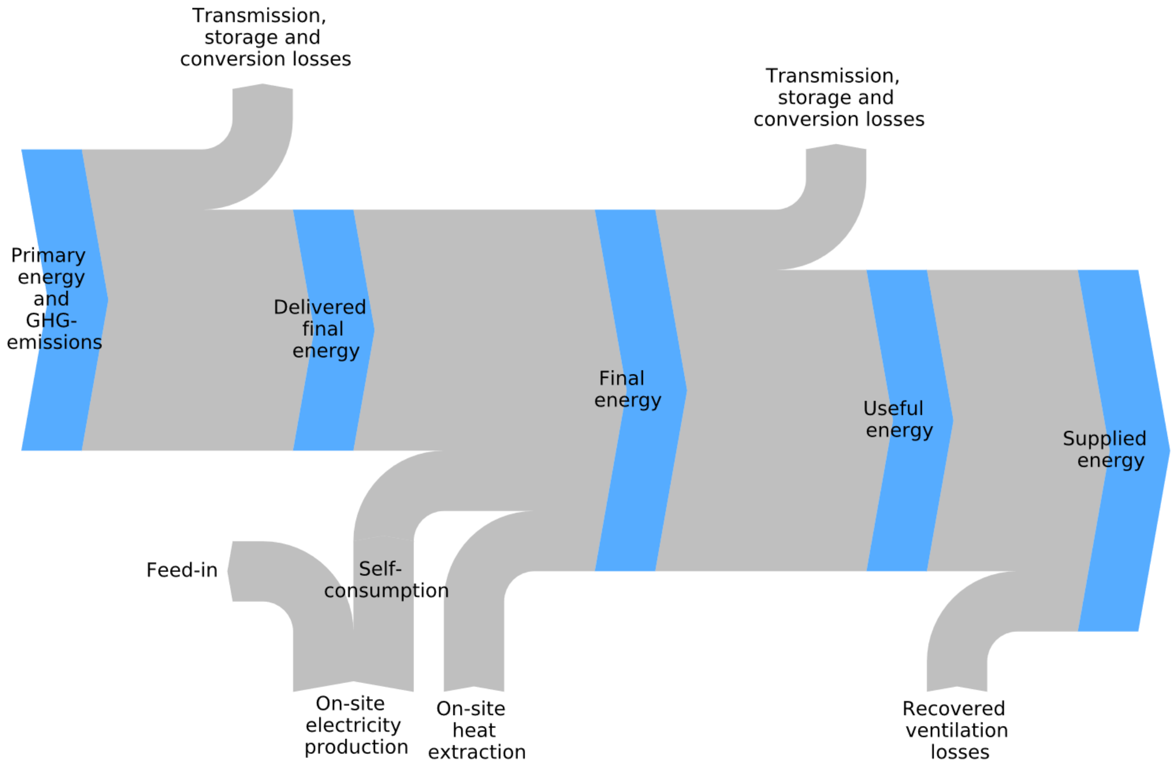

Figure 12 System boundaries for different types of energy terms used (adapted from Müller 2015)

The useful energy demand includes useful energy for space heating and hot water. The demand for space heating is based on a monthly steady-state energy balance based on the norm ISO EN 52016-1 [75]. The model is extended with a method to account for the performance gap and the fact that in general the indoor temperature is notably lower for inefficient buildings compared to newer energy efficient buildings, which affects their energy consumption [76,77]. This method adjusts the indoor temperature depending on the energy efficiency standard of the building based on [77]. The useful energy demand for hot water is calculated based on the number of occupants and a per person hot water consumption per dwelling.

The final energy demand is calculated according to energy service and differentiated according to energy carrier based on the useful energy demand and the HVAC systems installed in the building and their efficiencies. Different efficiencies are used for space heating and hot water in order to account for the different temperature levels and losses in distribution within the building. Solar thermal collectors are assessed separately based on a monthly energy balance of the possible production based on irradiation and the actual demand for hot water and/or space heating in the building. Additionally, the electrical loads of the buildings are also calculated. The electricity demand for appliances and lighting is calculated based on the number of occupants and size of the dwellings in the building.

Based on the final energy demand, the actual delivered final energy is calculated, which excludes the final energy provided from on-site heat extraction from the ambient through heat pumps as well as solar heat. On-site electricity production is included in Figure 12 for completeness sake but is currently not included in the model. The model primarily uses delivered final energy as total final energy (including solar and ambient heat) are only used for reporting and comparison with official energy statistics but are not considered by the decision model.

The primary energy demand and greenhouse gas (GHG) emissions are then calculated from the final energy demand based on primary energy and emission factors according to the energy carrier used.

8.3.1.1 Useful energy demand

The energy and impact assessment model calculates the monthly useful energy demand of each building agent for space heating and hot water. The useful energy demand for space heating is based on a monthly steady-state energy balance based on the norm ISO EN 52016-1 [75]. It is extended with a method by [77] to account for the energy performance gap and non-standard user behaviour.

The monthly energy demand for space heating ($Q_{H,m}$) of a building agent is calculated based on the balance between the heat losses and gains for each month according to equation (9).

$$Q_{H,m} = Q_{T,m} + Q_{V,m} - \eta_{g,m}\left(Q_{S,m} + Q_{P,m} + Q_{E,m}\right) \tag{9}$$

$Q_{H,m}$	*Useful energy demand for space heating of month m in kWh*
$Q_{T,m}$	*Heat losses through transmission in month m in kWh*
$Q_{V,m}$	*Heat losses through ventilation in month m in kWh*
$Q_{S,m}$	*Heat gains from solar irradiation in month m in kWh*
$Q_{P,m}$	*Heat gains from persons in month m in kWh*
$Q_{A,m}$	*Heat gains from electrical equipment in month m in kWh*
$\eta_{g,m}$	*Heat gains utilization factor*

The different heat losses ($Q_{T,m}$, $Q_{V,m}$) and heat gains ($Q_{S,m}$, $Q_{P,m}$, $Q_{A,m}$) are calculated based on equations (10)and (11) respectively

$$\begin{aligned} Q_{T,m} &= \sum_{c}^{components} U_c \cdot A_c \cdot \Delta T \cdot b_c \cdot t_m \cdot 24 \cdot 10^{-3} \\ Q_{V,m} &= \rho_a c_a \cdot \left(q_{v,act} \cdot (1 - \eta_{HR}) + q_{v,inf}\right) \cdot \Delta T \cdot t_m \cdot 24 \cdot 10^{-3} \end{aligned} \tag{10}$$

