Master Thesis
Energy Science

4th January 2016

Determining primary energy and CO_2 reduction potentials of the German residential building stock through retrofit application of Building Automation Systems

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30 ECTS

Abstract

The 2015 climate summit in Paris has shown the dedication of countries all over the world to prevent "dangerous anthropogenic interference with the climate system", [13]. The decision has been made, that exceeding the limit of a 2 °C increase in average world temperature compared to 1990 levels has to be avoided. Germany has been on the front of reducing its carbon footprint with its 'Energiewende'. The reduction of the energy consumption in the residential building sector plays a vital role in the country's policies, as the residential building accounts for 26 % of the final energy consumption [42]. The goal of the TABULA project is to categorise the residential building stock, [47]. This research uses the TABULA project to determine the potential energy savings and corresponding CO_2 emission reductions as a result of retrofit application of building automation systems in single family houses (SFH).

Building automation systems (BAS), and in particular automatic regulating heating systems in residential homes could play a role. In this research a Modelica [60] based residential building model (RBM) has been developed to simulate the automatic regulation of a central heating system in SFHs. Two BAS scenarios are considered and applied to three Stand Alone Houses (SAHs). The implementation of a time schedule thermostat that automatically reduces the set temperature when the residents are not occupying the building, and a self regulating thermostat valve that reduces the heat transmission in the room during manual ventilation over the windows.

Implementing scenario 1 BAS for the SAHs would lead to an annual final energy reduction of 10 % for SAH 1, 11 % for SAH 2 and 14 % for SAH 3. The corresponding annual primary energy reduction on the German building stock level results to 58 PJ. This would lead to a reduction of the CO_2 emissions by 3.1 Mt CO_2 on yearly basis.

The RBM has a dual functionality of assessing both the indoor climate conditions over the course of a year as well as the annual final energy consumption for space heating. Regulating the indoor set temperature requires a relatively high load during reheating periods compared to constant operation. The research shows the importance of a sufficient nominal load of the heating system to ensure the thermal comfort of the residents in winter.

The annual final energy saving potential for scenario 2 BAS (self regulation thermostat valves) in SAH 3 is 4 %, under minimal ventilation conditions. However, the results of the RBM have shown that different ventilation rates could influence this result significantly. Further simulations with the RBM could extend the results here to all SFHs and determine their combined potential in the future.

Contents

Abbreviations & Definitions

- BAS: Building Automation Systems
- Building envelope: the total outside surface area of the building. This comprises of all wall, roof, floor, door and window area adjacent to the outside air, ground or neighbouring building.
- Building technology systems: all technical systems that provide heating, cooling, warm water, ventilation and/or lighting in a building. This includes generation, distribution and transmission of heat within the building.
- CCHS: Combined Central Heating System. This is defined as a single heating system that is responsible for fulfilling the entire dwelling heat demand for space heating and domestic hot water.
- CHP: Combined Heat and Power generation.
- Condensing boilers: 'Brennwertkesseln'.
- Constant temperature boilers: 'Konstanttemperaturkesseln'.
- Dwelling: a house, apartment, or other substantial place of residence containing only one single household.
- DHW: Domestic Hot Water ('trinkwarmwasser TWW'). This is the hot drinking water used mainly for showering, bathing, washing, cooking and drinking.
- EED: Energy Efficiency Directive. "Directive 2012/27/EU of the European Parliament and of the Council of 25 October 2012 on energy efficiency, amending Directives 2009/125/EC and 2010/30/EU and repealing Directives 2004/8/EC and 2006/32/EC", [35].
- EnEG: German energy savings law ('Energieeinsparungsgesetz'), [9].
- Energy carrier: "a substance that is predominantly used as a source of energy", [7]. For instance, coal, oil, gas, electricity, steam or hydrogen.
- Energy services: "results of human activity obtained through the use of energy and satisfying a human need", [7].
- EnEV: Energy savings decree ('Energieeinsparungsverordnung'), [12].
- EPBD: Energy Performance of Buildings Directive. "Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings", [36].
- EU: European Union.
- Exemplary building: a reference building that represents the energy use within existing buildings in such a way that by collecting all the exemplary buildings they form an accurate representation of the energy consumption of the entire building stock.
- Feed-in temperature: the water temperature when entering the heat transmission system.
- Final energy: ('Endenergie') is the part of the primary energy, that is after conversion, available to the consumer for direct production of useful energy. For instance, heating oil, natural gas and electricity.
- GDR: German Democratic Republic, also known as East Germany (existing from 1949 to 1990).
- Heating curve: the sliding setpoint function for the regulation of the feed-in temperature.

- Heat sink: the exhaust heat flow; the heat which leaves the building. Heat sinks, also called 'heat losses' are indicated by a negative value and thus increase the heating demand.
- Heat source: all building heating sources except the heating system itself, e.g. humans, incoming solar radiation or electronic devices. Heat sources, also called 'heat gains', are indicated by a positive value and reduce the demand for heating.
- Heating systems: all systems with the main purpose to produce, store, transport and/or transmit heat within the building. Heating systems are part of the bigger group of 'building technology systems'.
- Heat transmission systems: all systems dedicated to transferring heat for the purpose of space heating in residential homes. They are installed the respective room and receive their hot water (with feed-in temperature) from the pipeline and deliver the resulting cold water (with a lower return temperature) back to it. Examples of heat transmission systems are: radiators, convectors and underfloor heating systems.
- Household: "A household consists of one or more people who live in the same dwelling and also share at meals or living accommodation, and may consist of a single family or some other grouping of people" [41].
- HRI: Hermann-Rietschell Institut for heating and ventilation systems, TU Berlin.
- Intermittent heating: the regulating of the heating systems based on the presence or activity of the residents in order to save energy.
- IPCC: Intergovernmental Panel on Climate Change.
- IWU: German Institute for Housing and Environment ('Institut Wohnen und Umwelt').
- LH: Linked House. A LH is a Single Family House that neighbours one or two other houses. Linked houses are divided into semi-detached houses and Terraced Houses.
- LHV: Lower Heating Value. The LHV is the heat content of the water that is the product of combusting hydrogen containing fuels (e.g. coal, oil, natural gas) measured in liquid form, [?]. LHV is used in cases where the latent heat (i.e. the condensation heat) of the water cannot be utilised.
- Low temperature boilers: 'Niedertemperaturkesseln'.
- MFH: Multi Family House. A MFH is a building consisting of 3 or more dwellings, like apartment blocks.
- Nominal power: the output of a heating system when operating at the design load as determined on installment.
- Useful energy, ('Nutzenergie'): Is the part of the Final energy that is available to cover the end user's needs. For instance, heat in the room, warm water or light.
- Primary energy: Primärenergie bezeichnet die Energieträger, die als natürliche Ressourcen vorkommen (z. B. Braunkohle, Erdöl, Erdgas, Sonnenenergie, Windenergie, Biomasse, Erdwärme) und noch keinen Umwandlungsprozess durchlaufen haben. [39].
- RBM: Residential Building Model. The created Modelica model in this research. Which has as goal to calculate possible energy savings and investigate room temperature control as a result of the retrofit application of Building Automation Systems.
- Return temperature: the water temperature when it returns to the boiler, after it has been used by any heat transmission system.

- SAH: Stand Alone House. A SAH is a single family house that is completely separated from any other buildings.
- Setback period: a scheduled lowering of the setpoint for the indoor room temperature, based on the residents´ expected presence at home.
- SDH: Semi-Detached House. A SDH is a Linked House consisting of exactly 2 dwellings, with separate entrances for the two households. For the purpose of this research SDH's are treated the same as Terraced Houses.
- Setpoint: the target value of any controlling system.
- SFH: Single Family House. A SFH is a house consisting of maximum 2 dwellings.
- TH: Terraced House. A TH is a Linked House that is situated in a row of 2 or more other Linked Houses. A TH that neighbours only one house and is situated at the end of the row, is called an end-unit (eTH). A TH that neighbours two other TH is called a mid-unit (mTH).
- Thermostatic valve, ('Thermostatventil'): is a valve regulating the volume flow of the hot water to the radiator based on the room temperature, see section 3.3.2.
- TRY weather data: Test Reference Year weather data, [6].
- UN: United Nations
- Zone: is one or a combination of several rooms with the same temperature and user conditions as defined by the DIN V 18599 [25].

1 Introduction

This thesis was written in cooperation with the Hermann Rietschel Institut in Berlin, for the master Energy Science of Utrecht University. This thesis aimed to improve the understanding of the possible energy savings within German residences, thereby accelerating the necessary change to a more sustainable society.

Societal Background

The UN IPCC has stated in their 5th assessment report [13] that to prevent "dangerous anthropogenic interference with the climate system" exceeding the limit of a 2 °C increase in average world temperature has to be avoided. The European Union (EU) has made it one of its goals to reduce its green house gas emissions in order to reduce its impact on the Climate. For the year 2020 the EU set itself a reduction target on CO_2-emissions of 20 % compared to 1990 levels [14]. Germany as a country set itself an even stricter target with a goal of reducing its CO_2-emissions by 40 % in 2020 and 80-95 % in 2050 compared to 1990 levels [10].

Energy savings in the building sector could help reach these goals as this sector currently accounts for 40 % of the total final energy consumption in the EU member states [36], which makes it the largest contributing sector. It is therefore not surprising that the EU has made energy reductions in the building sector one of their priorities. The Energy Performance of Buildings Directive (EPBD) [36] and the Energy Efficiency Directive (EED) [35] as adopted by the European Commission are in place to enforce these goals. All EU member states are obligated to enforce the rules drawn up under these directives under national law. Germany has on it's own accord adopted a law for energy savings in buildings in 2005 named the EnEG ("Gesetz zur Einsparung von Energie in Gebäuden") which was adjusted later in 2013 under the EPBD [80].

Research focus The goal of this Master thesis is to identify the possible primary energy and CO_2 reduction potential for retrofitted building automation systems in existing German single family houses (SFHs). By identifying this CO_2 reduction potential, the author hopes to provide a quantitative insight into the absolute contribution towards German CO_2 reduction targets through implementation of Building automation systems (BAS).

Building Automation Systems

Typical ways of achieving energy savings in buildings is improved thermal insulation, more efficient building energy systems, as well as more efficient household appliances. There are, however, alternative options as well, one such alternative is building automation systems (BAS). BAS comprise of all software and hardware for the automatic control of the building, in order to minimise the energy consumption and operating costs, while delivering the best services to the residents. The control and regulation of the heating systems of the building form a particular region of interest for energy savings. Although some BAS for consumers are on the market today [71], the knowledge surrounding their actual energy savings is limited. This research will try to determine the energy saving potential of BAS in the German residential sector by specifically investigating single family houses SFHs.

2 Research Problem

2.1 Aim of the research

To summarise the points given in the introduction, it can be stated that the potential for energy savings in the building sector are significant, and therefore form one of the most important priorities in EU energy saving policies. A distinction of the building sector can be made between non-residential and residential buildings, where the latter is responsible for the majority of the energy consumption, with 63 % [67]. As explained in the scientific background section 3.2, space heating is the main contributor to residential energy consumption. Taking this all into account, one can conclude that investigating energy savings on space heating in the residential sector is a relevant area to research. Building Automation Systems (BAS) that reduce residential energy consumption by regulating heating systems could play a role in these savings.

This research uses aggregated data on German residential buildings to model the baseline energy consumption and subsequent available reductions due to the implementation of BAS. In this way, the author hopes to provide policy makers with the necessary information to decide on the role of retrofit application of BAS in the EU residential sector to reduce the impacts of anthropogenic climate change.

2.2 Research question

The main question of the Research is:

> *What is the potential for energy- and CO_2-reductions of the German residential building stock through retrofit application of Building Automation Systems?*

2.3 Sub-questions

In order to answer the main research question the following sub-questions need to be answered:

- What is a representative model of a typical German residential building?
- What are building automation systems with the highest potential for energy savings?
- What is the energy saving potential for retrofitted building automation systems for a single building?
- What are the corresponding CO_2-reductions related to the calculated energy savings for a single building?
- What are the energy- and CO_2-reductions of the German residential building stock based on the calculated savings of a single building?

2.4 Research approach

In order to answer the research questions as described above, a combination of two different methods will be applied.

The main part of the research comprises of the creation of a residential building model (RBM). This model is applied to calculate possible energy savings as a result of the retrofit application of BAS. In order to determine the input values for the RBM, it is necessary to establish the reference building for the German residential building stock, which is treated in section 3.1. These are defined based on the TABULA research [47]. The calculations that form the core of the RBM are taken from German energy calculation norms as described in section 3.2. Literature research, on the BAS will result in the scope of the BAS applied within the model, see section 3.3. A research on the German energy calculation norms is performed in order to create the model. The Methodology section 4, describes the method of creating the RBM as well as the methods for evaluating the results, and their extension to the German building stock level. The Result section 5 describes the results of this research including their implications and uncertainties. The Conclusion section 6 contains the conclusions of this research and can be read separately. The final section, is the Discussion 7 which describes the significance of the research, its shortcomings and recommendations for further research.

3 Background

The section describes the background relevant for understanding the research. Here necessary references to literature, industry norms and appendices are made. The Background comprises of the following subsections:

1. **Residential building stock**, providing information on the EU and German building stock, its energy consumption and energy saving policies, explaining classification methods for building stocks in particular the TABULA project and describing energy calculation methods for residential buildings.

2. **Energy consumption in buildings**, providing a breakdown of the energy sinks and sources in a building and how to calculate them based on German and International calculation norms.

3. **Building automation systems**, introducing regulation and control technologies (specifically for heating systems), describing the status quo of BAS and their effect on user interaction and investigating the retrofit potential of these BAS.

3.1 Residential building stock

The EU building stock comprises all buildings, both for residential and other purposes (e.g. industry, governmental or commercial), currently existing in EU member states. The residential sector entails the majority of buildings with 75 % of the total EU Building stock (based on floor area) [61]. This average value, however, differs per member state where for example in Germany the residential sector is only 61 % of the German building stock [17]. Residential buildings in the EU building stock are sub-divided into SFHs and multi family houses (MFHs), with an average distribution based on m^2 floor area of 64 % SFHs and 36 % MFHs [61]. However, again there exist great differences between countries, as can be seen in Figure 1. Although similarities between national building stocks are found, the differences among countries on all levels (whether it is average floor area per building, building age or ownership), make a EU wide building stock research a complex and time consuming process. For the purpose of this research the focus lies on Germany and in particular it's residential building stock.

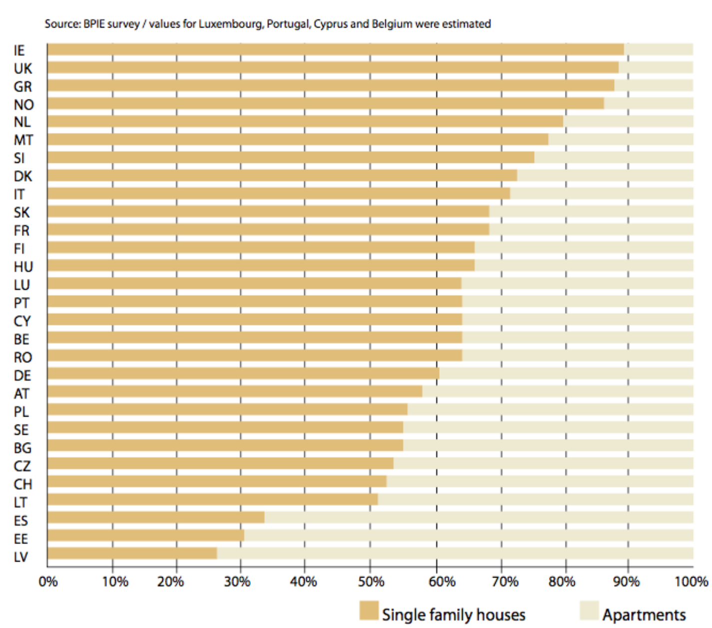


Figure 1: Percentage of SFHs and Apartment buildings (MFHs) in European countries, data obtained between 2010 and 2011 by the Buildings Performance Institute Europe (BPIE) survey [61].

3.1.1 Composition of the German residential building stock

The German residential building stock consists of 5,790 km^2 of building floor area, which is 61 % of the total German building floor area [17]. A breakdown of the residential building stock in three major building types is depicted in Figure 2, which shows that 83 % of the residential buildings are single family houses (SFH)[1].

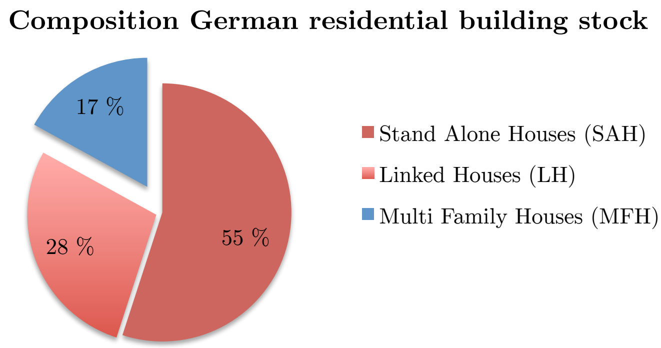


Figure 2: Composition German residential building stock in 2011, The sum of SAHs and LHs represent all SFHs with a share of 83 % of the entire residential building stock. Source: [46].

SFH

The focus of this research is single family houses (SFHs) (see section 4.1) which are divided in stand alone houses (SAHs) and linked houses (LHs), where LHs are further sub-divided into Terraced Houses (THs) and semi-detached houses (SDHs), see Figure 3.

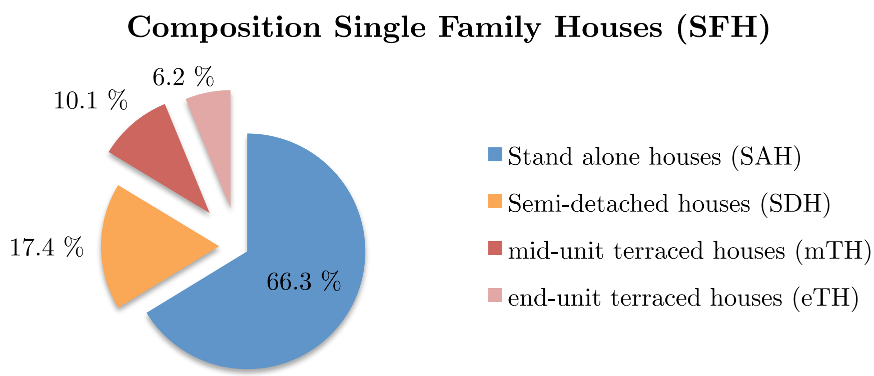


Figure 3: Composition SFHs, where THs are distinguished in mid- (mTH) and end-units (eTH). Based on data from: [46] and [52].

[1] In Figure 1, single family houses (SFHs) are defined as both the classical stand alone house (SAH) as well as terraced houses (THs) excluding duplex buildings or SFHs with an additional small apartment attached to it, whereas in Figure 2 these extra buildings are included in the SAH and LH percentages.

Demographics SFHs
SFHs consist of 1 or 2 dwellings containing 1 or 2 households[2], the majority of which having only one dwelling/household (80 %) [46]. Of all German households 46 % live in SFHs [46]. The total number of households in Germany is 40.2 million, with a population of 80.8 million, this results in an average household containing 2.01 people [19].

3.1.2 Energy consumption in EU and German residential buildings

The energy consumption of a country is calculated by investigating the financial flows related to the selling and buying of different energy carriers. The purpose of these energy carriers is the transport of the demanded energy to the place of consumption. Examples of energy carriers are: electricity, fossil fuels, bio fuels, uranium and hydrogen. Determining how much energy is consumed in each sector is precisely 'measured' by following the stream of energy carriers, and can be represented in a Sankey diagram, see Appendix A. Based on this diagram one can determine the final energy consumption per sector, see Figure 4, which shows that the residential sector with 26 % is the largest energy consuming sector of Germany. This is in line with the EU average of 26.2 % [68].

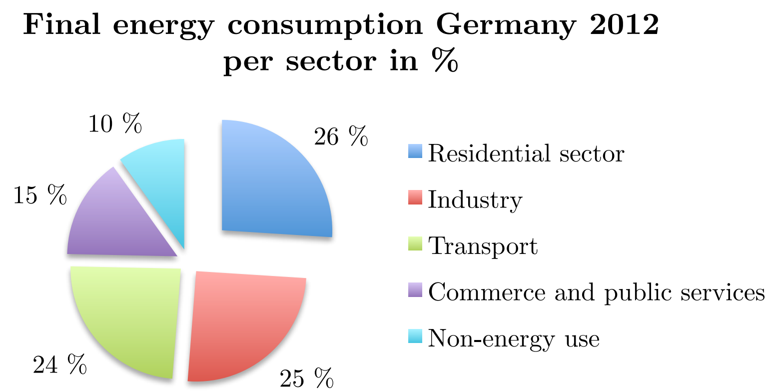


Figure 4: Final energy consumption Germany in 2012, per sector in %. Total: 9253 PJ, based on data from the IEA [42]. Where 'non-energy use' is defined as: "those fuels that are used as raw materials in the different sectors and are not consumed as a fuel or transformed into another fuel" [42].

The final energy consumption of the residential sector can be broken up per energy carrier, which is depicted in Figure 5.

[2]SFHs as defined by the TABULA project do contain in 20 % of the cases a second household, however, the term SFH is used to distinguish the buildings from MFHs, that have entirely different building geometries and energy consumptions. Which form the basis of the categorisation as used in the TABULA project, see section 3.1.5. The number of households per SFH is assumed to be 1 in the RBM.

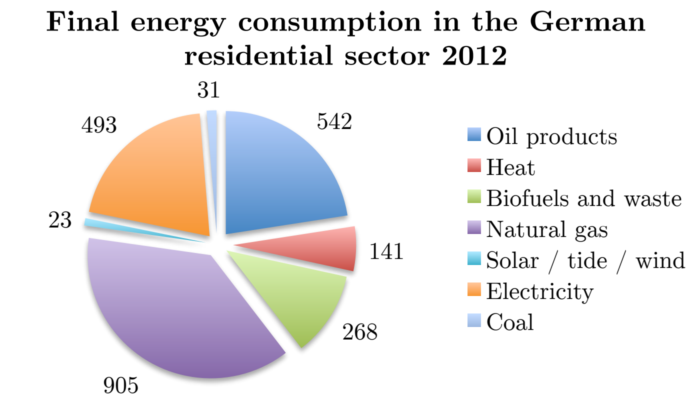


Figure 5: Final energy consumption in the German residential sector in 2012, per energy carrier in PJ. Total: 2403 PJ, based on data from [42].

More than half of the energy carriers are fossil fuels (oil, coal and natural gas) and furthermore the electricity consumed in the residential sector is also mainly produced by burning fossil fuels, which can be seen in Figure 6.

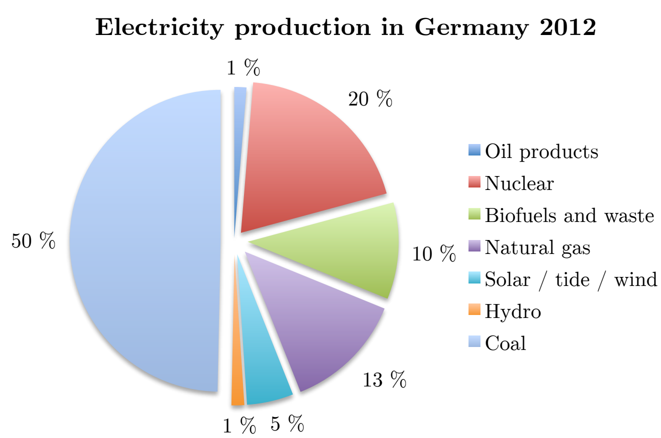


Figure 6: Electricity production in Germany 2012, use of primary energy carriers in %. Total: 5562 PJ, based on data from [42].

Based on the former, one can conclude that the residential sector is an energy intensive sector, which is in addition highly dependent on fossil fuels. Reducing the use of fossil fuels and saving energy in the residential sector is therefore an important step towards reaching our climate goals. This is acknowledged by the EU and the German government who have put policies in place in order to achieve these goals. The most important policies concerning the residential sector are explained in the next section.

3.1.3 Energy saving policies

In the year 2007 the European Commission set the "20 20 20 by 2020" goal to combat climate change. The goals are to reduce EU CO_2 emissions by 20 % in 2020 compared to 1990 levels, achieve a 20 % share of renewable energies in EU energy consumption by 2020 and save 20 % on EU primary energy consumption (compared to 1990) through energy efficiency by 2020, [14]. These goals led to the enactment of the Energy Performance of Buildings Directive (EPBD) and the Energy Efficiency Directive (EED) in 2002 and 2012 respectively, [11]. This section discusses both these EU policies and their German derivatives (EnEG) as well as additional German regulations on energy savings in buildings (i.e. the WärmeschutzVO, HeizAnIV and EnEV).

EED

The EED "establishes a common framework of measures for the promotion of energy efficiency" [11] for households and the services sector. It targets the building sector by stating that EU Member States should promote renovations of the building stock in order to save energy. One of the strategies to achieve this is by "evidence-based" estimations of the expected "energy savings and wider benefits" of such renovations, [11]. This led to the development of national and EU norms on how to estimate the energy consumption in buildings, see section 3.2.1.

EPBD

The Energy Performance of Buildings Directive of 2002 has been recast in 2010 with stricter requirements. The key demands of the EPBD ([11], [36]) are the following:

- All EU Member States should have an Energy Performance Certificate (EPC) system in place and certification of all new and existing buildings is mandatory.
- All EU Member States need to develop a corresponding calculation method for energy consumption in buildings, based on EU and national norms.
- All EU Member States should set minimum energy performance requirements for buildings in general, its building envelope as well as its building technology systems (e.g. Heating, Cooling and Ventilation).
- All EU Member States should ensure that existing buildings that are subject to major renovations meet the new minimum energy performance requirements.
- All EU Member States are required to ensure that new buildings are nearly-zero energy buildings by 2020 and in the case of public buildings already by 2018.

EnEG

The energy savings law or 'Energieeinsparungsgesetz' (EnEG, [9]) is a German law that aims to reduce energy consumption in buildings which was firstly adopted in 1976 during the first oil crisis. The law has changed several times over the years and since 2002 it includes the demands set by the EPBD. The current version of the law, from July 2013, states the following;

- Heated or cooled buildings need to be thermally insulated according to the current decree treating thermal protection in order to prevent avoidable energy losses.
- Building technology systems (i.e. systems for heating, cooling, warm water, ventilation and lighting) should not use more energy than necessary, according to the current decree on energy use of building technology systems.
- Demands for existing buildings can differ from requirements for new buildings, as described in the applicable decrees.
- Buildings are obligated to have an energy performance certificate, according to the EPBD.

The requirements on the buildings where up to the year 2002 listed in the 'Wärmeschutzverordnung' (thermal protection decree) and the 'Heizungsanlagen-Verordnung' (Heating system decree). The 'Energieeinsparverordnung' (Energy savings decree)' replaced the old decrees in 2002 with a new set of stricter requirements. Before the EnEG was in place, minimum requirements on thermal protection where already set by German industry. These standards are drawn up in the DIN V 4108-2, [20].

Wärmeschutzverordnung (WärmeschutzVO)
The 'Wärmeschutzverordnung' was first enacted in 1977, setting the requirements on thermal protection as mentioned in the EnEG, and was enforced until 2002. The requirements entail maximum values on the overall heat transfer coefficient (or *U-value*, as defined in equation 11) of the different parts of the building envelope as well as a maximum value on the annual demand for space heating ('Heizwärmebedarf' in kWh/m^{2}a). This demand is calculated with the method as described in the DIN V 4108-6, [22]. The WärmeschutzVO has been revised two times with more stringent minimum requirements on thermal protection.

Heizungsanlagen-Verordnung (HeizAnIV)
The 'Heizungsanlagen-Verordnung' or heating system decree was adopted in 1978 and was used together with the WärmeschutzVO in order to ensure energy savings in buildings. It set demands on the heating systems, e.g. limitations on operational losses, settings for controls and regulators and a minimum thickness for insulation material of pipes, [8]. It was replaced by the EnEV in 2002.

Energieeinsparverordnung (EnEV)
The 'energieeinsparverordnung' or energy saving decree treats the legal foundation of the EnEG since 2002, and is an extension of the earlier WärmeschutzVO and HeizAnIV decrees. The most recent version (EnEV 2014, [12].) will be enforced at the start of 2016. It distinguishes between residential and non-residential buildings as well as between new buildings and existing buildings. The requirements entail maximum values on the overall heat transfer coefficient (*U-value*), maximum values of thermal transmission losses over the building envelope (H'_T, see section 4.5.3) and maximum values on the primary energy demand of the whole building (Q_p). The last demand is a result of the incorporation of EU norms resulting from the EPBD, [80].

Calculation of H'_T and Q_p is performed based on the DIN V 18599 [25] (see section 3.2.1) or if the building is a residential building without a cooling system according to the DIN V 4108-6 [22] and DIN V 4701-10 [23].

Figure 7, shows how the different regulations preceded each other over time and how it influenced the maximum demand for space heating in German buildings.

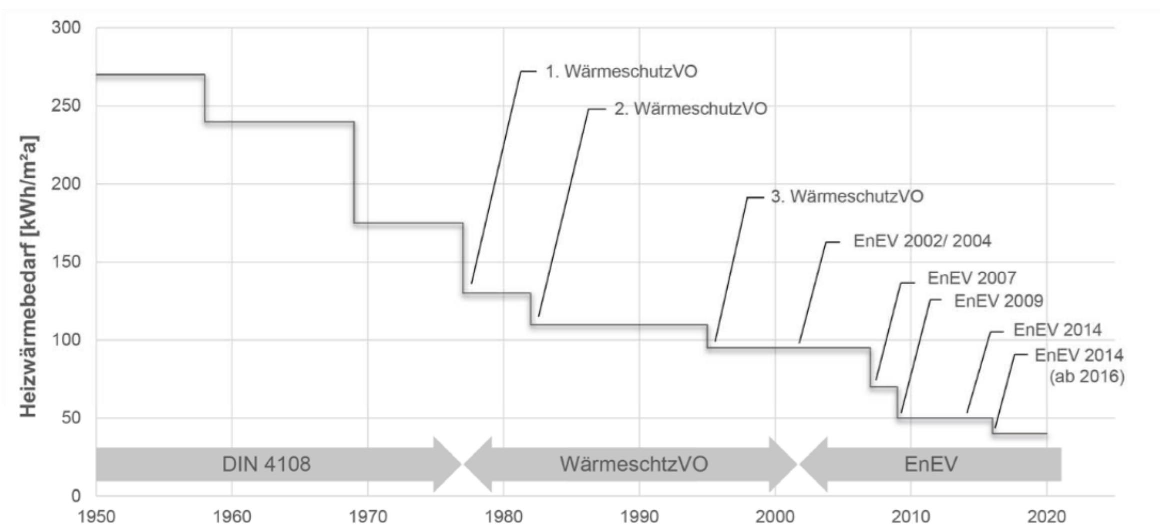


Figure 7: Development of the maximum demand for space heating 'Heizwärmebedarf' (in kWh/m^{2}a) in newly build German buildings under the norm DIN 4108, and the national regulations: the 'Wärmeschutzverordnung' and the 'Energieeinsparverordnung' (EnEV), [78].

3.1.4 Categorising building stocks

Building stock research on the EU and national level is readily available within scientific literature. Relevant research for this thesis is subdivided into 'descriptive research' and 'classification research'. 'Descriptive research' aims to investigate a building stock in order to identify its characteristics, based on empirical data. This data is used for further analysis of the building stock. In 'Classification research' the aim is categorising the building stock in order to facilitate further research on changes in the building stock, for example predicting energy savings by renovations of existing buildings, without having to consider every single building.

For the purpose of this research the goal is to investigate the German building stock based on what affects energy consumption in a building, see also section 3.2. In the scientific literature the most common classifications of buildings are based on **climate zone**, **building type**, **geometrical** and **thermal properties** ([17], [38]) and **building age** [1].

- The **climate zone** in which the building is built forms the boundary condition for its energy consumption and cannot be changed. This means that the building needs to be optimally adjusted to its location in order to minimise energy use. The main influences are the outside temperature, the amount of sun hours and the wind speed over the course of the year, which all affect the need for heating and cooling of the house. In order to categorise the German building stock based on the climate the country has been divided in 15 climate zones according to the DIN V 18599-10, [26].

- The **building type** differentiates between SFHs and MFHs but also SAHs, semi-detached and terraced houses [58] as previously described in section 3.1.1. The building type is an overarching classification which includes geometrical properties of the building, the number of residents as well as the installed building technology systems. These properties in turn affect the energy consumption of the building.

- The **geometrical building properties** of a building are: the building floor area, the amount of floors, the storey height, the corresponding volume of the building, the outside surface area (or building envelope), the compactness ratio (i.e. outside surface area / volume of the building) and the area and orientation of the windows. All these factors affect the thermal transmission losses over the building envelope (see section 4.5.3) as well as the capacity to store heat in the building.

- The **thermal building properties** also affect the thermal transmission losses as well as the thermal storage capacity of the building. These properties include the overall heat transfer coefficient (U-*value*) and heat capacity (C_p) of the building components (i.e. walls, ground floor, roof, windows and door), the solar energy transmittance of the windows (g-*value*) as well as thermal bridging and infiltration levels of the building. For a detailed description of these effects see section 4.5.3.

- The **building age** or more precisely the date of construction, is used as an aggregate classification type, in a similar way as the building type. Every period of time has its own construction techniques, materials and architecture style that in turn affect the thermal and geometrical building properties. The building age forms a valuable resource in assessing the energy consumption of single buildings in the building stock. This is the result of the fact that building age data is readily available and that this data gives information on the thermal building properties and compactness ratios, [1].

The categorising process starts by investigating a representative sample of the residential building stock. Based on the data obtained from this research and the characteristics as defined above it is possible to categorise the buildings in the sample into a limited amount of reference buildings. Since the building sample is deemed representative for the entire building stock, it is possible to extrapolate and divide all German residential buildings into the categories as represented by the reference buildings.

This method is by definition a simplification, however categorisation is in reality necessary since only data (on the building properties) of a limited building sample is available. This classification is used as a basis for identifying future energy savings and will be needed in this research in order to assess the potential for energy savings by BAS.

The importance of defining reference buildings for the assessment of future energy savings has been acknowledged by the European Commission, which adopted regulations that require Member States to define such reference buildings, [2]. These regulations provide in addition a set of guide lines on how to define these reference buildings: "it is recommended that reference buildings are established in one of the two following ways:

1. selection of a real example, representing the most typical building in a specific category (e.g. type of use and reference occupancy pattern, floor area, compactness of the building expressed as envelope area/volume ratio, building envelope constructions with corresponding U-value, technical systems and energy carriers together with their share of energy use)
2. creation of a "virtual building" which, for each relevant parameter, includes the most commonly used materials and systems.", [2].

3.1.5 The TABULA Project

The Intelligent Energy Europe (IEE) program of the European Commission launched the TABULA project in 2009 which continued until 2012. TABULA which stands for Typology Approach for Building Stock Energy Assessment involves thirteen European countries (including Germany). The goal of the project was "to create a harmonised structure for "European building typologies" in order to estimate the energy demand of residential building stocks at national level and, consequently, to predict the potential impact of energy efficiency measures and to select effective strategies for upgrading existing buildings", [2]. All participating countries developed their own exemplary buildings and categorised their building stock accordingly. The classification of the exemplary buildings is based on:

- Location of the building or climate zone.
- The construction period in which the building was built.
- The building type, i.e. "single-family houses, terraced houses, multi-family houses and apartment blocks", [52].

The result of the classification of the building stock is a "Building Typology Matrix" for each climate zone. "The matrix is characterised by two axes, the "Building Age Class" reflecting the construction period, and the "Building Size Class"", [2].

All countries apply the same method for classification, the exemplary buildings however are country specific. The method as used in the TABULA project elaborates on the guidelines as set by the European Commission (as described in section 3.1.4) by distinguishing three different approaches:

- "The "Real Example Building" (ReEx) approach identifies the building type by means of experience; the building type is selected by a panel of experts within an actual climatic context as the most representative of specific size and construction age classes. This approach is applied when statistical data are not available.
- The "Real Average Building" (ReAv) approach identifies the building type through the statistical analysis of a large building sample. The analysis is performed to find out a real building showing characteristics similar to the mean geometrical and construction features of the statistical sample.
- The "Synthetical Average Building" (SyAv) approach identifies the building type as an "archetype" based on the statistical analysis of a large building sample; the "archetype" is defined as "a statistical composite of the features found within a category of buildings in the stock" (IEA-ECBCS, 2004). The archetype is not a real building, it is a "virtual" building characterised by a set of properties statistically detected in a building category.", [2].

The project resulted in a classification of the building stock and an Excel based calculation tool for energy efficiency measures. Both the calculation tool, the building classification and the statistical data describing the building stock are made readily available and form a major source for this research.

The project was evaluated nationally in 2012, discussing possible improvements for the national building typology, recommendations for future research as well as methods for extending the project to non-residential buildings, [52], [53].

TABULA: the German building stock

The German research for the TABULA project was performed by the Institute for Housing and Environment ("Institut Wohnen und Umwelt, IWU"). It classified the German building stock in 10 age groups, the 4 standard "building types" and 10 exceptional cases (e.g. high-rise buildings, pre-fabricated buildings and former GDR buildings), [54]. The standard "building types" are defined according to the "Real Example Buildings" method (ReEx). The complete "building type matrix" for Germany can be found in Appendix B. For the purpose of this research the building matrix has been simplified to only include SAHs and LHs, see Table 1 and the continuation in Table 2.

Timescale	-1859	1860-1918	1919-1948	1949-1957	1958-1968	1969-1978
Building types	SAH	SAH & LH	SAH & LH	SAH & LH	SAH & LH	SAH & LH
Categorisation	I	I	I	I	I	I

Table 1: German building stock classification TABULA. Category I, houses built till 1978. With: SAH: a detached house or stand alone house and LH: a linked house.

Timescale	1979-1983	1984-1994	1995-2001	2002-2009
Building types	SAH & LH	SAH & LH	SAH & LH	SAH & LH
Categorisation	II	II	III	III

Table 2: German building stock classification TABULA. Category I, house built between 1979 and 1994. Category III, houses built after 1994. With: SAH: a detached house or stand alone house and LH: a linked house.

Important to note is that the first age class (until 1859) only considers SAHs and no LHs. Furthermore, the age classes are divided into three categories (see Table 1 and Table 2), which are used to distinguish between the heating systems installed in the corresponding houses, as described in section 4.3.2.

3.2 Energy consumption in buildings

The final energy consumption in a building is defined as the total use of energy in and around the building, which is the sum of all energy services and all energy carriers. The main contributing energy services and their share of energy consumption in German households is shown in Figure 8. The total energy consumption and the distribution over the energy services, however, differs greatly per building and household. Differences for space heating are mainly caused by the classification criteria as mentioned in section 3.1.4 in combination with changes due to different heating and cooling systems, the number of residents and their behaviour [40]. The demand for space heating can range from $Q_h \geq 200\,\mathrm{kWh/m^2 \cdot a}$ for un-renovated buildings built before 1979, to $Q_h \leq 60\,\mathrm{kWh/m^2 \cdot a}$ for buildings based on the EnEV 2009 standard, [39]. Differences in warm water use is mainly caused by the amount of residents, [30]. The biggest influence on energy consumption of lighting is the living area of the building, [28], which is easily determined. In contrast, the energy use for electronic appliances is very unpredictable and household dependent. Overall however, the average energy consumption for electronic appliances is on the rise with an increase of over 38 % in the last 20 years EU wide, [61].

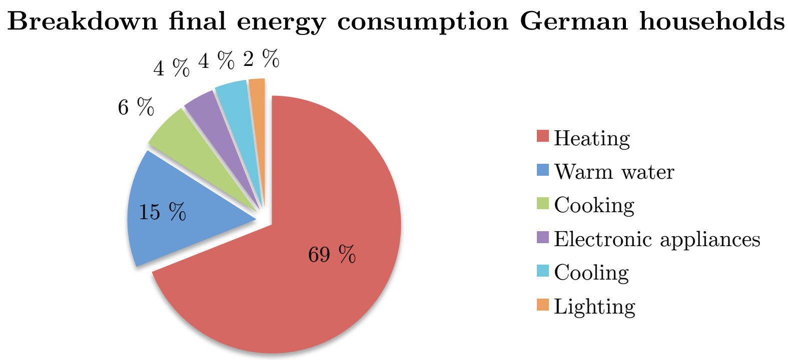


Figure 8: Breakdown of the final energy consumption of German households in 2012 in %, based on data from: [76].

3.2.1 Energy calculation norms

The goal of standardisation (or 'normierung' in German) in industry and science is to create an ordered structure of recommendations and guidelines in order to secure human safety, protect the environment as well as uphold the quality and consistency of products both nationally as internationally [65]. For the purpose of this paper the norms are classified in:

- **International norms**, which are set by the International Organisation for Standardisation and are coded by ISO and the International Electrotechnical Commission (IEC).
- **European norms**, which are set by the Comité Européen de Normalisation (CEN) and are coded by EN. All participating European countries need to adhere to the international norms and transfer the norms to the national level. Both Germany and the Netherlands are members of the CEN.
- **German norms,** which are set by the Deutsche Institut für Normung e.V. and are coded by DIN.

When International or European norms are translated to German norms the coding is changed to DIN EN ISO or DIN EN respectively. The norms are designed as guidelines, however, local, national or international institutions can include them in their laws and regulations, making them legally binding [65]. Based on national and international policies as described in section 3.1.3, German and European norms for the calculation of the energy consumption in residential buildings have been developed. The goal of these norms is to predict energy use under standard conditions and determine the performance of the building. Subsequently, the building performance level is used to compare the building to other buildings as well as to determine future energy savings by implementing energy efficiency measures. These norms form the basis for the model developed in this research. Important to note is that, due to the assumptions based on standard conditions and typical user interaction, the actual energy consumption of a house can differ significantly from the prediction based on these norms, [57]. The implementation of BAS could help diminish this discrepancy, see section 3.3.3.

Throughout this research the most recent norms have been applied unless otherwise indicated. Furthermore, all applied norms are included in the Bibliography.

3.2.2 Heating systems

Heating systems are defined as all systems contributing to the **production**, **storage**, **transport** and **transmission** of heat within the building for the purpose of space heating. The demand for heating is determined by all the heat 'sinks' and 'sources' of the building, which depends on the set temperature of the building's interior. Once all 'sinks' and 'sources' (as described in section 4.5.3) are summed up (which can be done for every arbitrary unit of time), the result is the heating demand that needs to be provided by the heating system[3].

A distinction is made between 'central' heating systems and 'room' heating systems, where 'central' heating systems provide the heating for the whole building or apartment whereas 'room' heating systems only provide heat locally in one room, e.g. (electric) stoves or a hearth. Central heating systems are the most common installed systems in Germany, with a penetration of 88 % for SFHs built before 1978, 93 % for houses built between 1979-1994 and 94 % for houses built between 1995-2009, [45]. The central heating systems as discussed here are water-based systems, where hot water is used as an energy carrier to transfer the heat to the respective rooms in the buildings.

All of these systems work according to the same principle, which is a closed loop system that transports hot water. First, water is heated inside the boiler, this hot water (with its respective 'feed-in temperature') is then transported throughout the building by means of a pipe and pumping system. The pipes lead to the different rooms in the building, where the transmission systems transfer the heat in the water to the room. After the water is cooled the water is returned back to the boiler, now with a lower 'return temperature'. In some cases the boiler is also responsible for heating the hot water supply (or domestic hot water DHW, drinking water for e.g. showers and baths) in these cases a water storage might be added to the system.

This research focusses on central heating systems that are responsible for both space heating as well as the domestic hot water supply (DHW), called combined central heating systems (CCHS), see section 4.1. Thorough descriptions of the heating system are provided only for those that apply to this research. The rest of this section is divided in the following three stages of the heating system:

- Heat production
- Heat transport
- Heat transmission

Heat production

Central heating systems based on warm water circulation were introduced in Germany in the beginning of the 20th century and since started to replace 'room' heating systems, [5]. The earliest systems functioned on coal which was replaced later by oil (in the 1960s) and natural gas (in the 1970s), [5, 4]. The heat production systems that are still dominant in the existing residential building stock are:

- Constant temperature boilers
- Low temperature boilers
- Condensing boilers

Currently gas and oil fired systems are the most common systems installed systems in Germany, [45]. Systems working on coal or other energy carriers are for this reason left out of the explanations below.

Constant temperature boilers

Constant temperature boilers ('konstanttemperaturkesseln'), are the oldest systems treated here, that only operate at a fixed operating temperature and are constantly running[4]. Return and feed-in temperatures are high with 70/90 °C, [4]. Such high temperatures are necessary to prevent corrosion damage inside the boiler. These temperatures, however, are not suitable for room heating, and as a result the hot water is mixed with cold water before it is transported through the building, [15]. Changing the

[3] A positive value would mean a demand for cooling instead of heating, for instance, in hot summer months. Cooling systems and their energy demand are not treated in this research

[4] This makes constant temperature boilers unsuitable for heating regulation which is why they are not included in the RBM, see section 4.1.2

amount of cold water that is mixed with the hot water regulates the heat supply to the building. This method results in a low level of efficiency compared to the other two boilers. Constant temperature boilers are soon a thing of the past since the EnEV 2014 [12] obliges that boilers older than 30 years are replaced by newer more efficient ones.

Low temperature boilers

Low temperature boilers ('niedertemperaturkesseln') started to replace constant temperature boilers in West-Germany in the 1980s after the oil crises and in the former GDR after the fall of the wall in 1989. In order to save energy these boilers operate at a lower temperature where mixing with cold water is not required. However, this requires that the boilers are built more resistant to corrosion, which is achieved by using special coated materials, [15]. The required room temperature in the building is obtained by operating the boiler at changing feed-in temperatures. Where the feed-in temperatures are varying between 40 °C and 75 °C, [4], dependent on the heating demand. This is regulated by a temperature sensor at the outside of the building wall, see section 3.3.2. By always delivering the exact demanded heat, through regulating the required feed-in temperatures, these boilers obtain a higher efficiency than constant temperature boilers.

Condensing boilers

Condensing boilers ('Brennwertkesseln', see Figure 9) were developed in the late 1980s and started to become the standard in the 1990s and beyond, [3].

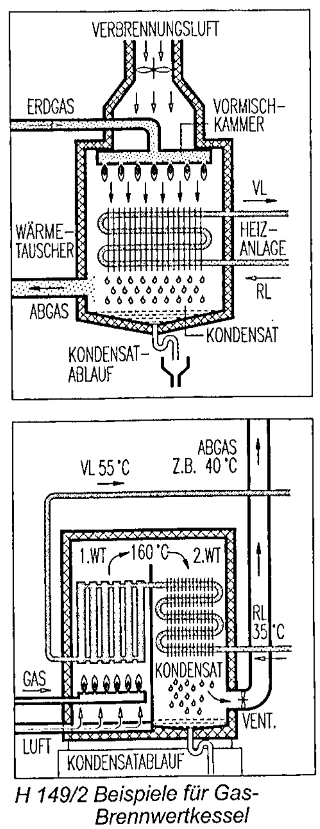


Figure 9: Two examples of (gas-fired) condensing boilers. Source: [66].

Condensing boilers reach an even higher efficiency than low temperature boilers by using the latent heat of the flue gases, see Figure 10. In order to do so the water vapor in the flue gas needs to condense, which requires a low return temperature. Condensing boilers typically operate at return and feed-in temperatures of 45/55 °C, [66].

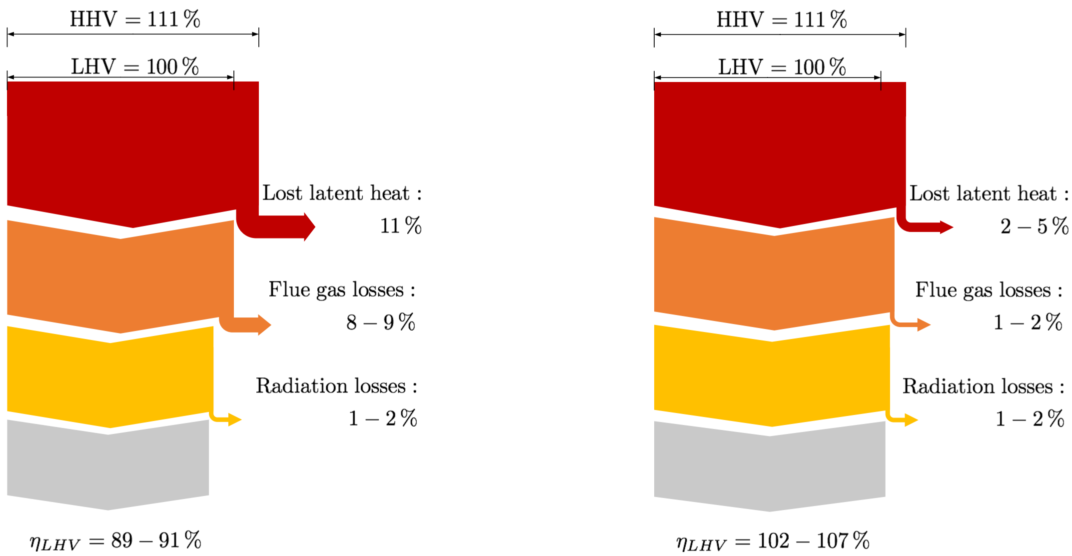


Figure 10: Energy flow diagram of a low temperature gas boiler (left) and a condensing gas boiler (right), where the efficiencies are based on the lower heating value (LHV). The grey arrow represents the remaining useful heat leaving the boiler. Based on data from [66].

Condensing boilers running on gas are more common and have a slightly higher efficiency than condensing boilers running on oil (with gas condensing boilers having an average increased efficiency of 10 percent points, and oil condensing boilers 5-7 percent points compared to low temperature boilers, [66]). Both types can additionally be used to heat drinking water. Combinations with solar collectors are also a possibility, however this type will not be treated in this research.