U_c	*U-value of the component in W/m² K*
A_c	*Surface area of the component in m²*
ΔT	*Adjusted temperature difference between internal and external temperature in K*
b_c	*Reduction factor for surfaces towards ground or unheated spaces*
t_m	*Length of month m in days*
$\rho_a c_a$	*Heat capacity of air in Wh/m³ K*
$q_{v,act}$	*Ventilation rate due to active ventilation (mechanical or natural) in m³/h*
η_{HR}	*Efficiency of heat recovery from ventilation*
$q_{v,inf}$	*Ventilation rate due to infiltration in m³/h*

$$Q_{S,m} = \sum_{c}^{Windows} I_G \cdot A_c \cdot g_c \cdot (1 - f_{frame,c}) \cdot f_{shading,C} \cdot t_m \cdot 24 \cdot 10^{-3}$$

$$Q_{P,m} = n_P \cdot q_P \cdot t_P \cdot t_m \cdot 10^{-3} \tag{11}$$

$$Q_{E,m} = (E_{A,m} + E_{L,m} + E_{V,m} + E_{Aux,m}) \cdot f_e$$

I_G *Global solar irradiation on the window surface in kWh/m²*
A_c *Surface area of the window in m²*
g_c *Solar gains factor of the window*
$f_{frame,c}$ *Frame ratio of the window*
$f_{shading,c}$ *Shading factor of the window*
n_P *Number of occupants in #persons*
q_p *Heat gain from each person in W/person*
t_p *Occupancy time in h/day and person*
$E_{A,m}$ *Electricity use from appliances in month m in kWh*
$E_{L,m}$ *Electricity use from lighting in month m in kWh*
$E_{L,m}$ *Electricity use from ventilation in month m in kWh*
$E_{Aux,m}$ *Electricity use from auxiliary sources (pumps, etc.) in month m in kWh*

The method to account for the performance gap and user behaviour developed by [77] is used to adjust the internal temperature and thereby the temperature difference between internal and external temperature (ΔT), see equation (12).The method accounts for the impact of nightly decrease of the internal air temperature, partially heated spaces as well as general user influence.

$$\Delta T = f_n \cdot f_r \cdot f_u \cdot (T_{i,m} - T_{e,m}) \tag{12}$$

f_n *Reduction factor for the nightly decrease of the internal air temperature*
f_r *Reduction factor for the partially heated spaces*
f_u *Reduction factor for user influence*
$T_{i,m}$ *Indoor set temperature in °C*
$T_{e,m}$ *External air temperature in °C*

The different reduction factors are calculated according to equations (13).

$$f_n = 0.9 + \frac{0.1}{h}$$

$$f_r = \frac{1}{0.5\sqrt{h} \cdot {n_r}^2 + 1} \tag{13}$$

$$f_u = 0.5 + \frac{1}{1 + 0.5 \cdot h}$$

h *Specific heat loss factor of the building in W/m²$_{floor\ area}$ K*
n_n *Share of indirectly or partially heated spaces in the thermal envelope*

The specific heat loss factor as well as the share of indirectly or partially heated spaces are in turn calculated according to equations (14).

$$h = \left(\sum_{c}^{components} U_c \cdot A_c \cdot b_c \cdot + \ \rho_a c_a \cdot \left(q_{v,act} \cdot (1 - \eta_{HR}) + q_{v,inf}\right) \right) \cdot \Delta T \cdot t_m \cdot 24 \cdot \frac{1}{A_T} \tag{14}$$

$$n_r = 0.25 + 0.2 \cdot \tan^{-1} \frac{A_D - 100}{50}$$

A_T Heated floor area in m^2
A_D Average dwelling size in the building in m^2

The monthly energy demand for hot water ($Q_{HW,m}$) of a building agent is calculated based on the hot water consumption each month according to equation (15).

$$Q_{HW,m} = \ \rho_w c_w \cdot n_O \cdot V_{HW} \cdot t_m \cdot 24 \cdot 10^{-3} \tag{15}$$

$Q_{HW,m}$ Useful energy demand for hot water of month m in kWh
$\rho_w c_w$ Heat capacity of water in Wh/m^3 K
V_{HW} Daily hot water consumption per occupant in m^3/day person

8.3.1.2 Final energy demand

Based on the useful energy demand the model calculates the delivered final energy demand for space heating and hot water based on the heating and hot water system of the building agent according to equation (16).

$$E_{H,m} = \frac{Q_{H,m} - f_{H,solar} \cdot f_{solar} \cdot Q_{solar,m}}{\eta_H}$$
$$E_{HW,m} = \frac{Q_{HW,m} - f_{HW,solar} \cdot f_{solar} \cdot Q_{solar,m}}{\eta_{HW}} \tag{16}$$

$E_{H,m}$ Final energy demand for space heating of month m in kWh
$E_{HW,m}$ Final energy demand for hot water of month m in kWh
$Q_{solar,m}$ Heat provided from solar thermal collectors in month m in kWh
f_{solar} Useable share of the heat provided by solar collectors
$f_{H,solar}$ Share of the heat provided by solar collectors used for space heating
$f_{HW,solar}$ Share of the heat provided by solar collectors used for hot water
η_H Seasonal efficiency for space heating in %
η_{HW} Seasonal efficiency for hot water in %

The heat generated by solar collectors (in case one is installed) is calculated according to equation (17).

$$Q_{solar,m} = I_{G,sc} \cdot A_{sc} \ \cdot \eta_{solar} \cdot t_m \cdot 24 \cdot 10^{-3} \tag{17}$$

$I_{G,sc}$ global solar irradiation on the collector surface in kWh/m^2
A_{sc} surface area of the collector in m^2
η_{sc} Efficiency of the solar collector in %

The model accounts for the fact that not all of the heat generated by the solar collector can be used due to a mismatch of supply and demand (especially in the summer months) and only limited storage capacity. This is taken into account with the reduction factor f_{solar}, calculated according to equation

(18). The reduction factor depends on whether or not the solar collector provides heat for both space heating and hot water or just hot water.

$$f_{solar} = \begin{cases} \tan^{-1} \frac{Q_{solar,m}}{Q_{H,m} + Q_{HW,m}} \; if\ both\ heating\ and\ hot\ water \\ \tan^{-1} \frac{Q_{solar,m}}{Q_{H,m}} \; if\ only\ hot\ water \end{cases} \tag{18}$$

In case the solar collector provides heat for both space heating and hot water the individual shares are calculated proportionally according to equation (19).

$$\begin{aligned} f_{H,solar} &= \frac{Q_{H,m}}{Q_{H,m} + Q_{HW,m}} \\ f_{HW,solar} &= \frac{Q_{HW,m}}{Q_{H,m} + Q_{HW,m}} \end{aligned} \tag{19}$$

The final energy demand for the remaining energy services (appliances, lighting, ventilation and auxiliary building services (e.g. pumps) are calculated according to equations (20).

$$\begin{aligned} E_A &= P_A \cdot t_m \cdot 24 \cdot 10^{-3} \\ E_L &= P_L \cdot t_m \cdot 24 \cdot 10^{-3} \\ E_V &= SFP \cdot\ q_{v,act} \cdot t_m \cdot 24 \cdot 10^{-3} \\ E_{Aux} &= P_{Aux} \cdot t_m \cdot 24 \cdot 10^{-3} \end{aligned} \tag{20}$$