The efficiencies of the boilers depend on the load and are depicted in Figure 11. Especially the efficiency of the condensing boiler increases with partial load. This increased efficiency at partial load is the result from a lower return temperature, which in turn leads to better use of the latent heat, [3].

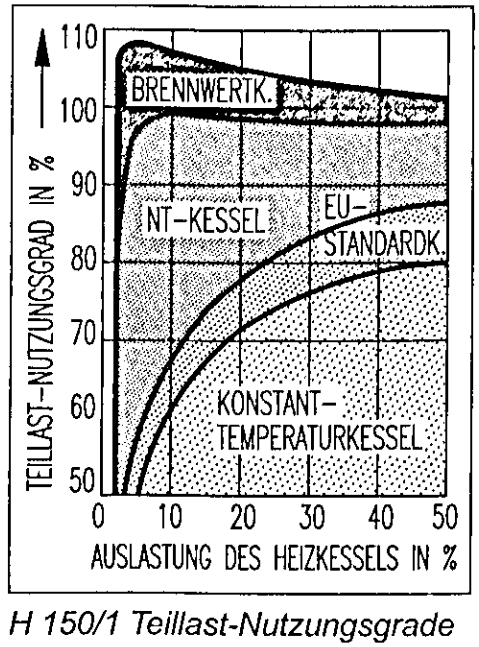


Figure 11: Efficiencies of the three boiler types as a function of the power output or load (in percentage of full load), Source: [66].

Heat transport
After the water is heated and potentially stored, it is transported either to the taps for DHW or transported to the heat transmitters for space heating. The volume flow for distribution of the hot water is regulated by pumps within the pipe system. Hot water transportation for DHW and space heating is divided into two separate pipeline systems, one open one for DHW, and a closed loop system for space heating. There exist several different pipeline system designs with different overall lengths and distribution methods, as described for DHW in DIN V 18599-8 [30] and for space heating in DIN V 18599-5 [29]. The different designs result in different heat losses, where in general, the efficiency of the heat transport system is around 98 %, [66]. However, when pipelines run through unheated rooms (e.g. cellars) heat losses increase, which is why the EnEV demands mandatory insulation of these pipelines, [12].

Heat transmission
The heat transmission is the final stage of transferring the generated heat for space heating to the rooms where it is needed. In general the following distinction is made between systems that transmit their heat predominantly by thermal radiation or convection and in a lesser amount conduction. This results in the following different types of transmission systems:

- Radiators
- Convectors
- Underfloor heating

In this research the focus lies on radiators only, as described in section 4.1.2. Which is why the explanation below is limited to these kind of transmission systems.

Radiators
Radiators, see Figure 12, transmit their heat for 20-45 % by radiation, [66]. The rest of the energy is transmitted by convection.

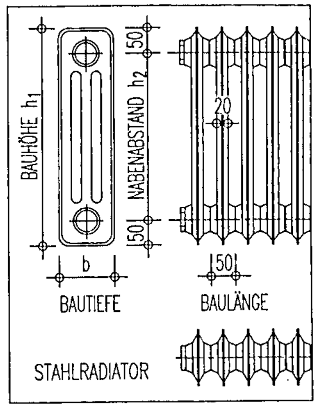
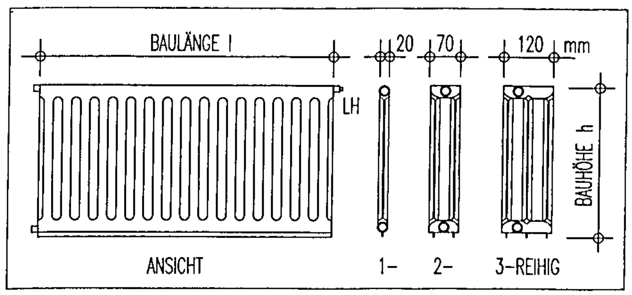


Figure 12: Steel radiator, with size indications in mm, Source: [66].

The more modern panel radiators "Plattenheizkörper", see Figure 13, transmit their heat for 75-100 % by radiation (the rest of the energy is transmitted by convection). They require a lower room temperature in order to achieve the required comfort levels (see section 3.3.3 on thermal comfort of the residents) and therefore use less energy than normal radiators, [66].



H 204/1 Profilierte Plattenheizkörper. Maße in mm

Figure 13: Panel radiator, size indications in mm. Source: [66].

The choice of the heat transmission system depends on several factors, of which an important one is the choice of boiler type. Boilers that deliver lower feed-in temperatures need bigger heat transmission areas in order to satisfy the heating demand in the room, see Figure 14. Bigger heating areas are most easily achieved by underfloor heating or panel radiators, which are often installed in newer buildings (buildings constructed after the 1980s) in combination with condensing boilers, [66]. The size of the heat transmission system needs to be determined according to the DIN EN 12831 and VDI 6030, [66, 77]. The placement of the radiators should be determined on where the temperature drop is the highest in the room, which is in general beneath the window. For good insulated buildings with double glazing, however, this becomes increasingly less important, [66].

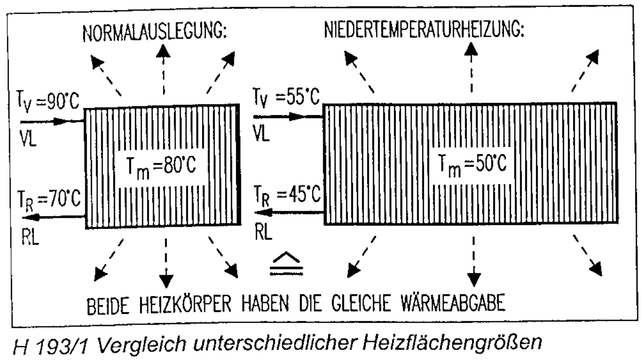


Figure 14: Size of the heat transmission system with different feed and return temperatures for the same heating demand, Source: [66].

3.3 Building automation systems

Building automation systems (BAS) or building automation and control systems (BACS) are formally defined as: "Equipment, software and services for automatic controls, monitoring and optimisation as well as operation and management, and for the energy-efficient, economic and reliable human intervention of the building services" [78]. Where "home automation" (HA) is the residential extension of BAS including user appliances. The general system of a BAS is divided into three main levels:

- The management level
- The automation / control level
- The field level (sensors & actuators)

A detailed illustration of these levels and their components are given in Figure 15.

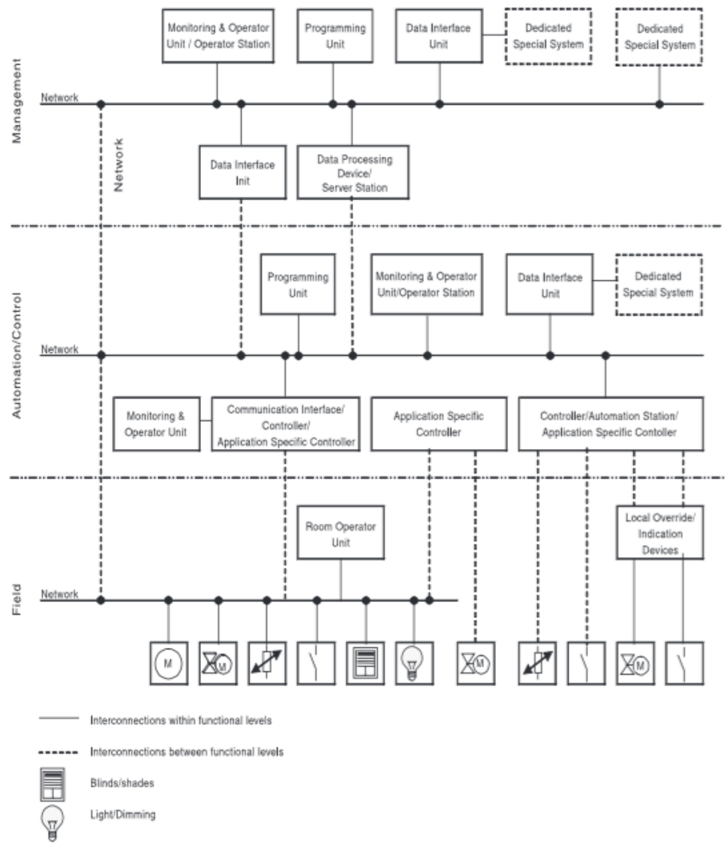


Figure 15: Building automation structure (DIN EN ISO 16484). Source: VDI 3814, [78].

The most important components for the purpose of this thesis are:

- Sensors & Actuators (field level). For instance; temperature, contact and presence sensors & pumps, valves and switches.
- Regulation and control technologies (automation level) For example P-control loops.
- Optimisation software (management level). For example time scheduling and night cooling.

These components work together in a HA system in order to regulate the following building equipment:

- Heating systems
- Cooling systems
- Ventilation systems
- Lighting
- Security and emergency systems
- Communication systems
- Sun screens
- and consumer appliances (like washing machines).

Within HA the BAS are increasingly connected, for example, by (wifi) networks, as well as more accessible to residents, due to integration with consumer appliances and mobile devices like smartphones and tablets. A house with state of the art HA systems is often also referred to as a SMART home. The interconnection between sensors, building equipment and energy monitoring, as well as the possibility for the user to interact with the HA systems in an effortless way makes it possible for the building to adapt to user behaviour, see section 3.3.3. The use of BAS in residential buildings could therefore reduce the impact of user interaction and result in significant energy savings. For instance Lu et al. [56] have shown that for only 25 US dollars spent on sensors once can reduce the energy consumption for heating by 28%. This was achieved by regulating the HVAC system based on whether the residents were away or asleep.

The international standard for BAS and its requirements are set by the DIN EN ISO 16484 [44] and extended upon by the VDI 3814 [78].

3.3.1 Regulation and control technologies

All regulation and control functions are part of control technology systems (or 'Leittechnik'). These functions, which are part of the automation level, form the core of the BAS as treated in this research. The goal of these functions is to automatically regulate physical quantities (for instance room temperature) based on measured input values and predefined requirements. To achieve this, they communicate with the field and management level. The physical input values are, for example, obtained on the field level by the installed sensors (e.g. thermometers), [65]. The final output, however, is the result of the performed work by the actuators (pumps and valves), which also takes place on the field level.

Control systems can either be open-loop (or 'Steuereinrichtung') or closed-loop systems (or 'Regeleinrichtung'), [32]. Open-loop systems are sensitive to unforeseen external changes, whereas closed systems are not.

Open-loop control systems
Open systems operate on a so called 'reference variable' (or 'Führungsgröße') based on predefined settings, which results in an output that is not evaluated. External changes or 'disturbance variables' (or 'Störgröße') that are not part of the predefined settings are not taken into account when producing the output. An example of an open-loop system is the regulation of the feed-temperature of the boiler based on the outside temperature, see section 3.3.2.

Closed-loop control systems
Closed-loop systems use the output value or 'controlled variable' (or 'Regelgröße') as an input for the evaluation of the control system. The result is that even unknown disturbance variables are taken into account when producing the output. An example of a closed-loop system is the regulation of the room temperature based on a temperature sensor in the room, see section 3.3.2.

Control functions
There exist an infinite amount of different control functions, of which the most common ones are described in the VDI 3814 [78]. The ones explained here are those that are used in the RBM.

- P-control (or 'P-reglung'): Is a common and very basic control that regulates the output variable (y) proportional to the change in the controlled variable (x).

  $$y = p_c \cdot x$$

  with p_c the proportional coefficient. The P-control operates around a fixed setpoint (or 'sollwert').

- Sliding/curve setpoint (or 'Kennlinie'): This function provides a variable setpoint, i.e. the setpoint is determined by either a reference variable or a pre-calculated function, [78].

- Setpoint / Output limitation (or 'begrenzung sollwert/stellgröße'): This function limits the value of the setpoint and/or output within a lower and an upper boundary, [78].

Optimisation
Calculation/optimisation as defined by the VDI 3814 [78] are processing functions that are part of the management level of BAS. These functions do not replace the control functions as described in the previous section, but adapt them to different requirements, for instance the requirement to save energy. These functions operate in an overarching way and are able to influence several other control functions, [78]. Examples of optimisation functions are a 'time schedule' (or 'Zeitabhängiges Schalten') or 'night cooling' (or 'Nachtabsenkung'), see section 3.3.2.

3.3.2 Heating system control technologies

The goal of heating system control technologies is to create an optimal indoor climate depending on the user needs and the weather conditions, while at the same time reducing the energy consumption and preventing damage on the heating system, [66]. Under the EnEV [12] it is even mandatory for central heating systems to regulate the heat supply based on the outside temperature and a time schedule. This section explains how these goals are achieved and which control technologies are required.

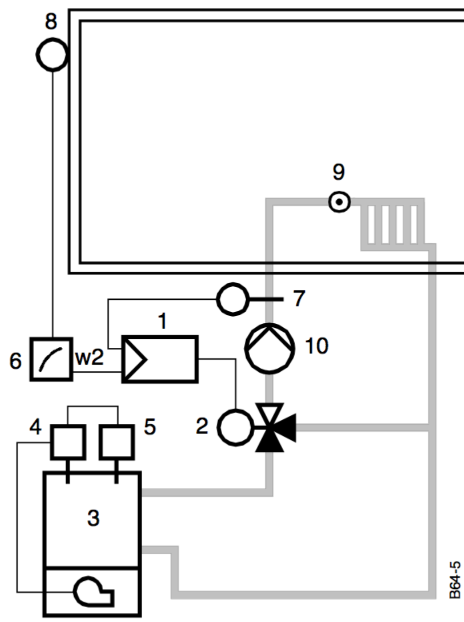
Regulation possibilities
In general there exist two methods to regulate the heat output of the heating system.

- By regulating the feed-in temperature of the water
- By regulating the volume flow of the water

The first is achieved by modulating the burner in the boiler, by temporary switching the burner off and/or by mixing the feed-in water with return water, [66]. In this research the focus lies on a modulating burner. These systems are widely available for low temperature and condensing boilers, where the burner flame is adjusted by adjusting the fuel and air ratios [73]. For condensing boilers there is the added benefit of a better latent heat recovery at lower return temperatures (which are a direct result of a lower feed-in temperature).

The second method of heat output regulation is achieved by adjusting the power of the circulation pump, switching it off, and/or by regulating the thermostat valves of the heat transmission system. This research focusses on the use of thermostat valves, see the explanation below.

The resulting heating system and its control technologies is depicted in Figure 16.



Legend:

1. Feed-in temperature control system
2. Mixing valve
3. Boiler with modulatable burner
4. Safety temperature limiter
5. Boiler temperature thermostat
6. Feed-in temperature heating curve
7. Feed-in temperature sensor
8. Outside temperature sensor
9. Thermostatvalve
10. Circulation pump

Figure 16: Heating system with control technologies to adjust the heat supply in a room. Source: [73].

Weather dependent regulation
Weather dependent regulation of the heating system (or 'Witterungsgeführte reglung') is achieved by an open-loop control system that regulates the feed-in temperature as a function of the outside temperature. In the outside of one of the building walls a temperature sensor is installed, [73]. This sensor is connected to a regulator that operates with a sliding setpoint for the feed-in temperature, this sliding setpoint is called the 'heating curve' (or 'Heizkurve'). The feed-in temperature then follows from the heating curve and the value of the outside temperature. A theoretical heating curve is given by [37],

$$T_{feed} = T_{in,set} + \frac{F_l \cdot (T_{feed,design} - T_{return,design})}{1 - e^{\frac{-\mathrm{Ln}\left(\left(T_{feed,design} = T_{in,set}\right) / \left(T_{return,design} = T_{in,set}\right)\right)}{F_l^{(1/EX-1)}}}} \text{ [K]} \tag{1}$$

with:

$T_{in,set}$ the setpoint temperature of the room/zone [K].

F_l the load factor, $F_l = \frac{T_{in,set} - T_{out,n}}{T_{in,set,n} - T_{out,,n}}$.

$T_{feed,design}$ the design value of the feed-in temperature of the boiler [K].

$T_{return,design}$ the design value of the return temperature of the boiler [K].

EX the heat transmission system's exponent, which describes the influence of the deviating actual feed-in and return-temperatures in comparison to their design values on the power of the heat transmission system. Which is dependent on the type of heat transmission system (e.g. radiators: $EX \approx 1.3$, convectors $EX \approx 1.4$, underfloor heaters $EX \approx 1.1$, [63]).

$T_{out,n}$ the norm outside temperature, which is -14 C for Potsdam, the reference location for Germany, [66].

$T_{in,set,n}$ the norm setpoint temperature of the room/zone, which is 293.15 [K] or 20 C, [37].

Programmable thermostat
Modern thermostats are interactive interfaces that provide several regulation options for the residents to control the heating system. One of those options is to program fixed time schedules with different/varying setpoint settings for the indoor room temperature. A change in the setpoint for the room temperature will shift the heating curve (almost completely parallel, see equation 1) up or down, which in turn results in a higher or lower feed-in temperature for the heat transmission system. Important to note is that these systems are in general equipped with a room temperature limitation, [78]. Which ensures that the room temperature doesn't sink below the dew point in order to prevent mildew, [70].

Night cooling The setting for night cooling typically lowers the setpoint for the indoor room temperature by 2-5 K for a period of 6-8 hours, [66]. Since both the transmission and ventilation losses of the building are linearly proportional to the difference between the inside and outside temperature (see section 4.5.3) one can estimate the energy savings by,

$$\Delta Q_{losses} \propto (T_{set} - T_{set,lowered}) \,/\, (T_{set} - T_{outside}) \;\; [\text{W}] \tag{2}$$

According to [66]. This could lead for example to savings of,

$$\Delta Q_{losses} \propto (T_{set} - T_{set,lowered}) \,/\, (T_{set} - T_{outside}) = (20 - 16) \,/\, (20 - 5) \approx 27\%$$

during the period of the reduced setpoint.

It is important to note that the lower indoor room temperature does not lead to less comfort for the residents, as the heat demand is reduced when the inhabitants are sleeping. However, choosing the right period of reduced setpoint is important. Because it takes some time for the building to cool down as well as heat up, one should set the start of the night cooling period before the residents actually go to sleep and the end before they wake up.

Time schedule A time schedule works on the same principle as night cooling, namely reducing the setpoint for the indoor room temperature. The difference is that time schedules are applied for moments during the day, week or year when the residents are not at home. The time it takes for cooling or reheating the building is dependent on whether the building is 'light' or 'heavy' (i.e. whether it has a low or high overall heat storage capacity, see section 4.5.4). Which results in the fact that the overall gains are expected to be higher for 'light' buildings, [66].

For both a time schedule or night cooling it is important to set the setback periods correctly. Improper use of the thermostat leads to heating and cooling at moments undesirable to the inhabitants, and can actually lead to increased energy consumption, [56] and [40].

Thermostat valves
All heating regulation systems as discussed so far regulate the feed-in temperature and are room independent. Thermostat valves however regulate the volume flow of the heated water that enter each heat transmission system individually (see Figure 16). In this way it is possible to obtain a comfortable room temperature independent of the room specific influences (internal heat gains or solar

heat gains, see section 4.5.3). Traditional thermostat valves can be regulated manually, in general by turning a nob onto one of the five settings (where setting '3' is designed to achieve a room temperature of 20 C, [66]). In addition, they also regulate the volume flow automatically. This is the result of a spring attached corrugated tube which is filled with an expansion fluid, [66]. The fluid reacts to the surrounding temperature by expanding/contracting, which in turn moves the tube onto a cone which blocks/unblocks the valve and reduces/increases the volume flow entering the heat transmission system. This mechanism operates linearly and can be considered a P-control (see section 3.3.1, [37].

Thermostat valves exist also as digital versions, with communication interfaces, [66]. These models have the possibility to interact with other control technologies. For instance with contact sensors on windows, see section 3.3.4. Such systems however need electricity which is often delivered by a small battery with a lifetime of 2-5 years, [66].

3.3.3 Building automation systems and user interaction

Policies that aim to reduce energy consumption in residential homes are mainly focussed on addressing insulation standards or the implementation of renewable energy sources (as discussed in section 3.1.3). Calculation methods to determine the possible achieved savings like the DIN V 18599 [25], however, fail to represent the actual (measured) savings after the energy saving measures are applied. This can be explained by the fact that the DIN V 18599 is a standard calculation method that cannot take into account all the specific variables (which influence the energy consumption) of the building in question. One of the most influential variables is the behaviour of the residents, Ren et al. [69] identified that up to half of energy use can be allocated to user interaction. This acknowledgement creates a significant potential for future energy savings, [55] and BAS could play a role here.

Current houses and their heating systems have limited capabilities to react to changing resident behaviour, whereas BAS offer interfaces that react to these changes of the residents and can adjust the heating systems accordingly, see section 3.3.4.

Thermal comfort
Thermal comfort is an important topic when investigating the influence of the user on the energy consumption for space heating. Discrepancies between predicted energy savings and actual energy savings are often the result of users that behave different from the norm in order to achieve the personal comfort standards. For instance, setting their room temperature to 21 C instead of the norm value of 20 C. When implementing BAS the goal should therefore not only be to save energy but also to uphold the thermal comfort requirements of the inhabitants.

The method for determining perceived thermal comfort levels of the residents are described in DIN EN ISO 7730 [24], norm parameters for the indoor climate in DIN EN 15251 [31] and comfort deficits in VDI 6030 [77]. Thermal comfort is dependent on:

- The operative temperature of the room
- The activity and clothing of the inhabitants
- The indoor air velocities
- The floor temperature
- The temperature gradient in the room
- The asymmetric thermal radiation

as stated by [66]. In this research the focus on the thermal comfort is limited to the indoor temperature, where the operative temperature is defined as (DIN EN 15251 [31]),

$$T_o = \frac{T_{air} + \bar{T}_{surface}}{2}$$

with

T_{air}	the indoor air temperature of the room/zone [K]
$\bar{T}_{surface}$	the average surface temperature of the walls, ceiling and floor of the room/zone [K]

The permitted operative temperature for ensuring a comfortable climate is a function of the outside temperature, as shown in Figure 17.

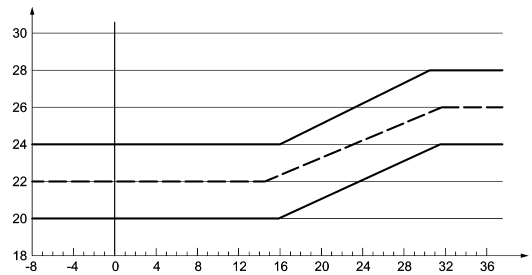


Figure 17: Comfort room temperature T_{comf} (dashed line) and the allowed tolerance region for the operative temperature T_o (solid line) as a function of the outside temperature. Source: [31].

Air quality
In addition to the thermal comfort it is also necessary to regulate the air quality to ensure a comfortable living environment. This requires a minimum air exchange (set by the EnEV [12]) either by manual ventilation or mechanical ventilation. The resulting energy losses due to ventilation are substantial and depend on this air exchange rate as described in section 4.5.3.

3.3.4 State of the art building automation systems

BAS for heat regulation on the market today distinguish themselves by increased connectivity between the different components and the implementation of more complex regulation software. A few examples are:

- Wifi connection between the installed components
- Applications for mobile phones to regulate the BAS from a distance, [70]
- Temperature setpoints per room, [56], [40].
- Adjustable and self learning systems that change the time schedules and room temperature setpoints automatically, taking heating and cooling periods into account, [70].

In addition to this, hardware components like sensors are increasingly affordable (motion sensors and magnetic reed contact sensors for 5 US dollars each, [56]).

For the purpose of this research the focus is on two separate systems:

- Time schedules with reduced setback temperatures during the day.
- Thermostat valves that adjust the volume flow based on whether a window is opened in the room.

This choice is based on the expected energy savings, based on previous studies like those by Ioannou et al, which states that the behavioural parameters like thermostat use and ventilation flow rate "[...] dwarf the importance of the building parameters." [43].

Time schedule
A time schedule system that is part of a programmable thermostat would not require any additional sensors, but would regulate based on either a predefined schedule or a adjustable schedule (modulating system, [66]). An adjustable schedule could be edited manually, where the inhabitant could indicate when they would like to have a warmer climate by pressing a button. The frequency of changes are recorded and the schedule is adjusted and stored, [50]. Another option is for the schedule (i.e. the start and stops of the setback periods) to be adjusted automatically by observing user presence, with infrared or ultra sound waves or contact sensors on doors, or a combination of both.

Connected thermostat valve
The connected thermostat valve functions just like the thermostat valve described in the previous section, but with one exception. The drawback of the thermostat valve is that whenever a window is opened, the room temperature drops and as a result the thermostat valve opens. This in turn increases the volume flow of hot water and the heat supply of the heat transmission system. This heat does not benefit the indoor temperature as the heat exits the room through the window by convection (that is when the outside temperature is lower than the inside temperature). The fact that the thermostat valve opens actually increases the energy consumption without any benefit.

The connected thermostat valve however senses when a window is opened and in turn closes the thermostat valve. This is achieved by placing a contact sensor in the window frame, which is connected to the (digital) thermostat valve. The result is a reduced heat flow when the window is opened and the thermostat valve resumes its normal regulating when the window is closed again.

4 Methodology

The research will comprise of two parts.

1. The first part is an explicit simulation of a reference building which will result in the energy saving potential of a single house.
2. The second part determines how these results can be scaled in order to estimate the potential for Energy and CO_2 reductions on the national level.

The focus of the research determines the framework of the Methodology and is defined in section 4.1, Scope & Definitions.

4.1 Scope & Definitions

The scope of the research is mainly determined by the problem definition and the research questions as given in section 2. Further restrictions on the scope of the research are described below and are divided in the following three categories:

- Restrictions on the amount of assessed buildings in the residential building stock
- Simplifications and generalisations on the assessed buildings
- Implemented building automation systems

Where the decisions for scoping are based on the knowledge gained from literature research, as described in the section 3, 'Background'.

4.1.1 Scope residential building stock

The building matrix in Appendix B shows that the German residential building stock is comprised of a diverse amount of different types of buildings. In addition to this, section 3.1.4 describes the effect of the building type and geometry on the energy consumption of the building, which is why these buildings are treated separately. Creating a model that accurately can assess the energy consumption for all these different buildings is therefore out of the scope of this research. This research focusses only on SFHs, as defined in section 3.1.1. The choice for these building types is justified by the following arguments.

- SFHs form the majority of the residential building stock, with 83 %, see Figure 2 and also "are likely to continue to account for around two thirds of the residential heat demand until in 2050", [59]. Achieving energy savings in SFHs would therefore have a high impact on a national scale.
- SFHs are geometrically uniform (in size, shape and number of storeys; typically 2 storeys, [47]) compared to MFHs (with a much higher range in number of storeys). Which simplifies creating an accurate general model, see section 4.5.1. In addition, the number of methods used for space heating is limited, see section 4.1.2.
- SFH are predominantly privately owned, [18], which eases the application of BAS.

4.1.2 Scope buildings

Although SFHs are previously described as uniform, there exist many differences between the SFHs that cannot all be specifically modelled in this research. For this reason, further simplifications and generalisations are made. For instance, all SFHs are modelled with flat roofs and winter gardens and attached unheated rooms (e.g. garages and sheds) are not included in the model. More important however is the fact that only energy for space heating is explicitly modelled (i.e. no energy for DHW, cooking, lighting or electric appliances). This decision is based on the fact that the majority of the domestic energy consumption is used for space heating, see Figure 8.

Although the number of different heating systems in SFHs is high, which includes different energy carriers (e.g coal, oil, natural gas, biofuels, heat and electricity) as well as different technologies for production and transmission of the heat (e.g. heat pumps, boilers, central or local heating systems, see also section 3.2.2), the focus of this research is only central water-based heating systems on oil or gas. In Germany today, these are the most commonly installed systems, see Table 3.

Building type category	Energy carrier	
	Heating oil	Natural gas
SFH I	39 %	44 %
SFH II	40 %	48 %
SFH II	19 %	66 %

Table 3: Building type categories as defined by the TABULA project, see Table 1 and 2 and the percentage of the houses in these categories that have central heating systems based on heating oil or natural gas. Source: [45].

Furthermore, even though the RBM is capable of modelling LHs these are not simulated in this research. The houses modelled are SAH 1, SAH 2 and SAH 3 as defined in section 4.3.2. This scoping results in a couple of different reference building models that together represent a share of 21 % of all SFH in Germany and 12 % of the entire German residential building stock[5].

4.1.3 Scope building automation systems

Section 3.3 shows a variety of building automation systems for the purpose of home automation. The goal of these systems is not necessarily to save energy but also to increase comfort for the residents. For the purpose of this research the focus lies on BAS that regulate the space heating system only, as the potential for energy savings is high 3.2. The implementation of the BAS and their resulting energy savings are calculated for the following two scenarios:

Intermittent heating
Intermittent heating is the regulating of the load of the heat producing system based on the presence or activity of the residents in order to save energy. Section 4.5.2 shows the user profiles of the residents which will be used as an input for the load regulation. These profiles describe the presence of the residents at home and whether they are asleep or not. Subsequently, the BAS will regulate the feed-in temperature of the heating system accordingly to fit this 'time schedule'.

Ventilation dependent heating
The ventilation dependent heating scenario calculates the possible energy savings achieved by reducing the heat transmittance in the rooms that are currently ventilated. The sensors of the BAS notice when a window is opened and shuts down the thermostatic valves of the heat transmission system, therefore reducing the heat losses to the exterior of the house.

It is important to note that the sensors and regulators necessary for these BAS are readily available and suitable for retrofitting, see section 3.3.4.

4.2 Data requirements

The (external) data needed in this research is subdivided into two parts, consistent with the two parts of the methodology.

[5]Percentages are based on the square meter living area of the houses, [46]

4.2.1 Part I: Modelling

The first group of data can be qualified as input data needed for the modelling section of the research. This data is used to set up a representative reference building, determine preconditions and boundary conditions, and create BAS within the model. In detail, the necessary data is comprised of three categories:

- Building data
- Weather data
- BAS data

Building data
Building data is provided by the TABULA project, as described in section 3.1.5. The data is adjusted to suit the requirements of the model, which is explained in section 4.3.2.

Weather data
The weather data is provided by the German institute for spatial planning and construction (BBR), [6]. It provides climate data for so called 'Test Reference Years' (TRY) for 15 different regions all over the country. The TRY datasets provide hourly data on 18 different variables concerning the weather. The first data entry on January 1 at 01.00 and the last entry is December 31 at 24.00. The dataset is the result of the average of measurements during the period 1988-2007, [6]. The average climate for Germany has been defined as similar to the climate of the city of Potsdam. Potsdam has been declared as the reference or norm location by the DIN V 18599-10 [26]. In this research the weather data is provided by the TRY data of the city of Potsdam (TRY-4).

The data is loaded into Modelica by the existing partial model 'Weather', see Figure 18.

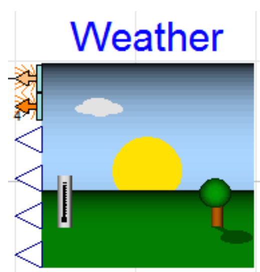


Figure 18: Modelica model 'Weather' as provided by the Modelica library, [60].

This model returns 3 outputs of interest from the TRY-4 dataset:

- The hourly outside temperature as seen in Figure 19.
- The incoming solar radiation on a horizontal surface.
- A vector containing the incoming solar radiation per cardinal direction (N, E, S and W).

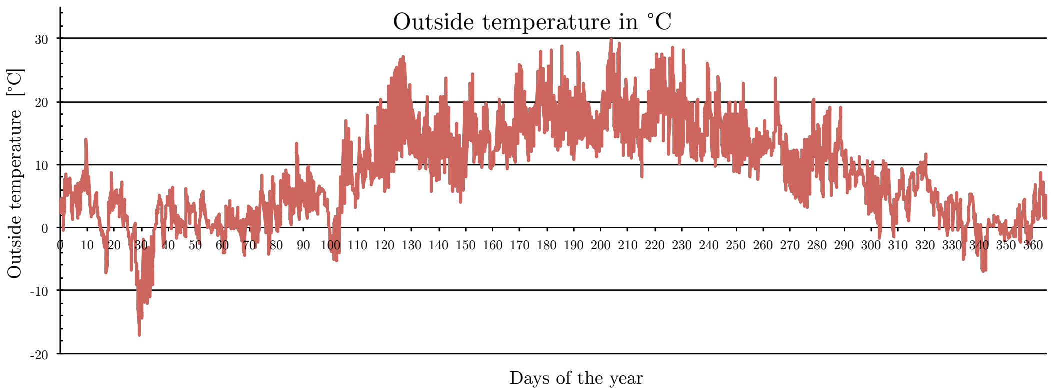


Figure 19: TRY-4 Dataset for the hourly average outside temperature in Potsdam, Germany. Source: [6].

BAS data
BAS data is all data necessary for the creation of the modelling components that model the implementation of BAS. For the purpose of this research these components contain:

- Thermostat settings, data obtained from the DIN V 18599-10 [26], see the component description in section 4.5.4.
- Duration and regularity of the opening of the windows, data obtained from the DIN V 18599-10 [26] and [66], for the time profiles of the window opening, see section 4.5.2.

4.2.2 Part II: Residential building stock analsyis

Data used for the interpretation of the model results (i.e. the energy savings of a single home due to implementation of BAS) and how these can be meaningfully expanded to the German level form the second group of external data used in this research. The data necessary for this is:

- The empirical and statistical data on the German building stock, that is the number of houses per building type. Data is provided by the TABULA project [47].
- The empirical and statistical data on the presence of different heating systems, as provided by [45].
- CO_2 emission factors of the utilised energy carriers.

4.3 Modelling preparations

The first part of the research is the creating of a system model of a typical residential building. A SFH is explicitly modelled, including the retrofitted building automation systems, in order to determine its potential for energy savings. The model is simulated in the program 'Dymola', a modelling environment based on the object-oriented modelling language 'Modelica'. In order to create the model and correctly interpret its results as given by Dymola it is necessary to understand the workings of the model. Section 4.3.1 contains a description of the modelling language, the solving algorithms and the implicit assumptions.

4.3.1 Modelica & Dymola

Modelica

The model is created and simulated with help of the Modelica and Dymola software. Modelica (version 3.3) is an open language provided by the Modelica Association [60] for physical system simulations. It is a dynamic, object oriented, acausal language that is based on the C-code meta language and is used in the field of engineering for modelling the behaviour of a multitude of different engineering systems [75]. Due to its open structure, as well as the access to the 'Modelica Standard Library', one can easily extend one's own models with already existing models. The 'Modelica Standard Library' consists of more than 340 generic models, 1000 functions and 1450 packages [64]. In addition to the 'Modelica Standard Library', the 'Berkeley Building Library'[51] is used to model the heating system as well as the radiation exchange. The implementation of the prefabricated models reduces the amount of code writing considerably and makes it possible to create complex models (of complete buildings for instance) in a relatively short time period. In this research the most used libraries include the models concerning thermal physics, (logic) control blocks, heating systems and fluid pipe flows. These models are extended upon by self written code in order to form the final reference model of a SFH.

The use of Modelica is particularly interesting for this research as it provides the possibility to easily change the boundary values and input parameters as given by the researcher. This makes comparison of several SFHs with different input parameters a simple straightforward task, for instance houses with different A/V-ratios could be easily analyzed. Such an easy comparison, of models with different input parameters, is very useful in both the extension of the results to the entire German building stock as well as for understanding the model itself.

Dymola

In this research the simulation environment for the Modelica code is the program 'Dymola' by Dassault Systems [16]. The program is both used for creating the model as well as for performing the simulation of the created model. For these two purposes the program is divided into two levels, the 'modelling' level and the 'simulation' level. The modelling level has the option to either work with a graphical or a text-based interface, where the text-based interface is used for writing new models, whereas the graphical interface is used for combining models in higher overarching models. The 'simulation' level displays the results from the simulated model, based on the set simulation conditions. The simulation itself is computed by a Microsoft Visual C Compiler, which compiles the created C-code based on the Modelica code within the Dymola environment. The applied solving method is the DASSL method or Differential Algebraic System Solver, by Petzold 1982. This method is a standard option in the Dymola simulation environment.

Model building basics

Constructing a thermal model of a complete residential building in Modelica requires modelling different physical processes and materials. To structure the model in a organised manner it is possible to save a piece of code as an separate model, here defined as a 'partial' model[6]. For example, one can create a partial model for thermal conduction and another partial model for thermal convection. These partial models are the parts or components that when connected form the the model for the total building. Partial models can be infinitely copied, linked together and placed inside other partial models. For the purpose of clarity the word 'model' will only be used for the total, representing the entire building.

To further structure the model it is possible to create a visual representation of the partial models, called an 'icon', see Appendix D.1. This helps to keep an overview in complicated models consisting of a lot of components. In addition, each component has its own name consisting of two parts. The first part refers to the partial model and the second part is to distinguish it from other copies of the same partial model (for example a partial model for thermal conduction to a composite material can

[6]Important to note is that in the Modelica language 'partial models' have a different meaning, this is however irrelevant here.

contain two other partial models called 'thermal conduction metal' and 'thermal conduction wood'). Finally all partial models can be distinguished in the following different types:

- Interfaces, which transmit information between partial models. These are often denoted by the name 'port', 'input' or 'output'.
- Sources, which are sources / inputs for calculations, for example a heat source that constantly emits a fixed amount of Watts.
- Other, which are all other components used in the calculations.

All of the information used for the calculations in the model is of one of the following three types, 'Real' (all real numbers), 'Integer' (only integer numbers, e.g. 0, 2, 6) or 'Boolean' (only 'true' or 'false'). Links between models are represented by lines between Interfaces. Links that contain 'Real' information are blue, 'Integer' links are orange and 'Boolean' links are pink.

The model tries to solve all equations by calculating the variables as specified by the programmer under the consideration of the provided starting conditions. Starting conditions need to be separately specified by initial equations or by fixed values, called parameters. Parameters are constants in the model.

For the purpose of the building simulation in Modelica a further distinction is made. All model components are separated into two types, those that form physical components of the building (e.g. walls, windows, floors, radiators etc.) and those that form components of the heating control system (e.g. actuators and sensors). For the first type the temperature of the component and the heat flow through the component is calculated by the model. In order to do this every component contains one or multiple 'heat ports', see section D.1 of the Appendix. These interfaces connect the several components and transmit both the heat flow variable (Q_flow) and the temperature variable (T). Important to note here is that no energy is lost and connecting ports always contain the same temperature, and the heat flow is conserved (that is if the heat flows out of one partial models' heat port the equal amount of heat flows into the connected partial models' heat port).

The model components of the heating control system transmit information between the different partial models by using ports of type Real, Integer or Boolean ports, see section D.1 of the Appendix.

4.3.2 TABULA data preparation

From the TABULA classification of all 19 SFHs as described in section 3.1.5 only three types are modelled in this research. These types are the following:

- SAH 1: built between 1860-1918
- SAH 2: built between 1984-1994
- SAH 3: built between 2002-2009

These three buildings do not represent all SFHs, however they span the whole range of the construction periods of German residential homes as used by the TABULA project, see Table 1 and 2. This is important since the building age is a main indicator for the energy consumption as described in section 3.1.4.

The TABULA data used as input for the RBM is listed for all three SAHs in appendix C.1, C.2 and C.3. This data contains the geometrical and thermal building properties of the three building types.

The construction type of the RBM for all SAHs are set as 'Medium', which corresponds to a brickwork construction. The heat capacities and the densities of the building elements are determined accordingly, as described in section 4.5.3.

4.4 Modelling scenarios

After creating these two building models, they are compared by simulating them under the same conditions. These conditions include, the climate boundary conditions for a typical year and the heat demand based on the user profiles of the inhabitants. By comparing these results, an energy saving potential for BAS retrofits in such a reference house can be determined.

For the BAS retrofits two main scenarios are created.

- Scenario 1: Includes the reduced set temperature during the day as regulated by the thermostat based on a time schedule as shown in Figure 27.
- Scenario 2: Models the effect of intermittent ventilation by the periodic opening of the windows according to the schedule as defined in Figure 23.

Firstly, the RBM is validated by comparing it to an existing Modelica model at the Hermann-Rietschel Institut (HRI) as created by M.Sc. Bahar Saeb-Gilani, research associate at the HRI, [72]. This model, which is based on the DIN V 18599 [25] calculation method, is depicted in Appendix D.4.

4.5 Building the residential building model

The model of the SFH represents the standard SFH as defined in the 'Background' of the thesis (see section 3). In this section a reference building is established based on this background. This reference building forms the basis of the modelling. An expansion on this reference building creates a building with BAS, their controllers and control algorithms. In this way two building models are created, one with and one without BAS. These steps are shown in the flowchart as given in Figure **??**.

The majority of the energy use in residential buildings can be allocated to the demand for space heating, as seen in section 3.2. Due to this, the main focus of this research is space heating. This section therefore treats only the calculation methods for calculating the energy consumption for space heating in buildings. Lighting and appliances are included in the calculations as sources of heat (i.e. internal heat gains), their energy consumption however is not calculated.

4.5.1 Reference residential building model

The reference building as created in Dymola is depicted in Figure 20 and consists of 66 partial models that are linked together to form a complete model of a residential building.

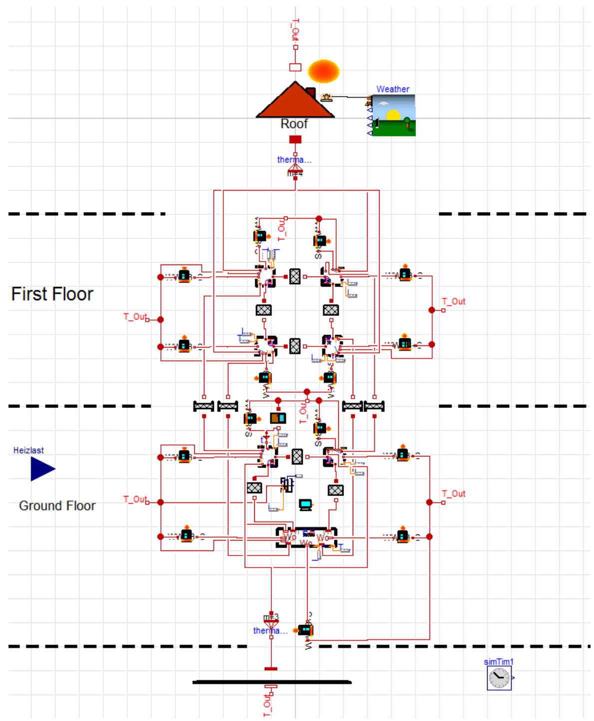


Figure 20: Model overview of a two storey residential building as created in Dymola. Screenshot of the final model, see also Appendix D.2.24 for an enlarged display.

Building Lay-out

The SFHs are modelled as two storey buildings with a square floor plan. The building data comes from the Tabula project as explained in section 4.3.2. The walls are oriented according to the four cardinal directions (north, east, south and west) and have all the same surface area[7]. The ground floor consists of one living room and two smaller rooms (which are both half the area of the living room) and the upper floor consists out of four equal rooms, see Figure 20 and D.2.24 to D.2.27 in the Appendix.

4.5.2 Assumptions and preconditions

Boiler type

In addition to the building stock data provided by the TABULA project, the three buildings need to be outfitted with a boiler for space heat production. As seen in section 3.2.2, low temperature boilers started being installed in the 1980s and condensing boilers in the 1990s, older building that have not replaced their boilers are still outfitted with constant temperature boilers. Roughly 50% of the SFHs built before 1978 fall in this category as 42% of these buildings have not modernised their heating system since the 1970s, [45]. Since constant temperature boilers are not suited for heating regulation systems they are left out as a reliable reference boiler in the model. The boiler as used in the RBM for the reference building SAH 1 is a low temperature boiler. A low temperature boiler is used because 39 % of the SFHs built before 1978 have modernised their heating systems in the period 1980-2000 (mainly low temperature boilers) and only 19 % since 2001 (mainly condensing boilers), [45].

SAH 2 falls in age category II of Table 2, of which 89% has installed or modernised its boiler in the period between 1980-2000, [45]. SAH 2 is therefore also modelled with a low temperature boiler.

[7] The surface area of the walls as provided by the Tabula project is equally devided over the four building faces

SAH 3 represents buildings built in the period between 2002-2009 and is modelled with the modern condensing boiler.

The used nominal feed-in and return temperatures of the boiler types in the RBM are given by Table 4 based on data provided by [37].

Boiler type	T_{feed}	T_{return}
Constant temperature boiler	90	70
Low temperature boiler	70	60
Condensing boiler	55	45

Table 4: T_{feed} and T_{return} temperatures under nominal conditions for a constant, low temperature and a condensing boiler in degrees Celsius. Based on data from [37].

Heat transmission system type and size

The chosen heat transmission system type in the RBM is a Type 11 compact heater with a height of 42 cm, which emits its heat by radiation (35 %) and convection (65 %), see Figure 21.

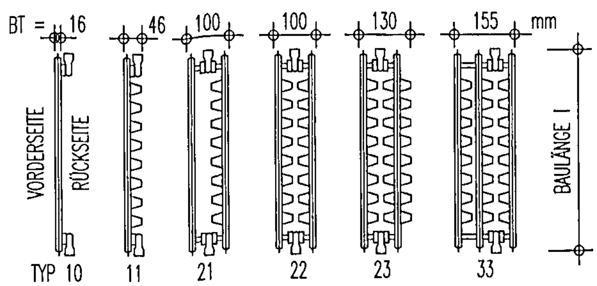


Figure 21: Different types of compact heaters. Type 11 is the chosen type in the RBM. Source: [66].

According to [66], this heater produces a nominal power of 725 W per meter of heater length (for T_m = 70 degrees Celsius, see equation 26). To correct for different feed and return temperatures, Table 14 of section 4.5.3 is used. The surface area of the heater can than be calculated by,

$$A_{heater} = \frac{\Phi_{trans,room}}{\Phi_{heater}} \cdot h_{heater} \ [\mathrm{m}^2]$$

with:

$\Phi_{trans,room}$ the required design load for the room according to equation 25 in Watt.

Φ_{heater} the nominal power of the Type 11 compact heater, 725 Watt.

h_{heater} the height of the Type 11 compact heater, 0.42 meter.

This area is used in the radiation exchange models as shown in Appendix D.2.13 and D.2.14.

User presence

The presence of the inhabitants in their home determines the demand for space heating, whether the residents regulate their heating system manually or by a thermostat. In the RBM the presence of the users is modelled by a simple step curve, see Figure 22. This curve describes when (all of) the residents are at home or not. Using one standard curve (that doesn't take into account different schedules, for instance, on weekend days or holidays) like the one depicted below is a simplification, as the presence of the residents in their home is in reality very irregular. However, it is similar to the 'Time Schedule' setting on most thermostats, see section 3.3.2.

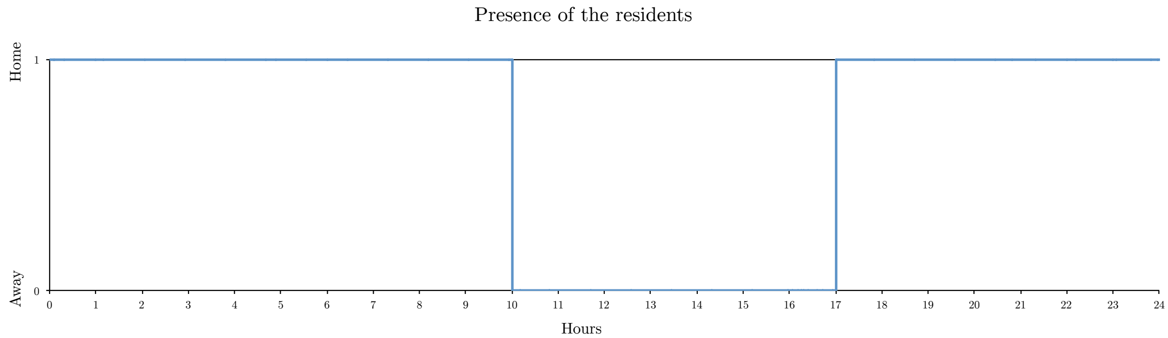


Figure 22: Presence of the residents over the course of an entire day. The presence of the residents influences the ventilation rate as well as the internal heat gains.

The demand for ventilation and the internal heat gains as described in section 4.5.3 are set to zero the moment the residents are not at home.

Window opening

In scenario 2 of the building modelling the effect of ventilation on the room temperature and the heating regulation by thermostat valves is investigated. In order to do so an assumption needs to be made on how often the windows are opened to ventilate. The energy losses as a result of opening a window are described in section 4.5.4. The duration of the opening of the window is based on the same minimum requirement for ventilation as set by the DIN V 18599-10, [26]. This is important to make the results comparable with scenario 1 (where a constant ventilation rate is assumed, see section 4.5.3). The minimum requirement for the air exchange is achieved by opening the windows for 5 minutes every hour, [66]. Scenario 2a models these 5 min openings for each hour the residents are at home and awake, whereas scenario 2b investigates the effect of a prolonged time of ventilation (30 min). It is important to note that the opening of the windows is assumed to be the same for every day in the year. In addition it is assumed that every room ventilates at the same time, but there is no air exchange between the rooms. Both scenarios are depicted in Figure 23.

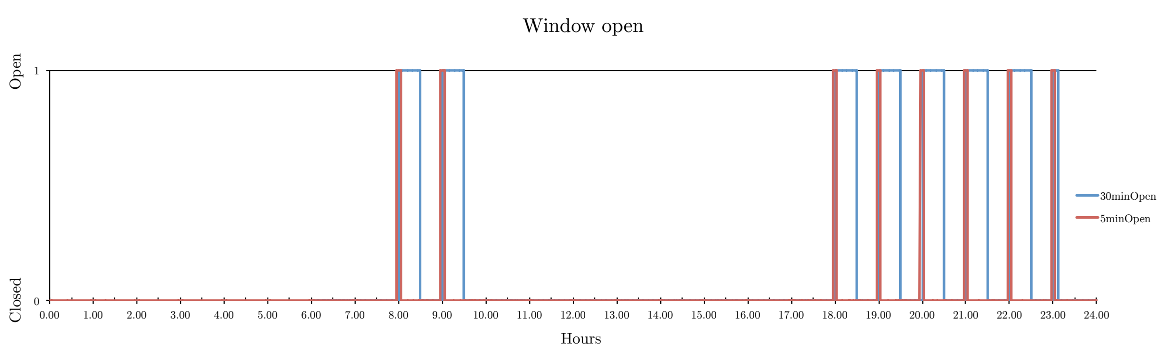


Figure 23: Window opening for scenario 2a (5 minutes open) and scenario 2b (30 minutes open).