P_A	*Average electric power demand for appliances in W*
PL	*Average electric power demand for lighting in W*
SFP	*specific fan power of the ventilation system in $W/(m^3/h)$*
P_{Aux}	*Average electric power demand for auxiliary building services in W*

8.3.1.3 Primary energy and greenhouse gas emissions

The primary energy demand and greenhouse gas (GHG) emissions are then calculated from the delivered final energy demand based on primary energy and emission factors according to the energy carrier used according to equation (21). Primary energy and emission factors are defined based on input data according to [67]. In case of electricity, the emission and primary energy factors for the consumption mix was used.

$$\begin{aligned} PE_{ES} &= PEF_{EC} \cdot E_{ES,EC} \\ GHG_{ES} &= GHGF_{EC} \cdot E_{ES,EC} \end{aligned} \tag{21}$$

PE_{ES}	*Primary energy of energy service ES in kWh*
GHG_{ES}	*Greenhouse gas emissions of energy service ES in kWh*
PEF_{EC}	*Primary energy factor of energy carrier EC in kWh/kWh*
GHG_{EC}	*Greenhouse gas emissions factor of energy carrier EC in $kgCO_2$-eq/kWh*
$E_{ES,EC}$	*Final energy demand for energy services ES in energy carrier EC in kWh*

8.3.2 Cost assessment

The model assesses the life cycle costs of building measures (reinstatement, retrofit or replacement) for both building envelope components and heating systems. The model calculates investment, maintenance and operation as well as energy costs of these technologies and thereby covers the entire life cycle costs. The individual cost elements are mainly an input to the decision model but can also be evaluated as a model output in terms of total market volumes of sold technologies.

8.3.2.1 Building envelope costs

The investment costs for building envelop component measures are calculated based on cost factors per surface area for different measures (reinstatement/retrofit) and the respective surface are of the component of the building agent, see equation (22). The different cost factors are differentiated based on the building component and the energy efficiency level of the retrofit measures (in terms of insulation thickness or U-value in case of windows) as well as are adapted over time based on construction and labour cost index (see section 8.1.1).

$$C_{I,c} = \frac{c_{I,c,o} \cdot A_c}{A_T} \tag{22}$$

$C_{I,c}$: *Investment costs for retrofit or reinstatement of component c in $CHF/m^2_{heated\ floor\ area}$*

$c_{I,c,r}$: *Investment cost factor for measure r of component c in CHF/m^2*

A_c: *Surface area of component c in m^2*

8.3.2.2 Heating system costs

The investment and maintenance costs for heating system measures are calculated based on specific cost factors for different measures (new construction, replacement and reinstatement). Costs factors for heating system, hot water and solar collectors are calculated differently, each based on a specific sizing factor. The different cost factors are differentiated based on the measures (new construction, replacement and reinstatement), the system type and the size of the system (either power, hot water consumption or collector surface area for the space heating, hot water and solar systems respectively) as are adapted over time based on construction and labour cost index (see section 8.1.1). Cost factors are included in the database of specific system sizes and are interpolated in between.

The investment and maintenance costs for the main heating system are calculated based on the installed nominal heating power, which is assessed using the energy demand model (8.3.1), see equations (23). Similarly, the costs for the hot water system are assessed based on the total daily hot water demand that needs to be covered by the system, see equations (24). Last but not least, costs for solar collectors are assessed separately based on the installed surface area of the collector, see equations (25).

$$C_{I,HS} = \frac{c_{I,HS,o} \cdot P_{HS}}{A_T}$$
$$C_{M,HS} = \frac{c_{M,HS,o} \cdot P_{HS}}{A_T} \tag{23}$$

$C_{I,HS}$: *Investment costs of heating system type HS in $CHF/m^2_{heated\ floor\ area}$*

$c_{I,HS,o}$: *Investment cost factor for option o of heating system type HS in CHF/kW*

$C_{M,HS}$: *Maintenance and operation costs of heating system type HS in $CHF/m^2_{heated\ floor\ area}$ year*

$c_{M,HS,o}$: *Maintenance and operation cost factor for option o of heating system type HS IN CHF/kW year*

P_{HS}: *Nominal power of the heating system in kW*

$$C_{I,HWS} = \frac{c_{I,HWS,o} \cdot V_{HW}}{A_T}$$
$$C_{M,HWS} = \frac{c_{M,HWS,o} \cdot V_{HW}}{A_T} \tag{24}$$

$C_{I,HWS}$: *Investment costs of hot water system type HWS in CHF/m²$_{heated\ floor\ area}$*
$c_{I,HWS,o}$: *Investment cost factor for option o of hot water system type HWS in CHF/l*
$C_{M,HWS}$: *Maintenance and operation costs of hot water system type HWS in CHF/m²$_{heated\ floor\ area}$ year*
$c_{M,HWS,o}$: *Maintenance and operation cost factor for option o of hot water system type HWS n CHF/l year*
V_{HW}: *Total daily hot water consumption in l*

$$C_{I,SC} = \frac{c_{I,SC,o} \cdot A_{SC}}{A_T}$$
$$C_{M,SC} = \frac{c_{M,SC,o} \cdot A_{SC}}{A_T} \tag{25}$$

$C_{I,SC}$: *Investment costs of solar collector in CHF/m²$_{heated\ floor\ area}$*
$c_{I,SC,o}$: *Investment cost factor for option o of solar collector in CHF/m²*
$C_{M,SC}$: *Maintenance and operation costs of solar collector in CHF/m²$_{heated\ floor\ area}$ year*
$c_{M,SC,o}$: *Maintenance and operation cost factor for option o of solar collector in CHF/m² year*
A_{SC}: *Surface area of solar collector in m²*

8.3.2.3 Energy costs

Energy costs are assessed by the model based on the energy price per energy carrier and the calculated final energy demand according to equation (26). Energy prices are defined by input data and include potential additional taxes (e.g. CO_2 tax).

$$C_{E,ES} = \sum_{energy\ carrier} \frac{EP_{EC} \cdot E_{ES,EC}}{A_T} \tag{26}$$

$C_{E,ES}$ *Energy costs for energy service ES in CHF/m²$_{heated\ floor\ area}$ year*
EP_{EC} *Energy price of energy carrier EC in CHF/kWh*
$E_{ES,EC}$ *Final energy demand for energy services ES in energy carrier EC in kWh/year*

8.3.2.4 Subsidies

Subsidies for different measures are calculated based on a percentage of the investment costs of the measure according to equation (27). The subsidy level depends on the system/component type as well as what measure (new construction, replacement, retrofit, etc.) as subsidy levels are adjusted to the different cost structure of when an energy efficiency or RES measure might be implemented.