4.5.3 Energy consumption calculation

The energy consumption for space heating as calculated in the residential building model is primarily based on the calculation method of the DIN V 18599 [25], however, the purpose of this calculation method is to determine the energy consumption on a yearly basis. This research focusses on the implementation of BAS in residential homes and in order to investigate its potential, it is necessary to determine the effect of the BAS on the internal temperature of the building. This requires a model that calculates the thermal behaviour of the building and its components on a real time basis. This enables the evaluation of the requirements on the comfort levels of the indoor climate, as well as whether the BAS regulates according to schedule. In order to do so, the calculations as described in the DIN V 18599 need to be adjusted. This section treats the physical calculations that form the core of the building model.

To structure the calculation a distinction is made between 'heat sinks' and 'heat sources', in accordance with DIN V 18599-1 [25]. A heat sink is a quantity of heat that exits the building and therefore increases the demand for heating where as a heat source is a quantity of heat that enters the building, reducing the demand for heating. The energy balance of a building is described by the following heat sinks (also defined as a 'loss' and indicated by a negative value) and heat sources (also defined as a 'gain' and indicated by a positive value):

- Heat sources (combined $Q_{source,tot}$):
  - Solar heat gains (opaque and transparent)
  - Internal heat gains
- Heat sinks (combined $Q_{sink,tot}$):
  - Transmission losses (including convection and thermal bridges)
  - Infiltration losses
  - Ventilation losses

The total demand for space heating $Q_{demand,tot}$ is then calculated by,

$$Q_{demand,tot} = Q_{sink,tot} - Q_{source,tot} \text{ [W]} \tag{3}$$

The calculations of the DIN V 18599 are expanded upon by including the following:

- Thermal storage
- Thermal radiation exchange
- Design heat load calculation based on the DIN EN 12831, [21].

Solar heat gains
The solar heat gains that benefit the building are the result of all absorbed solar radiation incidents on the building envelope. A distinction is made between transparent solar heat gains and opaque solar heat gains. Transparent solar heat gains are the heat gains resulting from the solar radiation that enters through the windows of the building. Opaque solar heat gains are the result of absorption of solar radiation by the opaque surfaces of the building envelope (i.e. the roof and all walls and doors).

Opaque solar heat gains

Section 6.4.2 of the DIN V 18599-2 [27] describes a simplified method for calculating the opaque solar heat gains of a building element i with cardinal direction j, see equation 4. This approach assumes that a fraction $\alpha$of the incident radiation (I_s) is absorbed by the outside building element. The amount that is not reemitted in the infrared or lost by convection will go through the building envelope by transmission (see equation 10).

$$\dot{Q}_{so,i} = R_{se} \cdot U_i \cdot A_i \left(\alpha \cdot I_{s,j} - h_r \cdot \Delta T_0\right) \text{ [W]} \tag{4}$$

with

R_{se} the heat transition coefficient of convection at the outside of the building element, see Table 6.

U_i the heat transfer coefficient of element i $[W/K \cdot m^2]$, see equation 11.

A_i the surface area of element i [m^2]

α the absorption coefficient of solar radiation is set to 0.6 according to Table 8 of the DIN V 18599-2 [27]. This standard value assumes a painted surface with a muted colour or 'gedeckter anstrich'. This conservative choice for αlies between that for a bright coloured ($\alpha = 0.4$) and a dark coloured ($\alpha = 0.8$) surface.

$I_{s,j}$ is the incoming solar radiation on the building element [W]. $I_{s,j}$ is dependent on the cardinal direction j (north, east, south or west) of the building element and whether the building element is aligned vertically or horizontally. This data is provided by the TRY04 data set, see section 4.2.1.

h_r the outer remittance coefficient for infrared radiation, which is defined as $h_r = 5 {\cdot} \epsilon$ [W/K $\cdot$ m^2]. With ϵ the emissivity of the building element, which is dependent on the type of material and the surface roughness. For the sake of simplicity $\epsilon = 0.9$ for all the building materials.

ΔT_0 the average difference between the temperature of the outdoor air and the so called sky temperature, set to 10 K by the DIN V 18599-2 [27].

In the RBM are the opaque solar heat gains modelled for each outward facing building element (i.e. walls and roofs), see partial models in Appendix D.2.4 and D.2.5.

Transparent solar heat gains

The calculation method for transparent solar heat gains in the model is based on the calculation as described in section 6.4.2 of the DIN V 18599-2 [27]. This method calculates the transparent solar heat gains in a room/zone as follows,

$$\dot{Q}_{sTra,tot} = \dot{Q}_{sTra,N} + \dot{Q}_{sTra,E} + \dot{Q}_{sTra,S} + \dot{Q}_{sTra,W} \text{ [W]} \tag{5}$$

This distinction per cardinal direction is necessary since the incident solar radiation [W] varies for each direction[8]. For each direction j the following equation holds,

$$\dot{Q}_{sTra,j} = F_f \cdot A_j \cdot g_{eff} \cdot I_{s,j} \text{ [W]} \tag{6}$$

with

F_f reduction factor for the window frame $F_f = 0.7$, which is assumed independent of the building.

[8] All windows in the model are located in the walls of the building, windows in the roof are neglected

A_j the combined surface area of all windows in the room/zone with cardinal direction j [m^2].

g_{eff} the effective solar energy transmission factor, see equation 7.

$I_{s,j}$ is the incoming solar radiation with direction j [W].

$$g_{eff} = F_w \cdot F_v \cdot F_s \cdot g = 0.81 \cdot g \tag{7}$$

with

F_w reduction factor for non-perpendicular incident radiation $F_w = 0.9$, as set in the DIN V 18599-2 [27]. F_w is assumed to be independent of the building.

F_v reduction factor for dirt on the window surface $F_v = 1$, as set in the DIN V 18599-10 [26]. F_v is assumed here to be independent of the building.

F_s reduction factor for shading $F_s = 0.9$, as set in the DIN V 18599-2 [27]. F_s is assumed here to be independent of the building.

g solar energy transmission factor of the window. This factor is dependent on the thickness of the glass, the number of panes, and optional sun shades. g is dependent of the building and one of the input values of the model that are obtained from the TABULA data, see section 4.3.2.

In the residential building model it is necessary to allocate these solar heat gains to a particular building element (in contrast to the method of the DIN V 18599-2 [27] which just models the yearly average). The total solar radiation incoming through the windows $\dot{Q}_{sTra,tot}$ is assumed to be absorbed by the floor of the room/zone in question (as depicted in Appendix D.2.18 and D.2.18) according to the following formula,

$$Q_{s,floor} = \alpha \cdot \dot{Q}_{sTra,tot} \text{ [W]} \tag{8}$$

with α the absorption coefficient of the floor surface. $\alpha = 0.95$, the assumption made here is that nearly all solar radiation is absorbed by the floor and only 5 % is lost due to reflection. In reality the solar radiation would be absorbed and reflected by not only the floor but also the walls and ceiling, and a small part would eventually leave back through the windows.

Internal heat gains

The internal heat gains in a building/zone are defined as thermal heat sources as a result of the presence of humans and animals as well as the heat production of electronic devices and lighting. The DIN V 18599-2 [27] simplifies the heat gain caused by residents, lighting and machinery for residential homes to an average value that only depends on the surface area of the building,

$$Q_I = q_I \cdot A \text{ [W]} \tag{9}$$

with:

q_i the average heat source per square meter as defined in Table 4 of DIN V 18599-10 [26] is: $q_I = 45$ [Wh/m^2 $\cdot$ day] for SFHs. Which is equal to $q_I = 1.875$ [W/m^2].

A the floor area of the building.

In the model these internal heat sources are calculated per room and based on the presence of the inhabitants[9], see section 4.5.2 and the partial model in Appendix D.2.12.

[9]The assumption here is that no machinery or electronic devices are running when the habitants are not at home. Which might be true for tv's, computers and lighting but not for refrigerators

Transmission losses
Transmission losses are defined as all heat flows that exit the building through transmission over the building envelope. Where the heat flow through each building envelope element i is defined as:

$$\dot{Q}_i = A_i \cdot U_{eff,i} \cdot F_{x,i} \cdot \Delta T \text{ [W]} \tag{10}$$

with:

A_i the surface area of element i [m^2]

$U_{eff,i}$ the overall heat transfer coefficient of element i [$W/K \cdot m^2$], as defined in DIN EN ISO 6946 [34] and equation 11.

$F_{x,i}$ the temperature correction factor of element i [-], see Table 5 based on Table 5 of the DIN 18599-2 [27].[10]

ΔT the temperature difference [K] between the outside and the inside of the envelope element.

$$U_{eff} = \frac{1}{\frac{1}{U} - R_{se} - R_{si}} \text{ [W/K} \cdot \text{m}^2\text{]} \tag{11}$$

where U is the heat transfer coefficient of the element itself and R_{se} is the heat transition coefficient of convection at the outside of the building element and R_{si} the heat transition coefficient of convection at the inside of the building element. Table 6 shows the used values of R_{se} and R_{si} in the model based on Table 9 of the DIN EN ISO 6946 [34].

Building Element	F_x	Comments
Outside facing walls	1	
Outside facing doors and windows	1	
Roofs	1	
Internal walls or ceilings	1	Heat loss between rooms/zones is explicitly modelled.
Ground floor	0.5	Table 5 of the DIN V 18599-2, [27], see footnote below.
Walls facing a heated building	0	THs do not lose any heat to the other adjacent THs.

Table 5: Temperature correction factor (F_x) of the different building elements as used in the model.

Heat transition coefficient	Direction of the heat flow		
[$m^2 \cdot K/W$]	Upwards	Horizontal	Downwards
R_{si} (inside the building)	0.10	0.13	0.17
R_{se} (outside the building)	0.04	0.04	0.04

Table 6: Heat transition coefficients of convection for different building elements as used in the model.

Convection
It is important to note that the heat losses due to convection are separately modelled by the convection partial model, see Figure 24. This partial model calculates the energy losses due to convection at the building elements surface, based on its area A and the heat transition coefficient of convection, see Table 6.

[10] Table 5 of the DIN V 18599-2 gives a building specific calculation for the F_x-value of the Ground floor, in this research a constant value is assumed, independent of the building size.

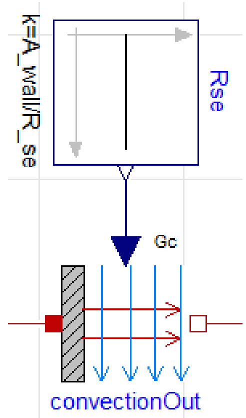


Figure 24: Partial model for convection. With the red 'heat port' connected to the building element and the white 'heat port' connected to the (outside) air. Source: Modelica Standard Library, [60].

This means that the thermal transmission losses are calculated by separating the thermal conduction through the building element from the the convection at the surface. All thermal conduction losses are calculated per building element by partial models for doors, windows, walls, floors/ceilings and roofs (see Appendix D.2.7, D.2.2, D.2.1, D.2.8, D.2.9, D.2.6 and D.2.5). Convection at the inside of the building element is modelled by adding the convection partial model to the room/zone partial model. Convection at the outside of the building element is calculated by adding the convection partial model to the thermal conduction partial model in the building element partial models. This however means that the overall heat transfer coefficient (U_{eff}) as given by the Tabula project needs to be broken down into the U, R_{se} and R_{si}. The partial model 'U-wert correction' (Appendix D.2.30) calculates the U for the use in the thermal conduction partial models by using equation 11.

Thermal bridges

Thermal bridges or 'Warmebrücken' are heat losses occurring at the intersection of different building materials, for instance, a roof and a wall or a window and a wall. These additional heat losses depend on the method for connecting these materials, [20]. The additional transmission losses (of element i) caused by thermal bridging are determined by,

$$\dot{Q}_{WB} = A_i \cdot U_{WB,i} \cdot F_{x,i} \cdot \Delta T \text{ [W]} \tag{12}$$

with $U_{WB,i}$ the surcharge heat transfer coefficient for thermal bridges. This coefficients vary per element and connecting method and should be determined by measurements on the house in question. However, the DIN V 18599-2 [27] states that when no measurement data is available one is allowed to use the standard value of $U_{WB} = 0.1$ [W/m$^2 \cdot$ K]. In this research the value for U_{WB} is given by the TABULA data depending on the house type, see section 4.3.2. The thermal bridges partial model is depicted in Appendix D.2.3.

Infiltration losses

No building is completely air tight, as they all contain small gaps and holes in and between the different building materials. Warm indoor air flows through these gaps and holes resulting in thermal losses, called infiltration losses. These losses are determined per room based on its volume (V) and the hourly average air exchange rate caused by infiltration (n_{inf}).

$$\dot{Q}_{inf} = \frac{n_{inf}}{3600} \cdot V \cdot c_{p,air} \cdot \rho_{air} \cdot \Delta T \text{ [W]} \tag{13}$$

with:

$c_{p,air}$ the specific heat capacity of air, 1008 $J/kg \cdot K$.

ρ_{air} the density of air[11], 1.23 kg/m^3.

ΔT the temperature difference $[K]$ between the outside and the inside of the envelope.

According to the DIN V 18599-2 [27] n_{inf} is determined by,

$$n_{inf} = n_{50} \cdot e \cdot f_{ATD} \; [\mathrm{h}^{-1}] \tag{14}$$

with:

n_{50} the air exchange rate at a pressure difference of 50 Pa. This measure of the airtightness of the building can be determined by experimenting (with the so called 'blower door' method) or less accurately by applying standard values from Table 6 of the DIN V 18599-2, [27]. In this research the air exchange rate is set to $n_{50} = 2$ [h^{-1}]. Which follows from Table 6 of the DIN V 18599-2 [27] for buildings with a volume of less than 1500 m^3.

e is the volume flow coefficient, which depends on the wind exposure of the building. The standard value of $e = 0.07$ from DIN V 18599-2 [27] is applied here.

f_{ATD} takes the presence of air transfer devices into account. Based on the DIN V 18599-2 [27] $f_{ATD} = 1.75$.

This results in an overall value of $n_{inf} = 0.245$ [h^{-1}]. Assumed here is that the rate of air exchange through infiltration is constant, and the resulting thermal losses are therefore only dependent on ΔT. Infiltration losses are modelled in the partial model as depicted in Appendix D.2.10

Ventilation losses

Ventilation losses are caused by the air exchange between the inside of the building/zone and the buildings exterior. Thermal ventilation losses can either be the result of manual ventilation or mechanical ventilation. Mechanical ventilation systems are not part of the scope of this research and are therefore not included in the model. All residential buildings as simulated in the model obtain the minimum requirement for ventilation by manual ventilation (over windows and doors). Refreshment of the indoor air is a prerequisite for comfortable living. Ventilation keeps the content of moisture, $CO_2$and O_2 in the air at acceptable levels, reduces odors, and prevents the formation of moulds, [66]. The DIN V 18599-10 [26] defines a minimum outside air exchange for residential homes as $n_{nutz} = 0.5$ h^{-1}. Meaning, that the complete indoor air volume of the building needs to be exchanged every 2 hours (when the inhabitants are at home).

Manual ventilation losses of a room/zone of volume (V) are calculated as follows,

$$\dot{Q}_{vent} = \frac{n_{win,mth}}{3600} \cdot V \cdot c_{p,air} \cdot \rho_{air} \cdot \Delta T \; [\mathrm{W}] \tag{15}$$

with:

$n_{win,mth}$ the monthly changing hourly air exchange rate [h^{-1}] over the windows according to equation 16 based on DIN V 18599-2 [27].

$c_{p,air}$ the specific heat capacity of air, 1008 $J/kg \cdot K$.

ρ_{air} the density of air, 1.23 kg/m^3.

ΔT the temperature difference $[K]$ between the outside and the inside of the envelope.

$$n_{win,mth} = n_{win} \cdot f_{win,season} \; [\mathrm{h}^{-1}] \tag{16}$$

with:

[11] Both the specific heat capacity and the density of air are constants within the model. Which is justified by the fact that the pressure and temperature differences in housing are small enough to assume that the properties of air are independent of temperature and pressure.

n_{win} the hourly air exchange rate [h^{-1}] over the windows according to equation 18.

$f_{win,season}$ a factor that adjusts for the seasonal effect on window ventilation. Here it is assumed that inhabitants will open their windows less when the outside temperature drops.

According to DIN V 18599-2 [27] $f_{win,seasonal}$ and n_{win} become,

$$f_{win,seasonal} = 0.04 \cdot T_{outside} + 0.8 \tag{17}$$

$$n_{win} = \max[0; n_{nutz} - (n_{nutz} - 0.2) \cdot n_{inf} - 0.1] \approx 0.33 \text{ [h}^{-1}]] \tag{18}$$

with

n_{nutz} the minimum outside air exchange for residential homes as defined above: $n_{nutz} = 0.5$ h^{-1}.

n_{inf} the air exchange rate through infiltration as defined above: $n_{inf} = 0.245$ [h^{-1}].

The calculation of the ventilation losses as described above according to equation 15 describe a constant ventilation rate over the time that the inhabitants are home. Meaning that the windows are always partly opened to obtain the minimum requirement of air exchange as defined in the DIN V 18599-10 [26]. In practice, however, the ventilation rate is all but constant. Windows are often opened for a short period of time, but the air exchange at that instant is significantly greater. Air exchange rates for completely open windows range from $9 - 15$ [h^{-1}], [66].

The simplification of a constant ventilation rate has little impact when studying the total energy losses over the course of a year. However, it does not model the effect of room ventilation on the indoor temperature accurately, as a constant low ventilation rate would not affect the indoor temperature. In reality one suspects that the room temperature is affected by an opened window (especially in winter). This effect is studied in scenario 2 of the BAS (see section 5.1.2) and the equations as described above are edited accordingly in the model.

The partial models for ventilation are shown in Appendix D.2.10 (for constant ventilation) and D.3.3 (for intermittent ventilation).

Thermal storage

The thermal storage capacity of the building elements is modelled by the heat capacitor partial model from the Modelica Standard Library. This partial model has been edited such that it has a variable thermal capacity value (C), see Figure 25. This addition makes it possible to change the thermal capacity of the building elements based on whether the building is considered 'light', 'medium' or 'heavy', see below. The thermal capacity (C) of element i is determined by,

$$C_i = c_{p,i} \cdot \rho_i \cdot d_i \cdot A_i \text{ [J/K]} \tag{19}$$

with:

$c_{p,i}$ the average specific heat capacity of the material of element i $[J/kg \cdot K]$.

ρ_i the average density of the building element i $[kg/m^3]$.

d_i the thickness of the building element i $[m]$.

A_i the area of the building element i $[m^2]$.

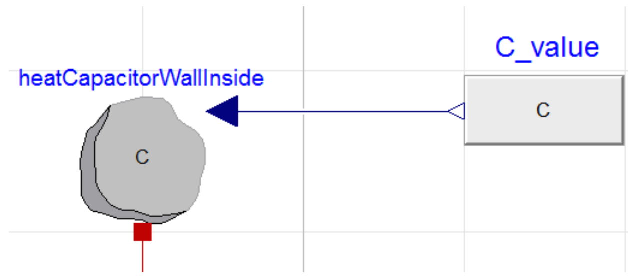


Figure 25: Partial model for thermal storage with variable thermal capacity C as given by equation 18. The red 'heat port' is connected to the storage element (either a building element or the air of the room). Source: Modelica Standard Library, [60].

The building element characteristics are listed in the tables below (Tables 7 through 13). The thickness of the building element (for example an outside wall) does not necessarily correspond to the thickness of the actual physical wall. A wall consists of multiple layers of different materials, with their respective specific heat capacity and density. The thickness, average density and average specific heat capacity as used here are only referring to the layers that reside within the insulation of the building. This approach is justified because the goal of the calculation is to determine the thermal storage capacity of the building. Building element layers that reside outside of the insulation will not contribute to the thermal storage as shown in Figure 26. The heat capacitor partial model is for this reason placed at the inside of the thermal conductor in all the respective partial models.

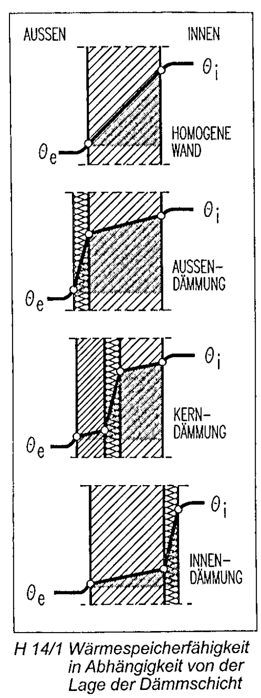


Figure 26: Temperature over the course of the building element (in this case a wall.) dependent on the location of the insulation. Source: [66].

Wall (Outside)	Characteristics		
Construction type:	Light	Medium	Heavy
Density, ρ $[kg/m^3]$	650	1800	2300
Specific heat capacity, c_p $[J/kg \cdot K]$	1425	1000	1000
Thickness, d $[m]$	0.1		

Table 7: Input values for an outside wall in the model

Wall (inside)	Characteristics		
Construction type:	Light	Medium	Heavy
Density, ρ $[kg/m^3]$	650	1800	2300
Specific heat capacity, c_p $[J/kg \cdot K]$	1425	1000	1000
Thickness, d $[m]$	0.1		

Table 8: Input values for an internal wall in the model

Ceiling	Characteristics		
Construction type:	Light	Medium	Heavy
Density, ρ $[kg/m^3]$	720	1800	2300
Specific heat capacity, c_p $[J/kg \cdot K]$	1600	1000	1000
Thickness, d $[m]$	0.1		

Table 9: Input values for a ceiling in the model

Roof	Characteristics		
Construction type:	Light	Medium	Heavy
Density, ρ $[kg/m^3]$	720	1800	2300
Specific heat capacity, c_p $[J/kg \cdot K]$	1600	1000	1000
Thickness, d $[m]$	0.1		

Table 10: Input values for a Roof in the model

Ground floor	Characteristics
Construction type:	All types
Density, ρ $[kg/m^3]$	1800
Specific heat capacity, c_p $[J/kg \cdot K]$	1000
Thickness, d $[m]$	0.04

Table 11: Input values of the Ground floor in the model

Door	Characteristics
Construction type:	All types
Density, ρ $[kg/m^3]$	500
Specific heat capacity, c_p $[J/kg \cdot K]$	1600
Thickness, d $[m]$	0.05

Table 12: Input values for a door in the model

Window	Characteristics
Construction type:	All types
Density, ρ $[kg/m^3]$	750
Specific heat capacity, c_p $[J/kg \cdot K]$	2500
Thickness, d $[m]$	0.02

Table 13: Input values for a window in the model

Thermal radiation exchange
The RBM, as described until now, only treats heat transfer through convection and transmission. The partial model 'RadExchange' treats the thermal radiation within each zone/room. To simplify the calculation the model assumes that all thermal radiation is radiated to the opposite surface (i.e. the north wall only radiates towards the south wall and vice versa just as the ceiling only radiates towards the floor) and is not inhibited by any objects in the room/zone. Radiation exchange with the windows is neglected, as they do not constitute a significant area of the wall and moreover have a reduced transmittance in the infrared band of the electromagnetic spectrum for radiation, [62]. Based on the law of Stefan-Boltzmann the emitted thermal radiation of surface element i is,

$$\dot{Q}_i = A_i \cdot \alpha_i \cdot \sigma \cdot T_i^4 + (1 - \alpha_i) \cdot \dot{Q}_{in} \text{ [W]} \tag{20}$$

with

A_i the area of surface element i $[m^2]$.

α_i the infrared absorptivity of surface element i [-], $\alpha = 0.8$ is assumed constant for all surface types.

σ the Stefan-Boltzmann constant, $\sigma \approx 5.67 \times 10^{-8}$ $[W/m^2 \cdot K^4]$.

T_i the temperature of surface element i $[K]$.

Q_{in} the incoming infrared radiation on surface element i [W]. The factor $(1 - \alpha_i)$ represents the reflected amount of the incoming radiation[12].

The partial model as used is based on the Radiosity partial model from the Modelica Buildings Library [51] and is depicted in Appendix D.2.13 and D.2.14.

Design heat load
The design heat load of the heating system is calculated based on the DIN EN 12831, [21]. This method calculates the energy demand under extreme circumstances (extreme cold), which in turn forms the basis for the design heat load of the to be installed heating system of the building.

$$Q_{norm,tot} = Q_T + Q_V + Q_{RH} \text{ [W]} \tag{21}$$

with

Q_T the norm transmission losses [W], according to equation 22.

Q_V the norm ventilation losses [W], according to equation 23.

Q_{RH} the norm demand for reheating a building in the case of intermittent operation of the heating system [W], according to equation 24 .