$$C_{S,c,m} = SL_{c,m} \cdot C_{I,c} \tag{27}$$

$C_{E,ES}$ *Subsidies for measure m in component c in CHF/m²$_{heated\ floor\ area}$*
$SL_{c,m}$ *Subsidy level for measure m in component c in %*
$C_{I,c}$ *Investment costs for measure m in component c in CHF/m²$_{heated\ floor\ area}$*

8.3.2.5 Equivalent annual costs of investments

The model converts investment costs into equivalent annual costs (EAC) in order to make them comparable to recurring costs such as energy or maintenance and operation costs to be used more easily in the decision model (see section 5.1.4.3). The EAC are calculated based on equation (28). The lifetime of the component is assessed based on the minimum technical lifetime according to the input data.

$$EAC_{I,c} = C_c \frac{r}{1-(1+r)^{-t_c}} \tag{28}$$

$EAC_{I,c}$: *Equivalent annual investment costs for component c in CHF/m²$_{heated\ floor\ area}$ year*
C_c: *Investment costs for component c in CHF/m²$_{heated\ floor\ area}$*
r: *Discount rate*
t_c: *Average lifetime of component c in years*

8.3.2.6 Willingness to pay

The model accounts for an additional (non-monatary) factors affecting the choice for a certain option with a willingness to pay (WTP) factor. The WTP factor may be positive (e.g. increased comfort through new windows) or negative (e.g. additional burden on user of manual wood-fired heating systems). The WTP is assessed relative to the investment costs of a given measure/technology, according to equation . The WTP factor ($f_{WTP,c,m}$) depends on the system/component type as well as what measure (new construction, replacement, retrofit, etc.) it applies to as the WTP might be different in case of new construction or refurbishment.

$$WTP_{c,m} = f_{WTP,c,m} \cdot EAC_{I,c} \tag{29}$$

$WTP_{c,m}$ *Willingness to pay for measure m in component c in CHF/m²$_{heated\ floor\ area}$ year*
$f_{WTP,c,m}$ *Willingness to pay factor for measure m in component c in %*

9 References

[1] V. Grimm, U. Berger, F. Bastiansen, S. Eliassen, V. Ginot, J. Giske, J. Goss-custard, T. Grand, S.K. Heinz, G. Huse, A. Huth, J.U. Jepsen, C. Jørgensen, W.M. Mooij, M. Birgit, G. Pe, C. Piou, S.F. Railsback, A.M. Robbins, M.M. Robbins, E. Rossmanith, R. Nadja, E. Strand, S. Souissi, R.A. Stillman, R. Drive, P. Moody, B.C. Vh, A standard protocol for describing individual-based and agent-based models, 8 (2006) 115–126. doi:10.1016/j.ecolmodel.2006.04.023.

[2] V. Grimm, U. Berger, D.L. Deangelis, J.G. Polhill, J. Giske, S.F. Railsback, The ODD protocol : A review and first update, Ecol. Modell. 221 (2010) 2760–2768. doi:10.1016/j.ecolmodel.2010.08.019.

[3] Tom Augspurger, Chris Bartak, Phillip Cloud, Andy Hayden, Stephan Hoyer, Wes McKinney, Jeff Reback, Chang She, Masaaki Horikoshi, Joris Van den Bossche, pandas: Python Data Analysis Library, 2018. (2018). https://pandas.pydata.org/index.html (accessed March 15, 2018).

[4] NumPy developers, NumPy, 2018. (2018). http://www.numpy.org/ (accessed March 15, 2018).

[5] D. Masad, J. Kazil, Mesa: An Agent-Based Modeling Framework, in: Proc. 14th Python Sci. Conf. (SCIPY 2015), 2015.

[6] C. Nägeli, C. Camarasa, M. Jakob, G. Catenazzi, Y. Ostermeyer, Synthetic building stocks as a way to assess the energy demand and greenhouse gas emissions of national building stocks, Energy Build. 173 (2018) 443–460. doi:10.1016/j.enbuild.2018.05.055.

[7] H. Mintzberg, D. Raisinghani, A. Théorêt, The Structure of "Unstructured" Decision Processes, Adm. Sci. Q. 21 (1976) 246–275.

[8] E.M. Rogers, Diffusion of Innovations, 4th ed., 1995. doi:citeulike-article-id:126680.

[9] H.A. Simon, A Behavioral Model of Rational Choice, Q. J. Econ. (1955). doi:10.2307/1884852.

[10] M. Lehmann, M. Meyer, N. Kaiser, W. Ott, Umstieg von fossilen auf erneuerbare Energieträger beim Heizungsersatz [Switch from fossil to renewable energy sources when replacing heating systems], Zürich, Switzerland, 2017.

[11] J.H. Roberts, J.M. Lattin, Consideration: Review of Research and Prospects for Future Insights, J. Mark. Res. 34 (1997) 406. doi:10.2307/3151902.

[12] R. Olshavsky, D. Granbois, Consumer Decision Maiking - Fact or Fiction?, J. Consum. Res. 6 (1979) 93–100.

[13] B.M. Sopha, C.A. Klöckner, E.G. Hertwich, Adoption and diffusion of heating systems in Norway: Coupling agent-based modeling with empirical research, Environ. Innov. Soc. Transitions. 8 (2013) 42–61. doi:10.1016/j.eist.2013.06.001.

[14] K.E. Train, Discrete choice methods with simulation, 2nd Editio, Cambridge University Press, New York, USA, 2003. doi:10.1017/CBO9780511753930.

[15] M.G. Mueller, P. de Haan, How much do incentives affect car purchase? Agent-based microsimulation of consumer choice of new cars-Part I: Model structure, simulation of bounded rationality, and model validation, Energy Policy. 37 (2009) 1072–1082. doi:10.1016/j.enpol.2008.11.002.

[16] P. de Haan, M.G. Mueller, R.W. Scholz, How much do incentives affect car purchase? Agent-based microsimulation of consumer choice of new cars-Part II: Forecasting effects of feebates based on energy-efficiency, Energy Policy. 37 (2009) 1083–1094.

doi:10.1016/j.enpol.2008.11.003.

[17] FOS, Eidgenössische Volkszählung 2000 Gebäude, Wohnungen und Wohnverhältnisse [Swiss Federal Census 2000 Buildings, apartments and housing], Neuchâtel, Switzerland, 2004.

[18] M. Jakob, G. Catenazzi, R. Forster, T. Egli, T. Kaiser, R. Looser, M. Melliger, C. Nägeli, U. Reiter, M. Soini, B. Sunarjo, Erweiterung des Gebäudeparkmodells gemäss SIA-Effizienzpfad Energie [Extension of the Building Stock Model according to the SIA Efficiency Path Energy], 2016.

[19] SIA, 380/1: Heizwärmebedarf [380/1: Space Heating Demand], 2016.

[20] SIA, SIA 380: Grundlagen für energetische Berechnungen von Gebäuden [SIA 380: Basics for energy calculations of buildings], (2015).

[21] M. Jakob, E. Jochem, K. Christen, Grenzkosten bei forcierten Energie-Effizienzmassnahmen in Wohngebäuden [Marginal Costs of Forced Energy Efficiency Measures in Residential Buildings], 2002.

[22] M. Jakob, S. Kallio, C. Nägeli, W. Ott, R. Bolliger, S. Von Grünigen, Integrated strategies and policy instruments for retrofitting buildings to reduce primary energy use and GHG emissions (INSPIRE) - Generic Strategies for buildings in Switzerland, Bern, 2014.

[23] Wüest und Partner, Energieplanungsbericht 1998 – Kontrollrechnung Sanierungstätigkeit [Energy Planning Report 1998 - Verification Calculation of Refuribishment Activities], Zürich, 1998.

[24] IP BAU, Alterungsverhalten von Bauteilen und Unterhaltskosten - Grundlagendaten für den Unterhalt und die Erneuerung von Wohnbauten [Ageing Behaviour of Building Components and Maintenance Costs - Data for the Maintenance and Retrofit of Residential Buildings], Bern, Switzerland, 1994.

[25] U. Agethen, K. Frahm, K. Renz, E.P. Thees, Lebensdauer von Bauteilen, Zeitwerte [Lifetime of Building Components, Time Values], Essen, 2010.

[26] M. Jakob, G. Martius, G. Catenazzi, H. Berleth, Energetische Erneuerungsraten im Gebäudebereich: Synthesebericht zu Gebäudehülle und Heizanlagen [Energy Efficiency Refurbisment Rates in the Building Sector: Synthesis Report for the Building Enevelope an Heating Systems], 2014.

[27] Y. Stettler, F. Betbèze, Schweizerische Holzenergiestatistik Erhebung für das Jahr 2015 [Swiss Wood Energy Statistics Survey for the year 2015], 2016.

[28] Prognos, Der Energieverbrauch der Privaten Haushalte 2000 - 2017 [Energy consumption of households 2000 - 2017], Bern, Switzerland, 2018.

[29] B. Aebischer, G. Catenazzi, M. Jakob, E. Jochem, G. Kumbaroglu, R. Madlener, R. Dones, U. Gantner, S. Hirschberg, S. Kypreos, S. Lienin, A. Röder, R. Frischknecht, N. Jungbluth, M. Faist, J. Schwarz, CO2-Reduktionspotential Erdgas - Projektphase 1: Referenzszenario, Zürich, Switzerland, 2002.

[30] SIA, Merkblatt 2024: Standard-Nutzungsbedingungen für die Energie- und Gebäudetechnik [Bulletin 2024: Standard Usage Conditions for Energy and Building Technology], 2006.

[31] FOS, Bau- und Wohnungswesen 2017 [Construction and Housing 2017], Neuchâtel, Switzerland, 2019.

[32] SIA, 380/4: Elektrische Energie im Hochbau [380/4: Electrical Energy in Buildings], 2006.

[33] FOS, Bilanz der ständigen Wohnbevölkerung [Balance of the permanent resident population], (2018). https://www.bfs.admin.ch/bfs/de/home/statistiken/bevoelkerung/stand-

entwicklung/bevoelkerung.assetdetail.5886172.html.

[34] FOS, Labour cost structural statistics: Structure of hourly labour costs (including apprentices), by economic section, (2018).

[35] FOS, Schweizerischer Lohnindex [Swiss wage index], (2018).

[36] KBOB, Preisänderungen im Bauwesen, Indexstand [Price changes in construction, index level], (2019).

[37] S. Kessler, B. Oettli, R. Iten, Harmonisiertes Fördermodell der Kantone (HFM 2003) [Harmonized subsidy model of the cantons (HFM 2003)], Bern, Switzerland, 2003.

[38] S. Kessler, C. Schneider, R. Iten, Harmonisiertes Fördermodell der Kantone (HFM 2007) [Harmonized subsidy model of the cantons (HFM 2007)], Bern, Switzerland, 2007.

[39] S. Kessler, F. Moret, Harmonisiertes Fördermodell der Kantone (HFM 2009) [Harmonized subsidy model of the cantons (HFM 2009)], Bern, Switzerland, 2009.

[40] D. Sigrist, S. Kessler, Harmonisiertes Fördermodell der Kantone (HFM 2015) [Harmonized subsidy model of the cantons (HFM 2015)], Bern, Switzerland, 2016.

[41] VSG, Verband der Schweizerischen Gasindustrie - Jahresstatistik 2010 [Association of the Swiss Gas Industry - Annual Statistics 2010], Zürich, Switzerland, 2010.

[42] VSG, Verband der Schweizerischen Gasindustrie - Jahresstatistik 2017 [Association of the Swiss Gas Industry - Annual Statistics 2017], Zürich, Switzerland, 2017.

[43] VFS, Verband Fernwärme Schweiz - Jahresbericht 2002 [Association of District Heating Switzerland - Annual report 2002], Niederrohrdorf, Switzerland, 2002.

[44] VFS, Verband Fernwärme Schweiz - Jahresbericht 2016 [Association of District Heating Switzerland - Annual report 2016], Niederrohrdorf, Switzerland, 2017.

[45] EnDK, Stand der Energiepolitik in den Kantonen 02 [State of energy policy in the cantons 02], Bern, Switzerland, 2002.

[46] EnDK, Stand der Energiepolitik in den Kantonen 03 [State of energy policy in the cantons 03], Bern, Switzerland, 2003.

[47] EnDK, Stand der Energiepolitik in den Kantonen 12 [State of energy policy in the cantons 12], Bern, Switzerland, 2012.

[48] EnDK, Stand der Energiepolitik in den Kantonen 13 [State of energy policy in the cantons 13], Bern, Switzerland, 2013.

[49] EnDK, Stand der Energiepolitik in den Kantonen 14 [State of energy policy in the cantons 14], Bern, Switzerland, 2014.

[50] EnDK, Stand der Energiepolitik in den Kantonen 15 [State of energy policy in the cantons 15], Bern, Switzerland, 2015.

[51] EnDK, Stand der Energiepolitik in den Kantonen 16 [State of energy policy in the cantons 16], Bern, Switzerland, 2016.

[52] EnDK, Stand der Energiepolitik in den Kantonen 17 [State of energy policy in the cantons 17], Bern, Switzerland, 2017.

[53] EnDK, Stand der Energie- und Klimapolitik in den Kantonen 18 [State of energy and climate policy in the cantons 18], Bern, Switzerland, 2018.

[54] EnDK, Stand der Energiepolitik in den Kantonen 04 [State of energy policy in the cantons 04], Bern, Switzerland, 2004.