[12] All radiation is assumed to be either absorbed or reflected, no radiation is transmitted trough the surface element as all elements (walls, ceilings and floors) are opaque.

$$Q_T = \sum_i Q_{T,i} = \sum_i A_i \cdot U_{eff,i} \cdot F_{x,i} \cdot \Delta T_{norm} \text{ [W]} \tag{22}$$

with

A_i the surface area of element i [m^2].

$U_{eff,i}$ the overall heat transfer coefficient of element i $[W/K \cdot m^2]$, as defined in DIN EN ISO 6946 [34] and equation 11.

$F_{x,i}$ the temperature correction factor of element i [-], see Table 5 based on Table 5 of the DIN 18599-2 [27].

ΔT_{norm} the norm temperature difference $[K]$ between the outside and the inside of the envelope element under extreme circumstances[13]. The reference location for Germany is Potsdam, which has a norm outside temperature of -14 C, [66]. The norm inside temperature is set to 20C. $\Delta T_{norm} = T_{norm,inside} - T_{norm,outside} = 293.15 - 259.15 = 34$ [K].

$$Q_V = 0.34 \cdot V_{min} \cdot \Delta T_{norm} \text{ [W]} \tag{23}$$

with

V_{min} the minimum hourly air exchange $[m^3/h]$ $V_{min} = n \cdot V$ [m^3/h], with $n = 0.5$ [h^{-1}] and V the buildings interior volume.

$$Q_{RH} = A \cdot f_{RH} \text{ [W]} \tag{24}$$

with

A the living area of the building $[m^2]$.

f_{RH} the reheat factor as obtained from the page 34 of [66] is set to $f_{RH} = 34$ [Q/m^2] for light buildings and to $f_{RH} = 10$ [Q/m^2] for medium and heavy buildings[14].

It is important to note here that this calculation ignores any thermal heat gains by the sun or internal heat sources, which is contradictory to the energy demand calculation of the DIN V 18599, [25]. This simplification results in a high design load, that in theory leads to the installment of a heating system with over capacity. The design heat load calculation is included in partial model 'U-value correction' as shown in Appendix D.2.30.

Design load transmission system

The design heat load for the heating system is used as basis for the calculation for the size of the heat transmission system (e.g. radiator or convector) in the respective rooms. In this research the design heat load is divided over the rooms based on the room area, however the DIN EN 12831, [21] also states that the design heat load can first be calculated explicitly for each room and then added to obtain the buildings total.

The design load or nominal load is calculated based on the DIN EN 442 [33] which states that,

$$\Phi_{trans,room} = \frac{Q_{norm,room}}{f_1} \text{ [W]} \tag{25}$$

with:

[13] More specifically, is the norm outside temperature defined as the lowest 2-day average air temperature that has been measured 10 times in the the last 20 years, [66].

[14] [66] states that the values are taken from the DIN EN 12 831 [21], however, consultation of this norm has shown other values. Which will be discussed in the discussion, section 5.1.3.

$\Phi_{trans,room}$ the design/nominal heat load for the transmission system of the respective room.

$Q_{norm,room}$ the design heat load for the room, based on equation 21 and the number and area of the rooms in the building.

f_1 correction factor for the type of transmission system. As seen in section 3.2.2 the emitted heat of the transmission system depends on the feed-in temperature. f_1 corrects for this effect and follows from Table provided by [66].

T_m	f_1
$T_m = 80$	1.27
$T_m = 65$	0.87
$T_m = 55$	0.51

Table 14: Correction factor f_1 as a function of T_m. Source: [66].

with T_m the average hot water temperature of the transmission system in ºC, where

$$T_m = \frac{T_{feed} + T_{return}}{2} \tag{26}$$

with:

T_{feed} is the nominal/design feed temperature of the heat production system.

T_{return} is the nominal/design return temperature of the heat production system.

See Table 4 in section 4.5.2 for the assumed values in the RBM.

4.5.4 Model components

The reference residential building model (RBM) consists of 25 different partial models linked to separate building elements. These partial models contain one or more of the calculations as described in the last section. A complete list of all partial models and their references to the appendix where the partial models are depicted is shown below.

- Wall Outside (D.2.1)
- Window (D.2.2)
- Thermal bridges (D.2.3)
- Outside wall combined (called WWHB) (D.2.4)
- Roof (D.2.5)
- Floor (D.2.6)
- Door (D.2.7)
- Wall Inside (D.2.8)
- Ceiling (D.2.9)
- Infiltration (D.2.10)
- Ventilation (D.2.10)
- Infiltration & ventilation (D.2.11)
- Internal Heat gains (D.2.12)
- Radiation exchange (D.2.13, D.2.14)
- Heat production system (D.2.15)
- Heat transmission system (D.2.16)
- Indoor air (D.2.17)
- Combined zone model (small) (D.2.18)
- Combined zone model (big) (D.2.18)
- Outside temperature (D.2.19)
- Heat curve (D.2.20)
- Feed-in temperature regulation (D.2.21)
- Efficiency curves (D.2.22)
- Heat production system combined (D.2.23)

Zone partial models
The partial models are either included in one of the two 'zone partial models' (the small zone: D.2.18 and the big zone: D.2.18) or are added separately to the complete RBM. The zone partial models include the following partial models:

- Transparent solar heat gains
- Internal heat gains
- Heat transmission system
- Thermal radiation exchange
- Indoor air
- Temperature sensor (for the room temperature)
- Infiltration & ventilation
- Partial model for thermal convection

Heat production & Heat transmission system
The heat production system partial model and the heat transmission system partial model together form the heating system in the RBM. They include: the production of hot water based on the provided feed-temperature setting, the transportation of the water towards the heat transmission system, the thermostat valve and the heat transmission system itself. The heat production system partial model is based on the DIN EN 442 [33], which describes the heat transmission for radiators and convectors based on their nominal feed-in and return temperature settings and the actual values (see assumptions in section 4.5.2). This partial model has been provided by the Modelica Buildings Library [51], it simulates a radiator that delivers the heat to the room through radiation and convection. Both partial models are depicted in Appendix D.2.15 and D.2.16.

Total RBM

The RBM consists of 6 small zones and 1 big zone, which are coded as follows:

Ground floor:

- Zone_GF_1
- Zone_GF_2B (big zone)
- Zone_GF_3

First floor:

- Zone_1F_1
- Zone_1F_2
- Zone_1F_3
- Zone_1F_4

The location of the zones/rooms with respect to each other are as follows,

Zone_1F_4	Zone_1F_1
Zone_1F_3	Zone_1F_2

Zone_GF_3	Zone_GF_1
Zone_GF_2B	

Interior walls are coded by 'Wi' for wall interior, 'GF' (ground floor) or '1F' (first floor) for the storey, and by '12', '23', '34' and '14' for the location of the interior wall (i.e. between which zones). For example: Wi_1F_14, which is the interior wall on the first floor between zone 1 and 4.

Ceilings are coded for example like: Ceiling_GF_1F_22, which is the ceiling between the ground floor and the first floor between ground floor zone 2 and first floor zone 2 [15].

All combined wall models (WWHB) are coded by 'W' for Wall, 'GF' or '1F' for the storey, '1' to '4' for the corresponding zone and 'N', 'E', 'S' or 'W' for the direction the wall faces. For example: W_GF_2_E, which is the eastbound outside wall of the second zone on the ground floor.

The model contains only one door which is situated at the north side of the building.

In addition to the building elements mentioned above, the total RBM includes the following other partial models.

Heating curve & feed-in temperature regulation

The heating curve partial model (or 'Heizkurve') sets the feed-in temperature for the heating system based on the boiler type (i.e. constant, low temperature or condensing boiler), the set temperature of the room (either 16, 18, 20 or 22) and the outside temperature. The resulting feed-in temperature is produced by equation 1 from [37]. The heating curve partial model is shown in Appendix D.2.20. It is combined with an outside temperature source and sensor in the 'Feed-in temperature regulation' partial model see Appendix D.2.21.

Efficiency curve

The efficiency curve partial model (or 'Heizungskennlinie') provides the efficiency of the boiler (i.e. constant, low temperature or condensing boiler) as a function of the load. The partial model is depicted in Appendix D.2.22 and is based on the data from Figure 11 by [66].

Combined heat production system

The combined heat production system partial model, combines the feed-in temperature regulation with the 'efficiency curve' partial model. It delivers the feed-temperature and uses the model to calculate the net energy consumption or primary energy consumption of the heating system. It is depicted in Appendix D.2.23.

4.5.5 Building automation retrofits

Components that are not included in the reference model or components that are adjusted when modelling the building with BAS (in scenario 1 or 2) are described below.

Thermostat

The thermostat partial model (see the depiction in Appendix D.3.1) delivers an Integer output that transfers the information for both the set value of the room temperature as well as the presence of the inhabitants. The presence of the residence is modelled according to the step function as depicted in Figure 22 of section 4.5.2. This model is identical for both the reference case and the RBM with BAS.

The set temperature is modelled according to the step functions as depicted in Figure 27 below. Where the reference case assumes a set temperature of 20 ºC during the day (between 6.00 and 23.00), and a night set back temperature of 16 ºC, which is considered standard for night cooling according to Table 4 of the DIN V 18599-10, [26]. In scenario 1 of the BAS modelling an additional reduced temperature during the day is implemented, which sets the thermostat at 16 ºC between the times of 10.00. and 17.00, when the residents are assumed to be away (e.g. at work). It is important to note here that the thermostat settings are used for all days in the year, disregarding weekends and holidays.

[15] The area of the ceiling of the big zone is divided by two and connected to two separate ceiling models

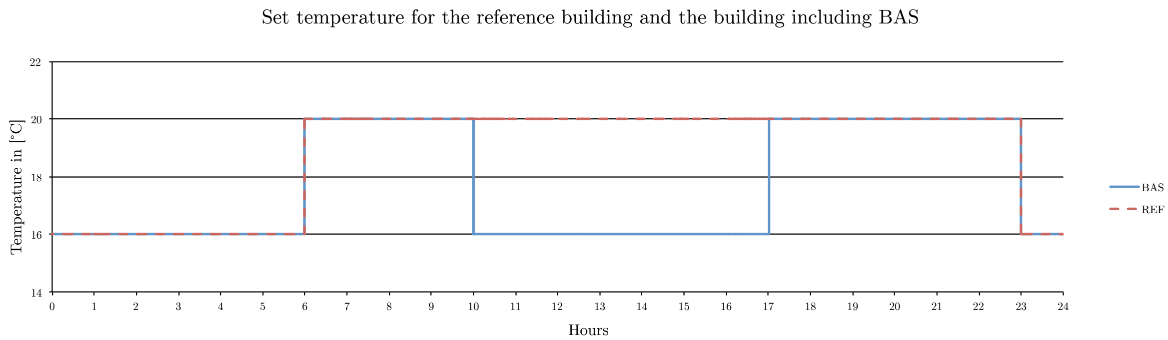


Figure 27: Daily set temperature settings for the indoor room temperature as used in the reference model and the building model including BAS (scenario 1).

Intermittent ventilation
The Intermittent ventilation as modelled in scenario 2 of the building modelling is the result of the opening of the windows at pre-described times for a set duration, see section D.3.2. The partial model covering the opening of the windows is shown in Appendix D.3.2. This in turn affects the previously created models for ventilation, the adapted versions are shown in Appendix D.3.3 and D.3.4.

Thermostat valve
In scenario 2 the BAS regulates the thermostat valve based on the opened windows. That is, when the window is opened the thermostat valve is automatically closed. This addition to the thermostat valve regulation of the reference model results in adaptation of the partial models for the heat production system, the heat transmission system, and the zone partial model. All of these are shown in Appendix D.2.23, D.2.16 and D.3.6 respectively.

4.6 Analysis of the model results

The analysis of the model results is described in section 5. It entails both the results from the reference building, the model validation as well as the results from the modelling of both the BAS scenarios.

4.6.1 Reference building & model validation

In order to determine whether the created RBM results are of any value, and whether the RBM accurately represents an existing building, the model needs to be validated. This validation is performed by comparing the RBM with the Modelica model as created at the HRI, [72]. The value compared between the two models is the annual demand for space heating for the reference building, over the course of the heating period. Since both the RBM and the HRI model are based on the calculation method as described in the DIN V 18599 [25] the results should be of the same order. Investigating the differences between the models gives an indication on the accuracy of the modelling method of the RBM. Further validation of the results are performed by comparing the final energy consumption of the reference case to actually measured values as provided by literature.

4.6.2 Building automation retrofits

The results of the RBM including BAS are described in section 5.1.2 and are treated per BAS scenario.

Scenario 1 For scenario 1, the annual demand for space heating and the resulting final energy consumption form the main results. These results are compared to the reference case as modelled under the same conditions. In addition to this an analysis of the room temperature has been performed.

Room temperature analysis As described in section 3.3.3 it is important that the thermal comfort of the residents is guaranteed. This means that the implementation of a heating regulation system (i.e. night cooling or time schedule) can only function well if the set temperatures are achieved under all circumstances. In order to investigate whether this is the case in scenario 1 of the BAS retrofit, a room temperature analysis is performed. This analysis models SAH 1 for the coldest week of the year, to see whether the heating system has the correct design load (see equation 21) to ensure the indoor room temperature keeps the set temperatures.

Scenario 2 Scenario 2a, which models the opening of the windows for a duration of five minutes, includes an similar analysis of the room temperature and a calculation of the final energy consumption. Scenario 2b and the scenarios 1 and 2 combined investigate the room temperature only.

4.7 Primary energy savings & CO_2 emission reductions

From the modelled annual final energy savings in section 4.6.2 it is possible to deduce the primary energy savings and CO_2emission reductions. This is applied to scenario 1 of the BAS retrofits. The method for obtaining these results are described below, the results are discussed in section 5.2.

Through the use of the data on the German residential building stock provided by the TABULA research [47], it is possible to extend the building specific results, to the German building stock. This is discussed in the section 4.7.3 below.

4.7.1 Primary energy consumption

Primary energy consumption is defined as the energy consumption of primary energy carriers (or natural resources) that have not undergone any (energy intensive) transforming processes, [39]. This means that even though natural gas and heating oil are primary energy carries, the final energy as consumed at home is not equal to the primary energy consumption. This is due to the fact that the natural gas and heating oil are transformed products of the original raw fossil resources. The EnEV 2014 states that the primary energy factors for both heating oil and natural gas are 1.1, [12]. The primary energy consumption is then,

$$E_p = 1.1 \cdot E_f \text{ [kWh/a]} \tag{27}$$

with E_f the annual final energy consumption of the home in question [kWh/a].

4.7.2 From energy to CO_2emissions

In addition to the primary energy consumption the amount of CO_2emissions is calculated as an indicator for the sustainability of the building. Under the EnEV 2014 it is voluntarily presented on the energy label of the house, [12]. Furthermore, the CO_2 emissions are of interest for German policy makers in the assessment of the energy saving policies, as seen in section 3.1.3. The annual CO_2 emissions of a building as a result of space heating are calculated based on the primary energy consumption as stated by the EnEV 2014, [12]. The reduced annual CO_2 emissions [kg/a] due to the implementation of the scenario 1 BAS retrofits become,

$$CO_{2,saved} = F_{emission} \cdot E_{p,saved}/1000 \text{ [kg/a]} \tag{28}$$

with $E_{p,saved}$ the annual saved primary energy consumption [kWh/a] and $F_{emission}$ the emission factor of the used fuel [g/kWh], where the $F_{emission}$ for natural gas is $F_{gas} = 200$ [g/kWh] and the one for (light) heating oil $F_{oil} = 260$ [g/kWh], [66].

4.7.3 German wide savings

TABULA data on the number of buildings represented by SAH 1, 2 and 3, in combination with the presence of natural gas or oil based central heating systems, facilitates the calculation of German wide primary energy and CO_2emissions savings. For each type of building i (SAH 1: $i = 1$, SAH 2: $i = 2$ and SAH 3: $i = 3$) the annually saved primary energy saving of one building $E_{p,i}$ can be extended to all buildings of type i with,

$$E_{p,i,Stock} = N_i \cdot E_{p,i} \text{ [kWh/a]} \tag{29}$$

and N_i the number of buildings of type i in the residential building stock. The same equation holds for the CO_2emissions savings where a distinction is made whether the fuel is natural gas or heating oil,

$$CO_{2,saved,i,Stock} = \frac{N_{i,gas} \cdot F_{gas} \cdot E_{p,i} + N_{i,oil} \cdot F_{oil} \cdot E_{p,i}}{1000000} \text{ [tCO}_2\text{/a]} \tag{30}$$

with $N_{i,gas}$ the number of buildings of type i heated by gas and $N_{i,oil}$ the number of buildings of type i heated by oil in the residential building stock. The total energy and CO_2 emission savings of the three houses combined is then,

$$E_{p,Stock,tot} = \sum_{i}^{3} E_{p,i,Stock} \text{ [kWh/a]} \tag{31}$$

and

$$CO_{2,saved,Stock,tot} = \sum_{i}^{3} CO_{2,saved,i,Stock} \text{ [tCO}_2\text{/a]} \tag{32}$$

respectively.

5 Results

The results of this research are organised in two main sections, in line with the methodology. These sections treat first and foremost the results of the RBM (section 5.1) and secondly the corresponding cost savings and primary energy and CO_2emission savings for the single houses as well as the German building stock total (section 5.2).

5.1 Residential building model

The RBM as designed during this master thesis is developed in order to determine possible energy savings as a result of retrofit application of BAS, on SAHs in particular. The results of the RBM as described in this section contain the calculated energy savings as well as an investigation of the RBM itself. Which is on its own a result of the research and needs to be assessed in order to determine whether the calculated results are of any scientific value.

A distinction is made between section 5.1.1 on the reference buildings, and section 5.1.2 which includes the BAS systems.

5.1.1 Reference building & model validation

The three SAH reference buildings results on annual space heating demand and final energy consumption are used to check validity of the RBM. The results on the annual space heating demand are compared with an existing model, whereas the final energy consumption is checked with measured data.

Demand for space heating

As described in section 4.6.1 the RBM is compared to the HRI model with the same input data. This comparison is focused on the yearly demand for space heating as modelled by the reference case of the three SAHs. The demand for space heating (in Watt) is calculated based on equation 3 and integrated over the course of a year. In order to compare houses of different size, the value is divided by the living area of the building. Resulting in a yearly heating demand in kWh/m^2.

The method as used by the HRI model, assumes that the demand for space heating is zero outside the heating period[16]. The heating period is defined as the period between October 1 and March 31 in the subsequent year, according to the DIN V 18599 [25].

SAH 1 SAH 1 the exemplary building representative for SAH built between 1860-1980 is the least insulated building and has, with a value of 295 kWh/m^2, the highest demand for space heating of the three modelled houses. The HRI model predicts for SAH 1 an 11 % higher value of 326 kWh/m^2. The demand for space heating over the year is depicted in Figure 28.

[16]This assumption has a big influence on the final heat demand as discussed in section 5.1.3

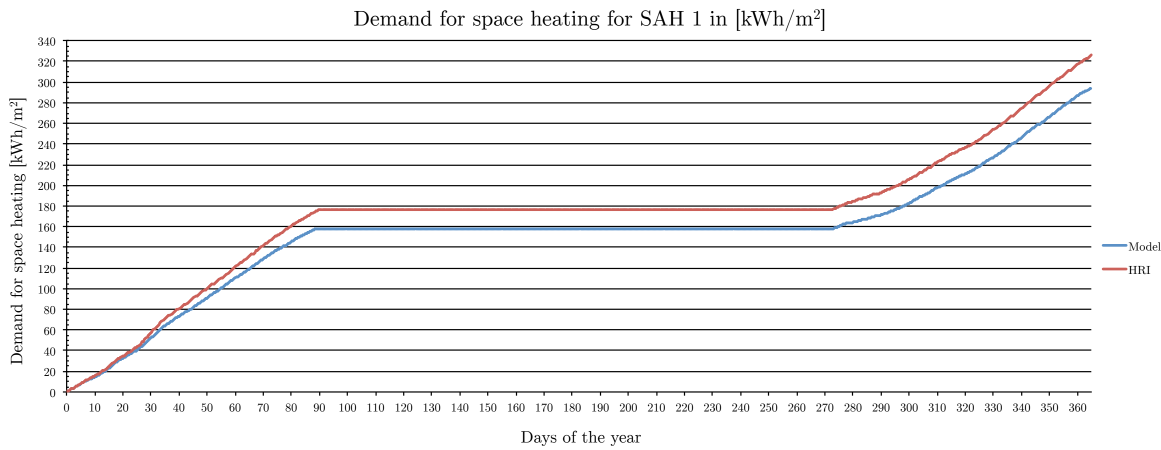


Figure 28: Comparison of the HRI-model results with the RBM results for SAH 1: Annual demand for space heating per square meter living area.

SAH 2 The RBM for the reference case of SAH 2, the exemplary building representative for SAH built between 1884-1994, has a resulting demand for space heating of 161 kWh/m^2. The HRI model predicts for SAH 2 a 10 % higher value of 177 kWh/m^2. The demand for space heating over the year is depicted in Figure 29.

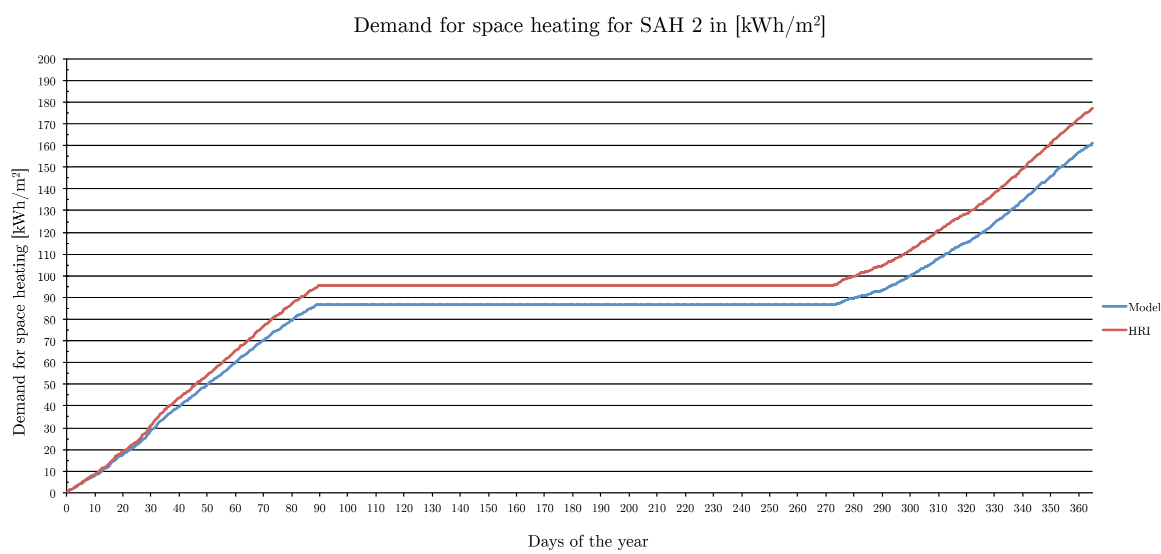


Figure 29: Comparison of the HRI-model results with the RBM results for SAH 2: Annual demand for space heating per square meter living area.

SAH 3 The lowest demand for space heating is calculated for SAH 3, the exemplary building representative for SAH built between 2002-2009. This new and insulated building has a demand for space heating of 76.4 kWh/m^2. The HRI model predicts for SAH 3 a 23 % higher value of 94.1 kWh/m^2. The demand for space heating over the year is depicted in Figure 30.

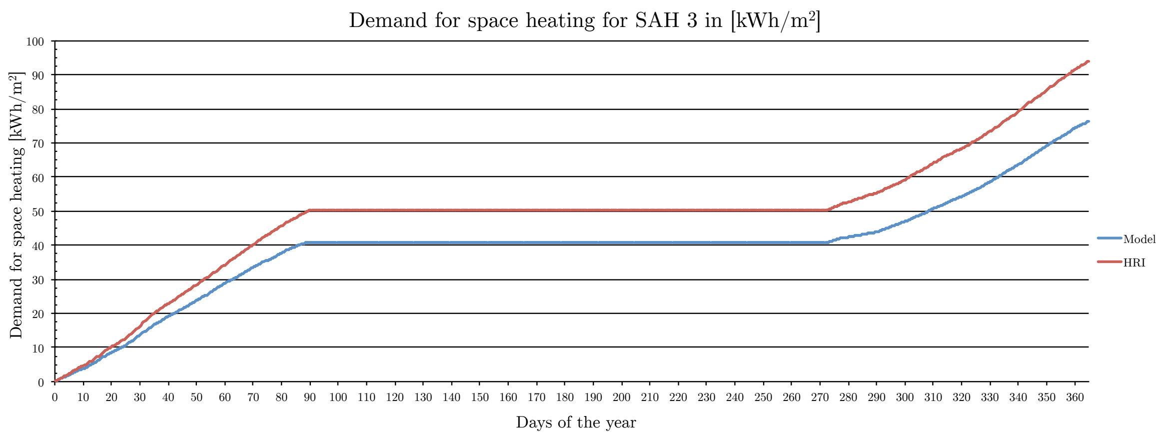


Figure 30: Comparison of the HRI-model results with the RBM results for SAH 3: Annual demand for space heating per square meter living area.