[55] EnDK, Stand der Energiepolitik in den Kantonen 05 [State of energy policy in the cantons 05], Bern, Switzerland, 2005.

[56] EnDK, Stand der Energiepolitik in den Kantonen 06 [State of energy policy in the cantons 06], Bern, Switzerland, 2006.

[57] EnDK, Stand der Energiepolitik in den Kantonen 07 [State of energy policy in the cantons 07], Bern, Switzerland, 2007.

[58] EnDK, Stand der Energiepolitik in den Kantonen 08 [State of energy policy in the cantons08], Bern, Switzerland, 2008.

[59] EnDK, Stand der Energiepolitik in den Kantonen 09 [State of energy policy in the cantons 09], Bern, Switzerland, 2009.

[60] EnDK, Stand der Energiepolitik in den Kantonen 10 [State of energy policy in the cantons 10], Bern, Switzerland, 2010.

[61] EnDK, Stand der Energiepolitik in den Kantonen 11 [State of energy policy in the cantons 11], Bern, Switzerland, 2011.

[62] EnDK, Mustervorschriften der Kantone im Energiebereich (MuKEn). Ausgabe 2000 [Model regulations of the cantons in the field of energy (MuKEn). Edition 2000], Bern, Schweiz, 2000.

[63] EnDK, Mustervorschriften der Kantone im Energiebereich (MuKEn). Ausgabe 2008 [Model regulations of the cantons in the field of energy (MuKEn). Edition 2008], Bern, Schweiz, 2008. http://www.endk.ch/media/archive1/dokumentation/muken/MuKEn2014_d20150109.pdf (accessed February 26, 2015).

[64] EnDK, Mustervorschriften der Kantone im Energiebereich (MuKEn). Ausgabe 2014 [Model regulations of the cantons in the field of energy (MuKEn). Edition 2014], Bern, Schweiz, 2015. http://www.endk.ch/media/archive1/dokumentation/muken/MuKEn2014_d20150109.pdf (accessed February 26, 2015).

[65] ProPellets, Preisindex Holzpellets [Price index wood pellets], (2019).

[66] CH, Bundesgesetz über die Reduktion der CO2 -Emissionen [Federal law on the reduction of CO2 emissions], Die Bundesversammlung Der Schweizerischen Eidgenossenschaft. 2011 (2011) 14. https://www.admin.ch/opc/de/classified-compilation/20091310/201301010000/641.71.pdf.

[67] KBOB, Liste Oekobilanzdaten im Baubereich [List Life Cycle Assessment Data in the Building Sector], Bern, Switzerland, 2016.

[68] CRB, EAK Kostenkennwerte [EAK cost factors], Zürich, Switzerland, 2011.

[69] M. Jakob, B. Fürst Grodofzig, N. Gross, Energetische Gebäudeerneuerungen – Wirtschaftlichkeit und CO2-Vermeidungskosten: Eine Auswertung des Gebäudeprogramms der Stiftung Klimarappen [Energetic building renewal - efficiency and CO2 abatement costs: an evaluation of the building program of the S, Zürich, Switzerland, 2010.

[70] HSLU, Heizkostenvergleichsrechner [Heating costs comparison calculator], (2019).

[71] SIA, Merkblatt 2028: Klimadaten für Bauphysik, Energie- und Gebäudetechnik [Bulletin 2028: Climate Data for Buildign Physics, Energy and Building Technology], Zürich, 2008.

[72] UWE, Gebäude-Heizenergiebedarf - Methodik zur Schätzung des Heizenergiebedarfs der

Wohngebäude mittels kantonalem Gebäude- und Wohnungsregister [Building Heating Demand - Method for the Estimation of the Heating Demand of Residential Buildings using the Canton, Luzern, 2013.

[73] M. Aksözen, U. Hassler, M. Rivallain, N. Kohler, Mortality analysis of an urban building stock, 3218 (2017). doi:10.1080/09613218.2016.1152531.

[74] FOS, Bau- und Wohnungswesen 2016 [Construction and Housing 2016], Neuchâtel, Switzerland, 2018. doi:10.11655/zgywylc2017.01.024.

[75] ISO, ISO 52016-1:2017: Energy performance of buildings – Energy needs for heating and cooling, internal temperatures and sensible and latent heat loads – Part 1: Calculation procedures, (2017).

[76] D. Majcen, L.C.M. Itard, H. Visscher, Theoretical vs. actual energy consumption of labelled dwellings in the Netherlands: Discrepancies and policy implications, Energy Policy. 54 (2013) 125–136. doi:10.1016/j.enpol.2012.11.008.

[77] T. Loga, M. Großklos, J. Knissel, Der Einfluss des Gebäudestandards und des Nutzerverhaltens auf die Heizkosten [The Influence of Building Standards and the User Behaviour on the Heating Costs], Darmstadt, Germany, 2003.

10 Appendix

10.1 Agent State Variables Description

Table 4 Building agent attributes and state variables

Aspect	Attribute	Type	Unit	Description
Building	ID	int	#	Unique identifier of the building
	buildingType	string	#	Type of the building according to classification: Single-Dwelling Building Multi-Dwelling Building
	climateZone	string	#	Attribute describing the climate zone the building is located in, currently no climate zones are differentiated.
	constructionYear	int	year	Construction year of the building
	scalingFactor	float	#	Number of buildings in the stock that this building represents
	repArea	float	m2	Floor area in the stock that this building agent represents
	numberFloorsAbove	int	#	Number of floors above ground
	numberFloorsBelow	int	#	Number of floors below ground
	roofType	string	-	Roof type of the building: flat pitched
	numberDwellings	int	#	Number of dwellings in the building
	floorAreaResidential	float	m2	Residential floor area of the building
	floorAreaHeated	float	m2	Heated floor area of the building
	areaFootprint	float	m2	Footprint area of the building
	heightRoom	float	m	Average room height of the building
	heightBetweenFloors	float	m	Average height between floors of the building (i.e. ceiling thickness)
	heightFloor	float	m	Average floor height of the building (sum of heightRoom and heightBetweenFloors)
	perimeter	float	m	Building perimeter around footprint
	volume	float	m3	Building volume
	airExchangeInfiltration	float	m3/h	Air exchange rate due to infiltration
	internalHeatCapacity	float	kJ/K m2	Internal Heat capacity of the building construction
	elBuildingServices	float	W	Average electricity load for auxiliary building services (pumps, etc.)
Energy use	usefulEnergy	float	kWh/m2 year	Useful energy demand of the building, differentiated based on energy services

	finalEnergy	float	kWh/m2 year	Final energy demand of the building, differentiated based on energy services and energy carriers
	primaryEnergyToal	float	kWh/m2 year	Total primary energy demand of the building, differentiated based on energy services
	primaryEnergyNonRenewable	float	kWh/m2 year	Non-renewable primary energy demand of the building, differentiated based on energy services
	primaryEnergyRenewable	float	kWh/m2 year	Renewable primary energy demand of the building, differentiated based on energy services
	ghgEmissions	float	kgCO2-eq/m2 year	GHG emissions of the building, differentiated based on energy services
	energyCosts	float	CHF/m2 year	Energy costs of the building differentiated based on enregy services and enregy carriers
Location	systemAvailabilityGas	boolean	-	Availability of gas at building location
	systemAvailabilityDistrictHeating	boolean	-	Availability of district heating at building location
	systemAvailabilityHeatPumpGround	boolean	-	Availability of ground source heat pumps at building location
	systemAvailabilityHeatPumpGroundwater	boolean	-	Availability of groundwater heat pumps at building location
Owner	discountRate	float	%	discount rate
	betaEAC	float	-	Weighting factor for equivalant anual investment costs
	betaMC	float	-	Weighting factor for maintenance costs
	betaEC	float	-	Weighting factor for energy costs
	betaWTP	float	-	Weighting factor for willingness to pay
	betaMS	float	-	Weighting factor for technology market share
Dwelling	area	float	m2	Total dwelling floor area
	numberRooms	int	#	Number of Rooms in the Dwelling
	numberOfOccupants	int	#	Number of Occupants
	occupancyTime	float	h/day person	Average occupancy hours per person and day

	setTempHeating	float	°C	Average Demand Indoor Temperture in the dwelling
	consumptionDHW	float	l/person day	Average Hot Water Consumption per person and day
	elAppliances	float	W	Average electricity load for appliances
	elLighting	float	W	Average electricity load for lighting
Opaque Components	componentType	string	-	Type of components: Roof CeilingToUnheated WallToAir WallToUnheated WallToGround FloorToGround FloorToUnheated FloorToAir
	area	float	m2	Total Window Surface Area
	uValue	float	W/m2 K	U-Value of the Window (both frame and glazing together)
	insulationThickness	float	-	Thickness of applied Insulation (if known)
	orientation	int	°	Orientation of the Window (0° North, 90° East, 180° South, 270° West)
	angle	int	°	Angle of the component (0: Horizontal, 90: Vertical)
	year	int	year	Year of construction or last implemented refurbishment
Transparent Components	componentType	choice	-	Typ of component: Window Door
	area	float	m2	Total Window surface area
	uValue	float	W/m2 K	U-Value of the window (both frame and glazing together)
	gValue	float	-	Solar energy transmittance of the window glazing (0.0: no light passes through (opaque=, 1.0: all light passes through)
	shading	float	-	Shading Factor of the window (0.0: completely shaded from sun, 1.0: no shading)
	frameRatio	float	-	Share of the Frame of the total Window Surface Area (0.0: no frame, 1.0: all frame (no transparent parts))
	orientation	int	°	Orientation of the Window (0° North, 90° East, 180° South, 270° West)

	angle	int	°	Angle of the component (0: Horizontal, 90: Vertical)
	year	int	year	Year of construction or last implemented renovation/replacement
Ventilation	ventilationType	choice	-	Type of ventilation: Natural Exhaust Decentral Exhaust And Supply With Heat Recovery Central Exhaust And Supply Central Exhaust And Supply With Heat Recovery Exhaust Ventilation With Heat Pump
	central	boolean	-	Central ventilation system: yes/no
	airFlowRate	float	m3/h	air exchange rate of the system
	controlFactor	float	%	Average load factof of the ventilation (100% of the specified air flow rate)
	effHeatRecovery	float	%	Efficiency of the heat recovery system (0: no recovery, 100%: all heat recovered)
	specificFanPower	float	W/(m3/h)	Specific Fan Power of the ventilation system
	year	int	year	Year of installation or last replacement
	maintenanceCosts	float	CHF/year	Yearly maintenance costs of the system
Heating System	heatingSystemType	string	-	Type of heating system according to BSM classification: Oil boiler Gas boiler Wood boiler Heat pump air/water Heat pump ground/water Heat pump water/water District heating Electric resistance heating Coal boiler Oil stove Gas stove Wood stove Electric resistance heater Coal stove Heat pump air/air
	central	boolean	-	Central heating system: yes/no
	nominalPower	float	kW	power of the system (if known)

	efficiency	float	%	seasonal efficiency of the system (1.0: "perfect" (no losses))
	energyCarrier	string	-	energy carrier of the system accoring to BSM calssifcation: Oil Gas Wood Electricity District Heat Solar Heat Ambient Heat Coal
	year	int	year	Year of installation or last replacement
	maintenanceCosts	float	CHF/year	Yearly maintenance costs of the system
Hot Water System	hotwaterSystemType	string	-	Type of hot water system according to BSM classification: Combined Electric water heater Heat pump water heater Gas water heater
	central	boolean	-	Central hot water system: yes/no
	volume	float	l/day	Reference hot water consumption per day
	efficiency	float	%	seasonal efficiency of the system
	energyCarrier	string	-	energy carrier of the system accoring to BSM calssifcation: Oil Gas Wood Electricity District Heat Solar Heat Ambient Heat Coal
	year	int	year	Year of installation or last replacement
	maintenanceCosts	float	CHF/year	Yearly maintenance costs of the system
Solar System	systemType	string	-	System Type
	area	float	m2	Total solar collector area
	efficiency	float	%	Optical Efficiency of the solar collector
	orientation	int	°	Orientation of the Window (0° North, 90° East, 180° South, 270° West)

	angle	int	°	Angle of the collector (0: Horizontal, 90: Vertical)
	year	int	year	Year of installation or last replacement
	maintenanceCosts	float	CHF/year	Yearly maintenance costs of the system

Table 5 Environment agent attributes and state variables

Aspect	Attribute	Type	Unit	Distribution	Description
New Building Typology	newBuildingTypes	float	%	-	Share of building types in new construction per year
	newBuildingCharcteristics	float	%	-	Share of building characteristics (number of floors, number of dwellings) in new construction per year and building type
	newDwellingCharcteristics	float	%	-	Share of dwelling characteristics (number of rooms, dwelling area) in new construction per year and building type
	sharePitchedRoof	float	%	-	Share of buildings with pitched roofs in new construction per year and building type
	shareBasement	float	%	-	Share of buildings with basements in new construction per year and building type
	oneSideAttached	float	%	-	Share of buildings with one side attached in new construction per year and building type
	twoSidesAttached	float	%	-	Share of buildings with two side attached in new construction per year and building type
	roofAngle	float	degree	Normal	Distribution of roof angles in new construction per year and building type
	planDepth	float	m	Lognormal	Distribution of plan depth in new construction per year and building type
	heightRoom	float	m	Lognormal	Distribution of room height in new construction per year and building type
	heightBetweenFloors	float	m	Normal	Distribution of height between floors in new