Final energy consumption

The HRI model only models the demand for space heating, not the delivered energy by the heating system, nor the primary energy consumption of the energy carrier consumed (gas or oil). In the RBM however, the heating system forms a crucial part of the calculations. Figure 31, 32 and 33 depict the yearly useful energy ('Nutzenergie') as provided by the boiler (E_{heater}) and the corresponding final energy demand ('Endenergie') [17] of the boiler (E_p) for all three reference houses per square meter living area.

SAH 1 The energy consumption as shown in Figure 31 describes the energy consumption under the assumption that the heating system is not shut of in the summer. When taking into account that the heater is only functioning in the heating period, the resulting final energy consumption is 525 kWh/m^2. The yearly average efficiency of the low temperature boiler can be obtained by $\eta = E_{heater}/E_p$, and is 98%.

[17] The Figures depict the final energy as E_p which gives the impression that it indicates the primary energy consumption. This confusion arises from the fact that the final energy corresponds to the primary energy carriers (gas or oil). The difference between final energy and primary energy is according to the EnEV 2014 [12] a factor 1.1, which is further treated in section 5.2.1 and the discussion.

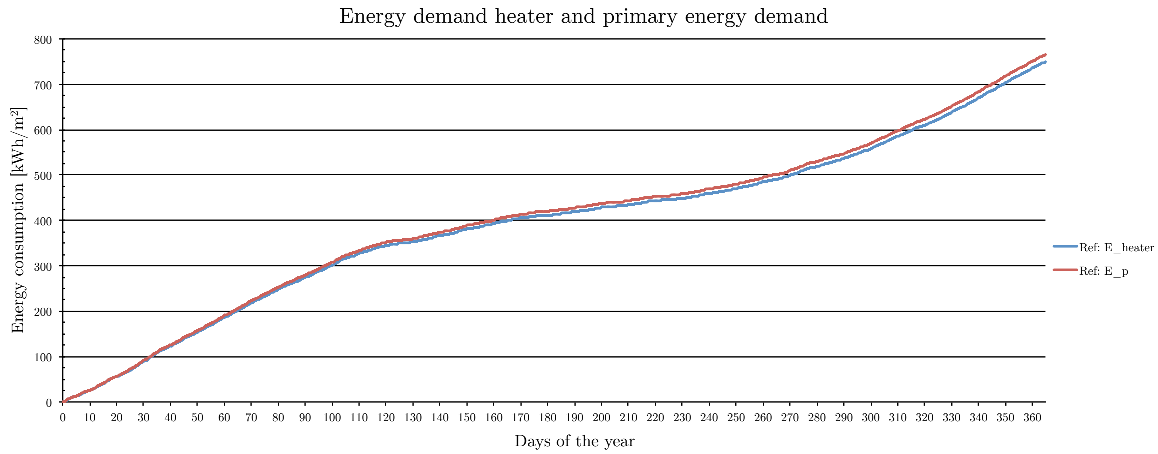


Figure 31: Energy demand of the heat transmission system as provided by the low temperature boiler and the corresponding **final** energy demand for SAH 1. Results of the RBM for the reference case, modelling time: 1 year.

SAH 2 The energy consumption of SAH 2 as shown in Figure 32 also assumes a heating system that runs the entire year. The resulting final energy consumption for the heating period for SAH 2 is 290 kWh/m^2. The yearly average efficiency of the low temperature boiler is, according to $\eta = E_{heater}/E_p$, 98%.

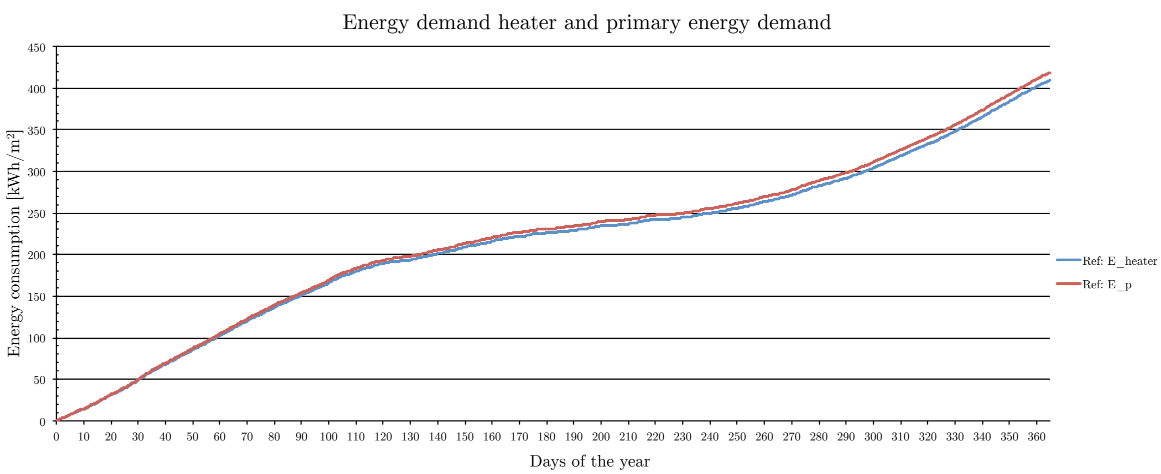


Figure 32: Energy demand of the heat transmission system as provided by the low temperature boiler and the corresponding **final** energy demand for SAH 2. Results of the RBM for the reference case, modelling time: 1 year.

SAH 3 The energy consumption of SAH 3 as shown in Figure 33 also assumes a heating system that runs the entire year. The final energy consumption for the heating period for SAH 3 is 152 kWh/m^2. The yearly average efficiency of the installed condensing boiler is, according to $\eta = E_{heater}/E_p$, 101%[18].

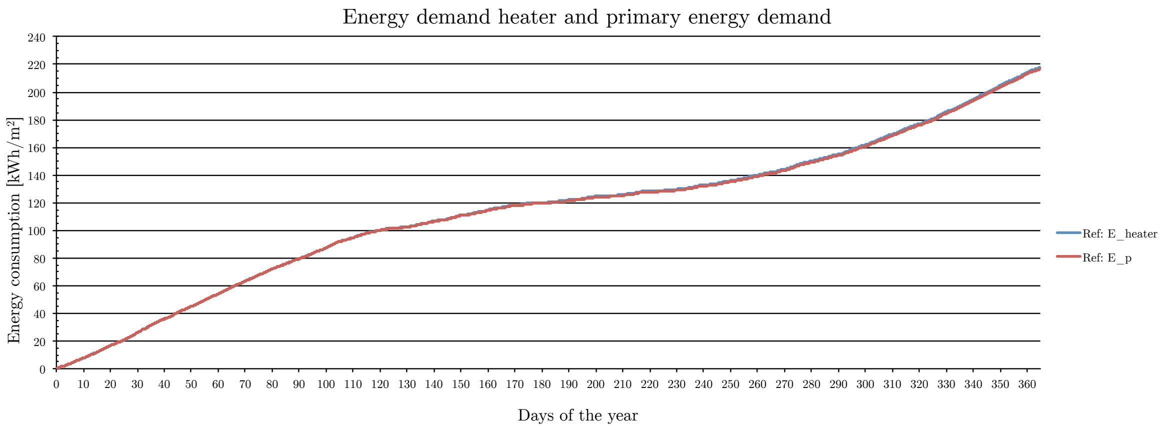


Figure 33: Energy demand of the heat transmission system as provided by the condensing boiler and the corresponding **final** energy demand for SAH 3. Results of the RBM for the reference case, modelling time: 1 year.

5.1.2 Building automation retrofits

This section describes the results of the modelling of the three SAH with retrofitted BAS in the RBM.

Scenario 1 As described in section 4.4, the goal of scenario 1 is to determine the energy savings as a result of the retrofit application of a time schedule thermostat. This time schedule reduces the set temperature of the room during the day by 4 degrees Celsius. The yearly demand for space heating per square meter living area, and the yearly final energy consumption per square meter of living area, are calculated for all three SAH. The generated graphs below show the results in comparison to the reference buildings.

SAH 1 From Figure 34 one can conclude that the yearly demand for space heating per square meter living area is reduced by 61 kWh/m^2 by retrofitting SAH 1 with a time schedule thermostat. Which is a reduction of 21 %.

[18]Based on the Lower Heating Value as described in section 3.2.2

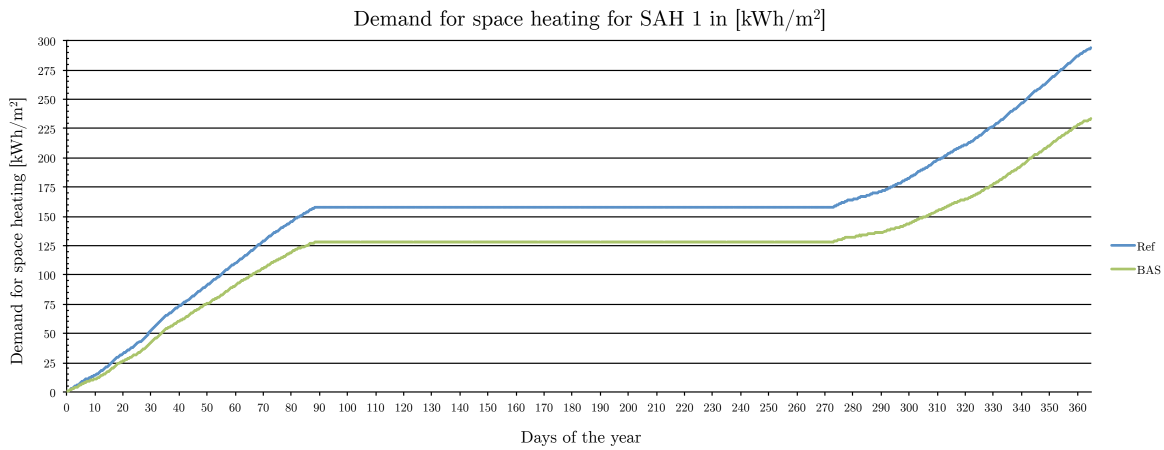


Figure 34: Demand for space heating, savings for scenario 1 and SAH 1, over the period of an entire year.

The final energy consumption for the SAH 1 with BAS retrofits is calculated and shown in Figure 35. The final energy consumption of SAH 1 with BAS, as a result of operation in the heating period only, is 474 kWh/m^2. The final energy savings due to the BAS retrofit is then 51 kWh/m^2, which is a reduction of 10 %.

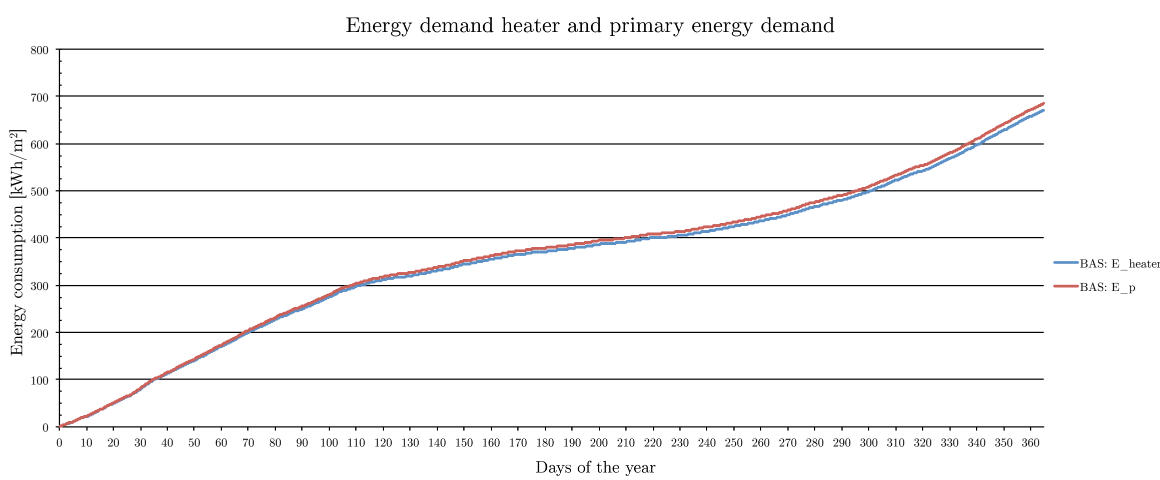


Figure 35: Energy demand of the heat transmission system as provided by the low temperature boiler and the corresponding primary energy demand for SAH 1. Results of the RBM for the building with BAS, modelling time: 1 year.

SAH 2 Figure 36 shows a reduced yearly demand for space heating per square meter living area of 23 kWh/m^2 as a result of retrofitting SAH 2 with a time schedule thermostat. Which is a reduction of 14 % compared to the reference case.

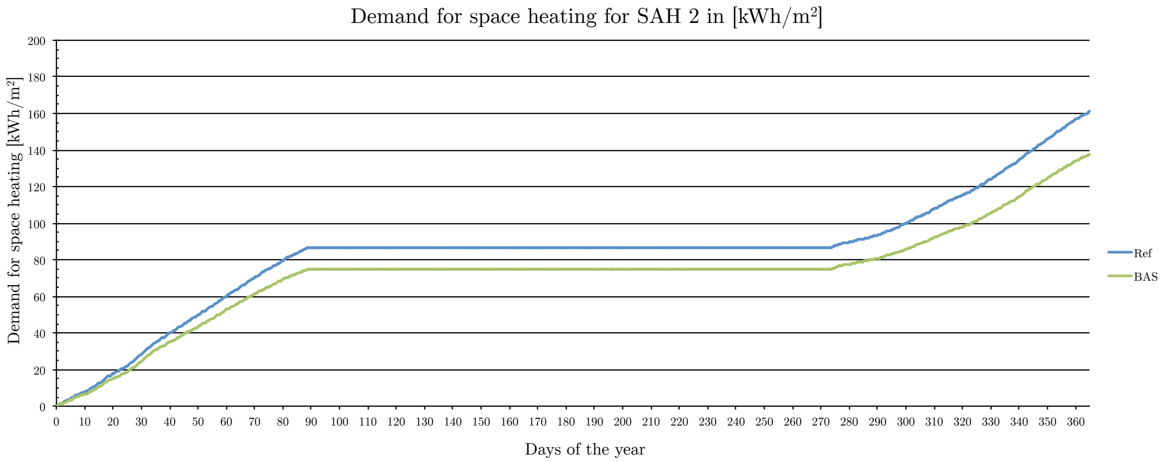


Figure 36: Demand for space heating savings for scenario 1 and SAH 2, over the period of an entire year.

The final energy consumption of SAH 2 with a time schedule retrofit is shown in Figure 37. The final energy consumption as a result of operation in the heating period only is 259 kWh/m^2. The final energy savings due to the BAS retrofit is then 31 kWh/m^2, which is a reduction of 11 %.

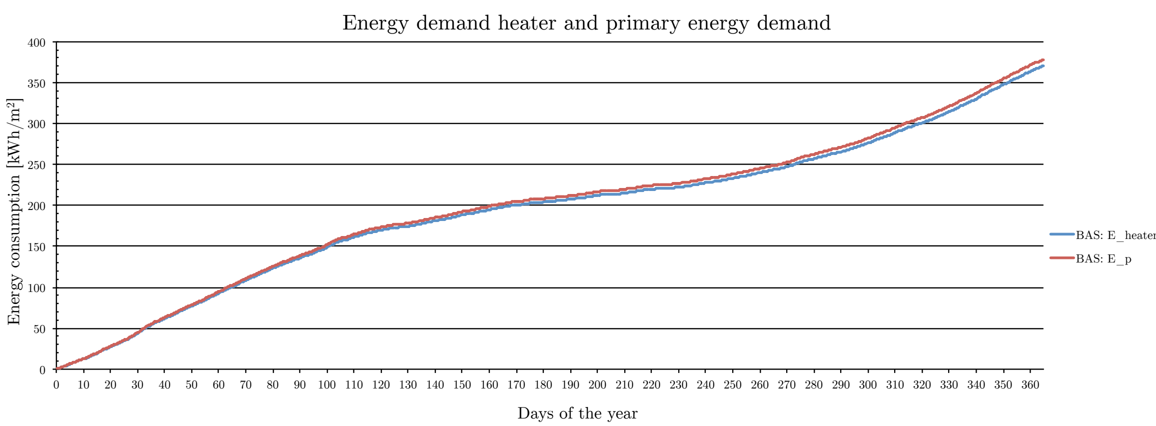


Figure 37: Energy demand of the heat transmission system as provided by the low temperature boiler and the corresponding primary energy demand for SAH 2. Results of the RBM for the building with BAS, modelling time: 1 year.

SAH 3 Figure 38 shows a reduced yearly demand for space heating per square meter living area of 13 kWh/m^2 as a result of retrofitting SAH 3 with a time schedule thermostat. Which is a reduction of 17 % compared to the reference case.

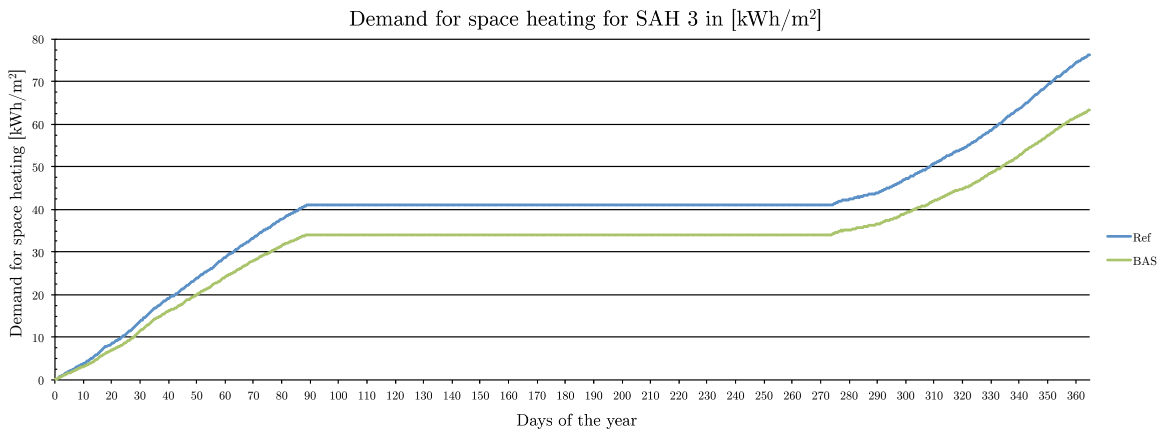


Figure 38: Demand for space heating savings for scenario 1 and SAH 3, over the period of an entire year.

The final energy consumption of SAH 3 with time schedule retrofit is shown in Figure 39. The final energy consumption as a result of operation in the heating period only is 131 kWh/m^2. The final energy savings due to the BAS retrofit is then 21 kWh/m^2, which is a reduction of 14 %.

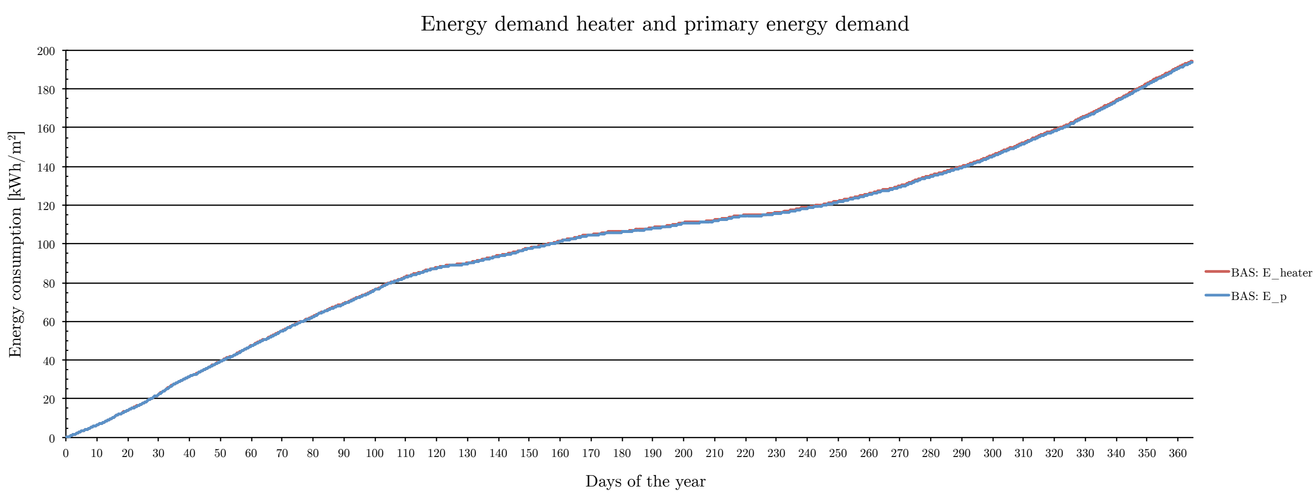


Figure 39: Energy demand of the heat transmission system as provided by the low temperature boiler and the corresponding primary energy demand for SAH 3. Results of the RBM for the building with BAS, modelling time: 1 year.

Room temperature analysis

Section 4.5.3 described the method for calculating the design heat load of the heating system which is used at instalment to make sure that the heating system is capable of heating the room to the desired set temperature under all circumstances. In this calculation the reheating of a room after it was set to a setback temperature (for instance after night cooling or time scheduling) was taken into account.

In order to test whether the used heating system of the BAS scenario 1 is designed correctly, a room temperature analysis is performed. The analysis is executed by modelling the least insulated house SAH 1 for the coldest week of the year. The house is outfitted with a condensing boiler that operates at low temperatures, see Table 15 for the boiler characteristics.

T_feed_nominal [K]	T_return_nominal [K]	Q_max [W]
343.15	333.15	2994

Table 15: Feed-in and return temperatures of the condensing boiler and the maximum output of the transmission system (per room) for SAH 1 as modelled for the coldest week of the year.

The coldest week of the year lies between the 29th of January and the 5th of February, the outside temperature for this period is depicted in Figure 40.

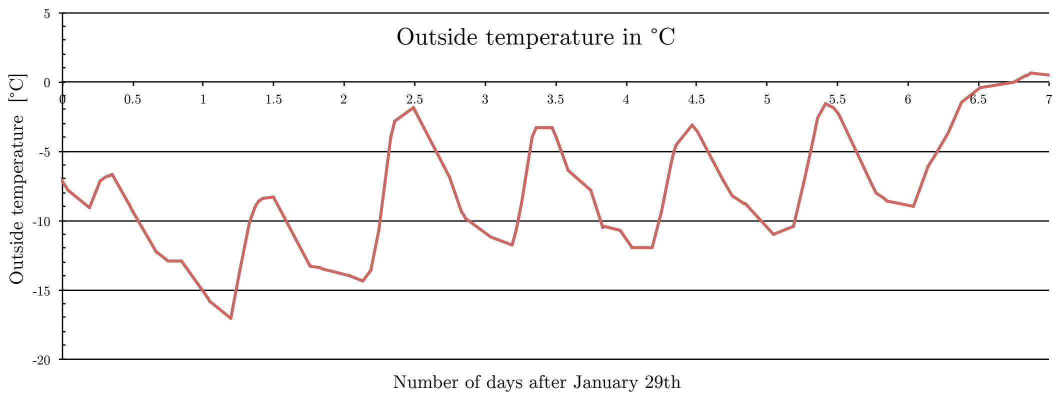


Figure 40: Hourly average outside temperature over the course of the coldest week of the year, between January 29th and Febuary 5th. TRY-4 data for Potsdam, Germany. See section 4.2.

The indoor temperatures of the separate rooms are not always the same, the distinct temperatures are mainly caused by a different cardinal direction, the location of the rooms with respect to the ground floor, and the area of the windows. Initial investigations on the indoor temperature of the three reference buildings has shown that the room 'GF1' is the room with the most stable indoor temperature. In contrast, the room '1F2' has the most fluctuating indoor air temperature. These two rooms are used to investigate the functioning of the heating system in combination with the time scheduling thermostat.

Temperature

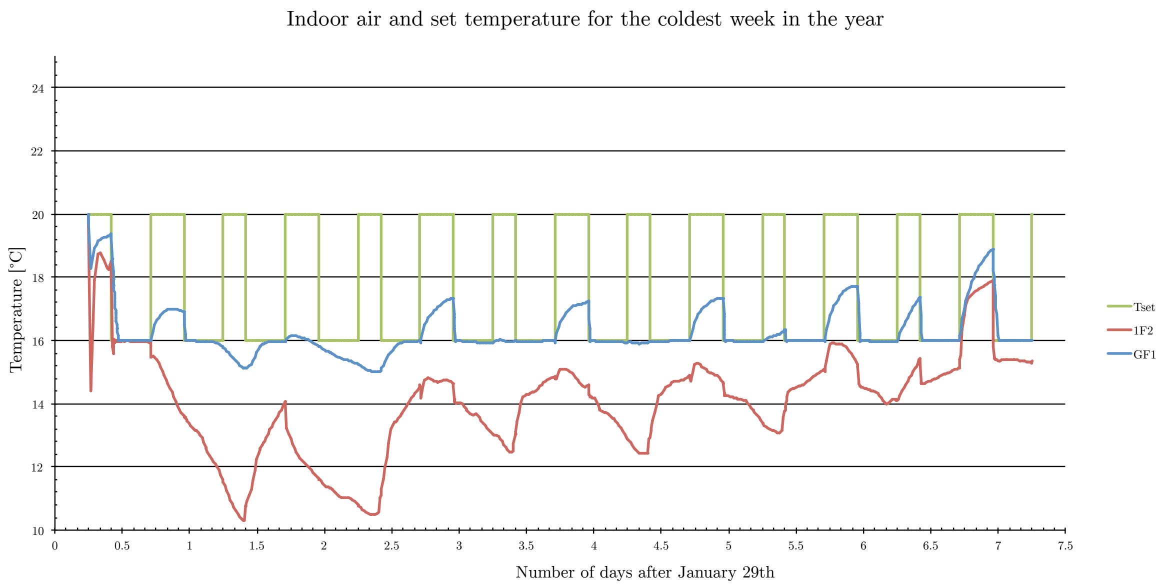


Figure 41: Indoor room temperature of room GF1 and 1 F2 during the coldest week of the year,between January 29th and Febuary 5th. The results start at 6.00 a.m. on January 29th.