					construction per year and building type
	windowWallRatio	float	%	Normal	Distribution of window to wall ratio in new construction per year and building type
	windowFrameRatio	float	%	Normal	Distribution of window frame ratio in new construction per year and building type
	shadingFactor	float	%	Normal	Distribution of shading factor in new construction per year and building type
	internalHeatCapacity	float	kJ/m2	Normal	Distribution of internal heat capacity in new construction per year and building type
Building Usage	numberOfOccupants	float	#	Binominal	Distribution of number of occupants based on number of rooms
	setTempHeating	float	degree	Normal	Distribution of indoor set temperature in new construction per year and building type
	consumptionDHW	float	l/pers day	Normal	Distribution of hot water ocnsumption in new construction per year and building type
	occupancyTime	float	h/day	Normal	Distribution of occupancy presence time in new construction per year and building type
	elLighting	float	W/m2	Normal	Distribution of electricity demand for lighting in new construction per year, number of rooms and building type
	elAppliances	float	W/m2	Normal	Distribution of electricity demand for appliances in new construction per year, number of rooms and building type
	elBuildingServices	float	W/m2	Normal	Distribution of electricity demand for auxilary building services in new construction per year and building type
Lifetimes	Component	int	years	Weibull	Building component lifetimes differentiated for each building component type
	Building	int	years	Loglogistic	Building lifetime distribution

Energy Carriers	energyPrice	float	CHF/kWh	-	Energy price for each energy carrier per year
	co2tax	float	CHF/kWh	-	Energy tax for each energy carrier per year
	GHGfactor	float	kgCO2-eq/kWh	-	Greenhouse gas emission factor for each energy carrier per year
	PEtotFactor	float	kWhPE/kWhFE	-	Total primary energy factor for each energy carrier per year
	PEnonrenewFactor	float	kWhPE/kWhFE	-	Non renewable primary energy factor for each energy carrier per year
	PErenewFactor	float	kWhPE/kWhFE	-	Renewable primary energy factor for each energy carrier per year
Heating System Development	efficiencySpaceHeating	float	%	Normal	Space heating efficiency of each heating system per heating system type and installation year
	efficiencyHotWater	float	%	Normal	Hot water efficiency of each heating system per heatigng and hot water system type and installation year
Ventilation System Development	heatRecovery	float	%	Normal	Heat recovery efficiency of each ventilation type per ventilation type and installation year
	specificFanPower	float	W/(m3/h)	Normal	Specific fan power of each ventilation type per ventilation type and installation year
	airFlowRate	float	m3/m2 h	Normal	Specific air flow rate each ventilation type per ventilation type and installation year
Solar System Development	efficiceny	float	%	Normal	Efficiency of solar systems per installation year
Costs Opaque Components	materialCosts	float	CHF/m2	-	Material costs of opaque building components
	labourCosts	float	CHF/m2	-	Labour costs of opaque building components
	additonalCosts	float	CHF/m2	-	Additional costs of opaque building components
	maintenanceCosts	float	CHF/m2 year	-	Maintenance costs of opaque building components
	materialCosts	float	CHF/m2	-	Material costs of transparent building components

Costs Transparent Components	labourCosts	float	CHF/ m2	-	Labour costs of transparent building components
	additonalCosts	float	CHF/ m2	-	Additional costs of transparent building components
	maintenanceCo sts	float	CHF/ m2 year	-	Maintenance costs of transparent building components
Costs Heating Systems	materialCosts	float	CHF/k W	-	Material costs of heating systems
	labourCosts	float	CHF/k W	-	Labour costs of heating systems
	additonalCosts	float	CHF/k W	-	Additional costs of heating systems
	maintenanceCo sts	float	CHF/k W year	-	Maintenance costs of heating systems
Costs Hot Water Systems	materialCosts	float	CHF/l	-	Material costs of hot water systems
	labourCosts	float	CHF/l	-	Labour costs of hot water systems
	additonalCosts	float	CHF/l	-	Additional costs of hot water systems
	maintenanceCo sts	float	CHF/l year	-	Maintenance costs of hot water systems
Costs Solar Systems	materialCosts	float	CHF/ m2	-	Material costs of solar systems
	labourCosts	float	CHF/ m2	-	Labour costs of solar systems
	additonalCosts	float	CHF/ m2	-	Additional costs of solar systems
	maintenanceCo sts	float	CHF/ m2 year	-	Maintenance costs of solar systems
New Building Standard	uValue	float	W/m2 K	Normal	Distribution of U-value for new buildings differentiated based on year
	gValue	float	-	Normal	Distribution of window g-value for new buildings differentiated based on year
	infiltrationRate	float	m3/m 2 h	Normal	Distribution of air infiltration rate for new buildings differentiated based on year
Retrofit Standard	insluationThickn ess	float	mm	-	
	uValue	float	W/m2 K	-	Distribution of U-value for building retrofit differentiated based on year and retrofit standard

	gValue	float	-	-	Distribution of window g-value for building retrofit differentiated based on year and retrofit standard
	infiltrationRate	float	m3/m2 h	-	Distribution of air infiltration rate for building retrofit differentiated based on year and retrofit standard
Scenario Drivers	Population	float	#persons	-	Population development per year
	shareVentilationSystems	float	%	-	Share of ventilation systems with heat recovery in new buildings per year
	labourCostDevelopment	float	%	-	labour cost development per year
	materialCostDevelopment	float	%	-	material cost development per year and technology
	subsidies	float	%	-	Subsadies as share of the investment costs per year and technology
	willingnessToPay	float	%	-	Willingness to pay for a technology as share of the investment costs per year and technology
	locationAvailability	float	%	-	Development of location based availablity of gas, district heating and ground and groundwater heat pumps
Climate	solarIrradiation	float	kWh/m2 month	-	Solar irradiation per month and orientation
	externalTemperature	float	°C	-	External air temperature per month
	minimumTemperature	float	°C	-	Minimum external air temperature for heating system sizing
Other	heatCapacityWater	float	Wh/m3 K	-	Heat capacity of water
	heatCapacityAir	float	Wh/m3 K	-	Heat capacity of air
	averageHeatPerson	float	W/person	-	Average heat emission per person

10.2 List of Technologies

Table 6 List of building technologies defined in the model

Technology Group	Technology Name
Heating Systems	Oil boiler
	Gas boiler
	Wood boiler
	Heat pump air/water
	Heat pump ground/water
	Heat pump water/water
	District heating
	Electric resistance heating
	Coal boiler
	Oil stove
	Gas stove
	Wood stove
	Electric resistance heater
	Coal stove
	Heat pump air/air
Hot Water Systems	Combined with main heating system
	Electric water heater
	Heat pump water heater
	Gas water heater
Ventilation Systems	Natural
	Central exhaust
	Central exhaust and supply
	Central exhaust and supply with HR
	Central exhaust with heat pump
	Decentral exhaust
	Decentral exhaust and supply with HR
Solar Systems	Solarthermal System