Heat transmission system output

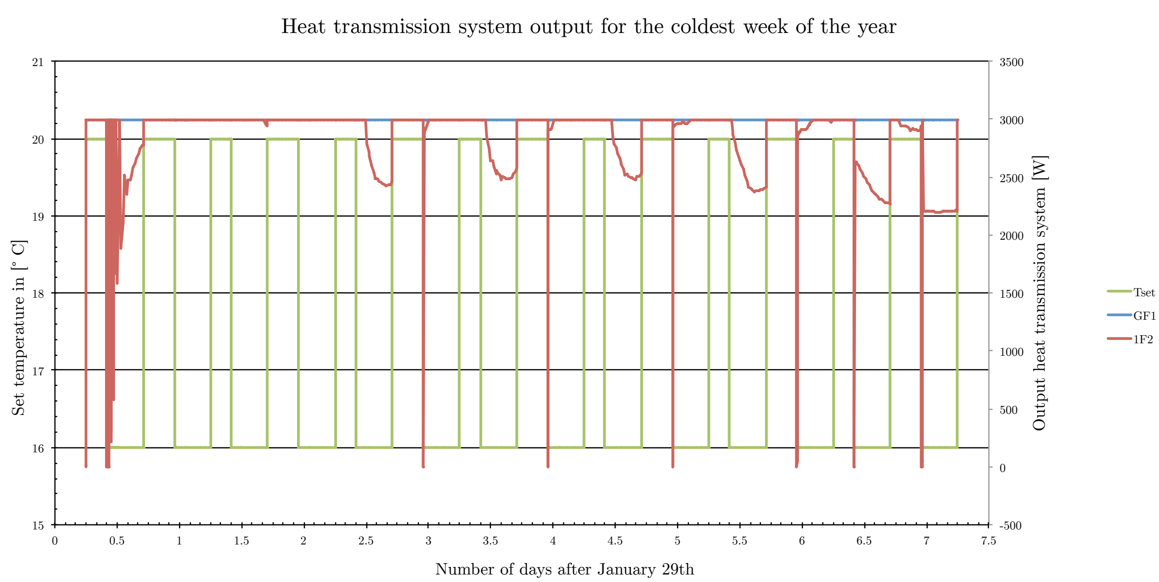


Figure 42: Heat transmission system output in Watt for room GF1 and 1F2 during the coldest week of the year, between January 29th and Febuary 5th. The results start at 6.00 a.m. on January 29th.

Scenario 2a
This section on Scenario 2a investigates the effects of thermostat valve control under intermittent ventilation conditions. The reference building SAH 3 is adapted to have intermittent ventilation, as described in section 4.5.5. It is important to note here that the room set temperature is kept constant here (at 20 ºC), no night cooling or time scheduling is implemented.

Temperature

Reference case The effect of the five minute opening of the windows in room GF1, GF2B and 1F2 on the indoor air temperature for a winter day (January 29) is depicted in Figure 43.

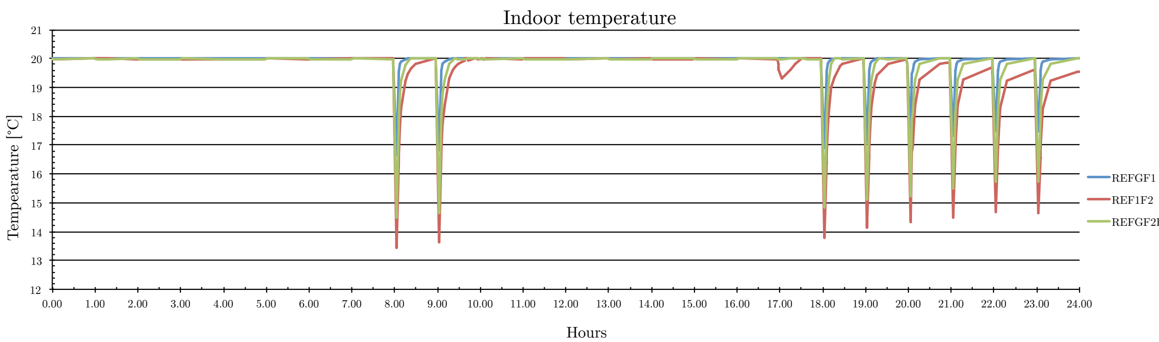


Figure 43: Indoor room temperature for room GF1, GF2B and 1F2. SAH 3, scenario 2a, reference case, modelling time = 24 hours (January 29th).

Figure 43 shows the opening of the windows in the periods that the residents are home. A sudden temperature drop in the rooms is the result of the opened windows. Figure 44 is a close up of the previous Figure which shows that the duration for reheating the room to comfort levels (20 ºC) takes around eight, sixteen, and thirty minutes after the lowest temperature point for the rooms GF1, GF2B and 1F2 respectively.

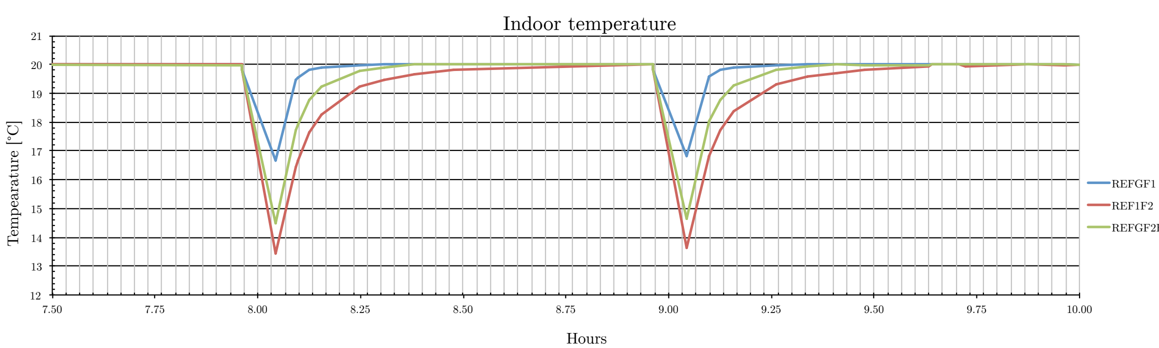


Figure 44: Indoor room temperature for room GF1, GF2B and 1F2. SAH 3, scenario 2a, reference case, modelling time = 2.5 hours (January 29th).

Building automation retrofits The implementation of a BAS that automatically shuts the thermostat valves of the heat transmission system when a window is opened has its effect on the internal room temperature as depicted in Figure 45. The room temperature curve follows a similar trajectory, however with slightly lower minimum temperatures $\Delta T < 0.5$ ºC and a longer reheating time, see Figure 46. With reheating times of around ten, eighteen and thirty two minutes for the rooms GF1, GF2B and 1F2 respectively, this is not, however, very significant. The difference in the reheating times is so small that it has no noticeable impact on the comfort levels of the residents.

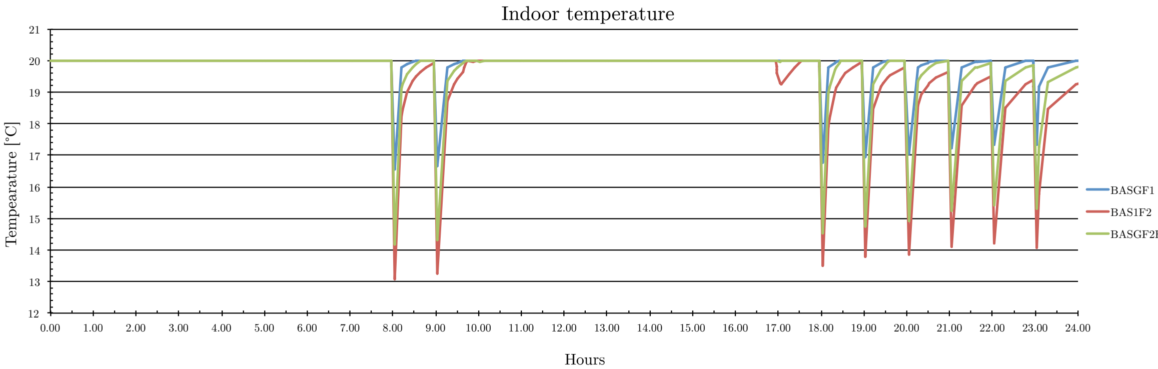


Figure 45: Indoor room temperature for room GF1, GF2B and 1F2. SAH 3, scenario 2a, building with BAS (i.e. window opening dependent thermostat valve regulation), modelling time = 24 hours (January 29th).

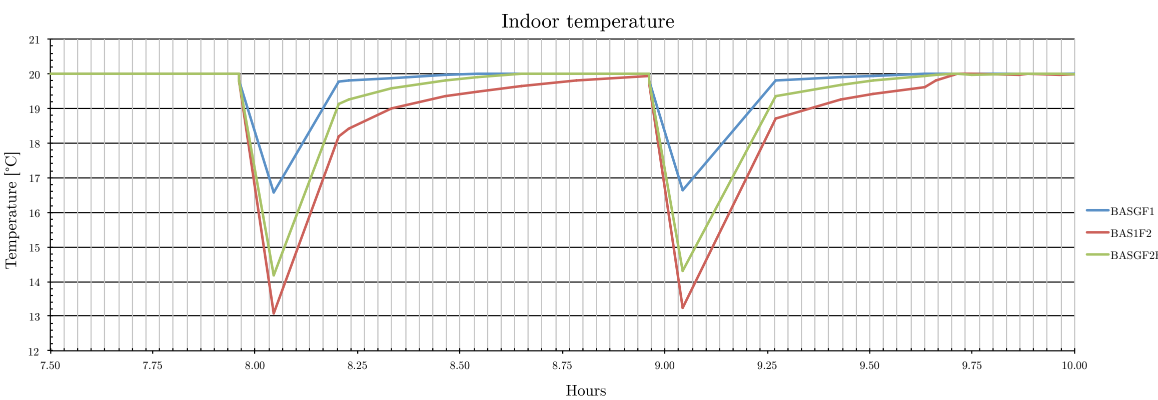


Figure 46: Indoor room temperature for room GF1, GF2B and 1F2. SAH 3, scenario 2a, building with BAS (i.e. window opening dependent thermostat valve regulation), modelling time = 2.5 hours (January 29th).

Power

The automatically closed thermostat valves result in a reduced power output of the heat transmission system as depicted in Figure 47

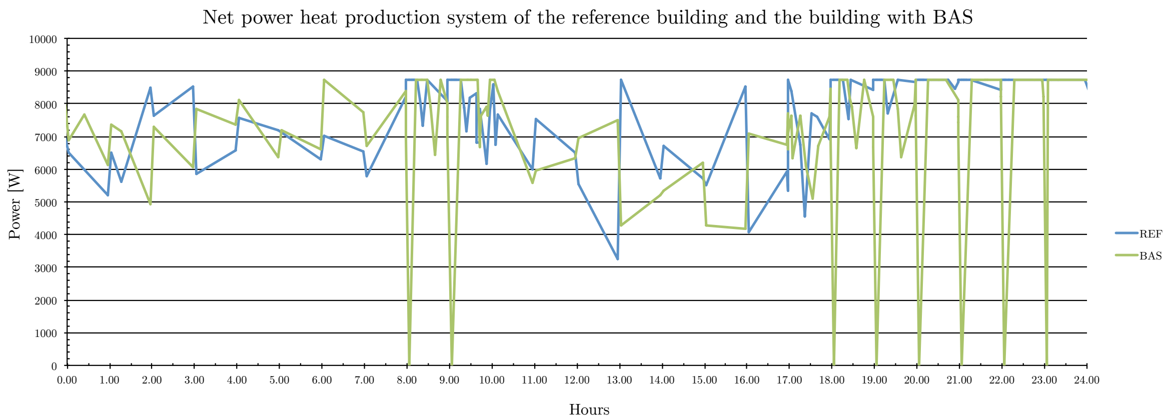


Figure 47: Comparison of the net power output of the heat production system for both the reference case and the building with BAS. SAH 3, scenario 2a, modelling time = 24 hours (January 29th).

When calculating the resulting energy savings for the first ninety days of the year[19] for the entire building, it can be concluded however, that the BAS retrofit has limited impact. This is evident since the saved energy calculated by the model is 1.8 kWh/m^2, which is only 2 % for this time period. For the entire year, a savings of around 4 % could therefore be achieved.

Scenario 2b

Described in section 4.5.2 is the opening of the windows in scenario 2a, based on the minimum hourly air exchange. This is achieved by opening the windows for this minutes every hour. Scenario 2b investigates the the extreme case where the window is opened for a duration of thirty minutes, see FigureD.3.2. Figure 48, 49 and 50 depict the indoor room temperature of room GF1, GF2b and 1F2 for January 29 of both the reference case and the BAS case. The differences with scenario 2a are as expected, where the prolonged opening of the windows results in even lower temperatures and also longer reheating times.

Temperature

[19] This is the period until the end of the heating period. The period between October 1 and December 31 was not modelled here explicitly due to time constraints, however the energy saving results are expected to be of the same order of magnitude for this period.

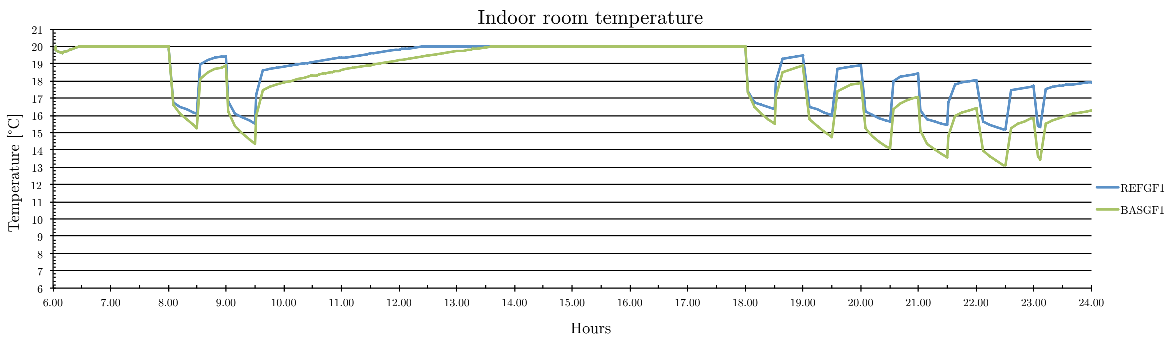


Figure 48: Indoor room temperature for room GF1. SAH 3, cenario 2b, comparison reference case and building with BAS (i.e. window opening dependent thermostat valve regulation), modelling time = 24 hours (January 29th).

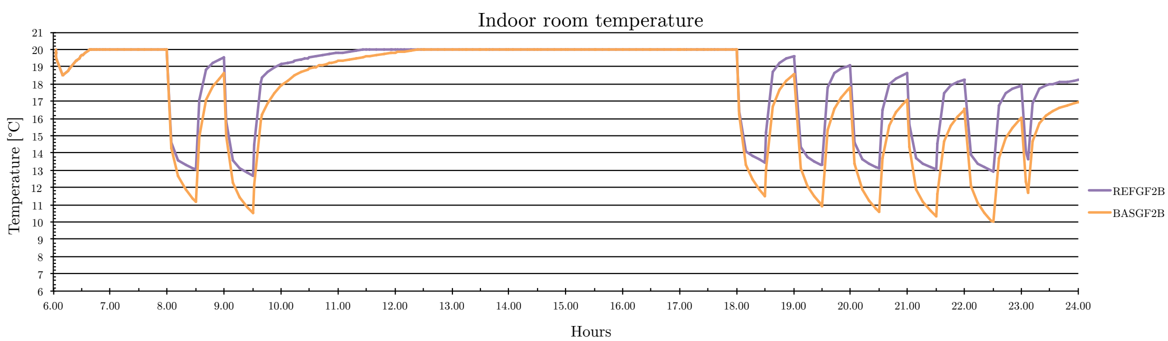


Figure 49: Indoor room temperature for room GF2b. SAH 3, scenario 2b, comparison reference case and building with BAS (i.e. window opening dependent thermostat valve regulation), modelling time = 24 hours (January 29th).

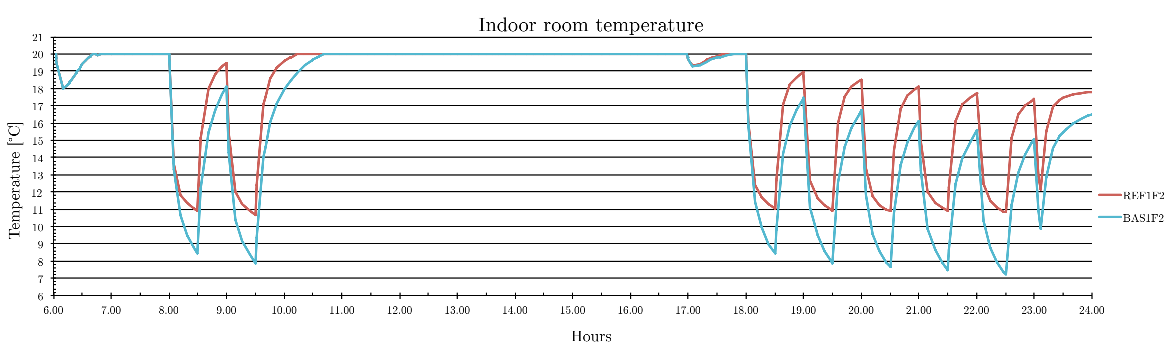


Figure 50: Indoor room temperature for room 1F2. SAH 3, scenario 2b, comparison reference case and building with BAS (i.e. window opening dependent thermostat valve regulation), modelling time = 24 hours (January 29th).

Power and energy Figure 51 depicts the corresponding power output of the heating system (which has a maximum power output of 8747 W, based on the design heat load calculation).

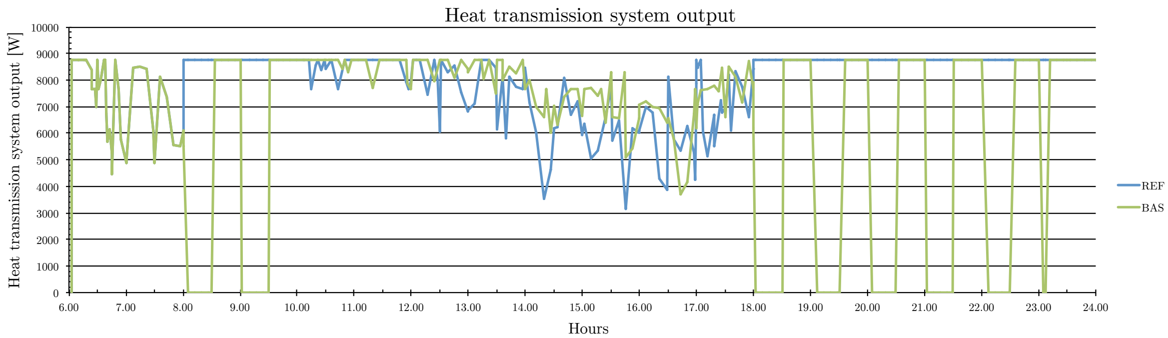


Figure 51: Comparison of the heat transmission system power output of SAH 3, for both the reference case and the building with BAS (i.e. window opening dependent thermostat valve regulation). Scenario 2b, modelling time = 24 hours (January 29th).

The effect that the closing of the thermostat valves has on the energy consumption is, for this prolonged opening of the windows, expected to be greater than in scenario 2a. Figure 52 confirms this assumption. The final energy consumption of the heating system for one winter day (from January 29, 6.00 am to January 30, 6.00 am.) is in the reference case, 193 kWh, and for the BAS retrofit ,166 kWh. This yields a reduction of 14 %.

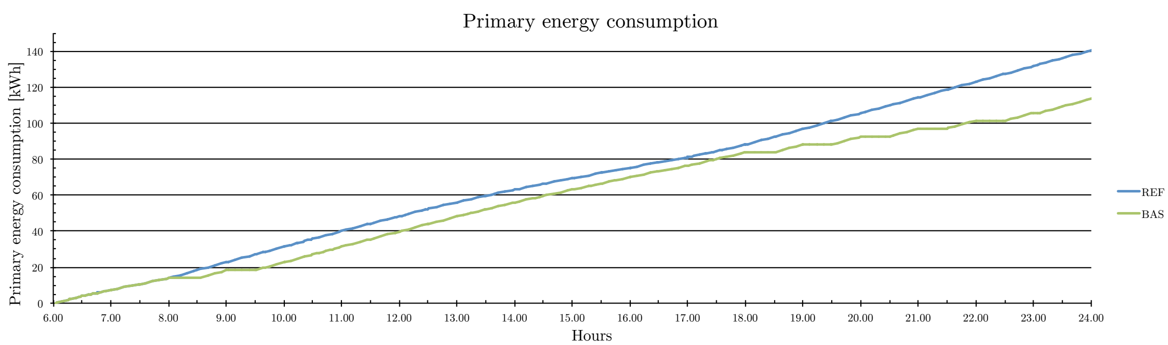


Figure 52: Comparison of the primary energy consumption of SAH 3, for both the reference case and the building with BAS (i.e. window opening dependent thermostat valve regulation). Scenario 2b, modelling time = 24 hours (January 29th).

Scenario 1 and 2 combined

Scenario 2a assumed a constant set temperature of the room (20 ºC), and under these circumstances the heating system is capable of reheating the room back to the set temperature. It has been found that when scenario 1 and 2a are combined (i.e. A BAS with night cooling, time schedule and reactive thermostat valves) that this is in fact not the case, as Figure 53 indicates. The indoor room temperature of room GF1 (which is the most stable room) of SAH 3 (which is the best insulated building) drops far below the desired values both during set back periods (thermostat set at 16 ºC) and during the normal set temperature (thermostat set at 20 ºC). This finding indicates an inadequate design heat load of the heating system.

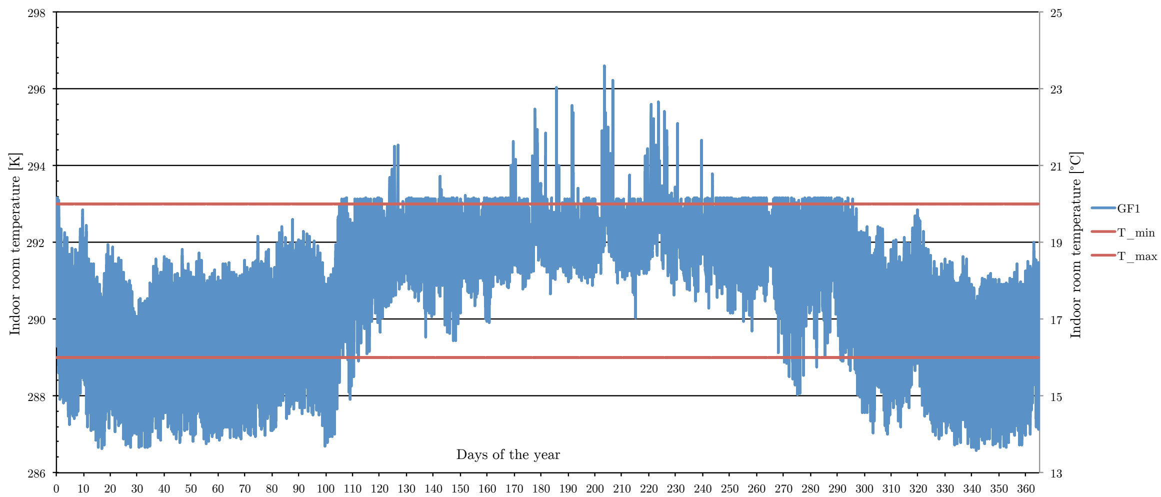


Figure 53: Indoor room and set temperatures for room GF1 of SAH 3 over the course of an entire year. With $T_{min} = 16$ °C and $T_{max} = 20$ °C.

5.1.3 Discussion

Model validation

The differences between the modelled demand for space heating between the HRI model and the RBM are not for all three SAH of the same order (11, 10 and 23 % respectively). Further investigation has shown that the input values for infiltration and thermal bridges were not adjusted accordingly for SAH 3 in the HRI model (see Model inputs in Appendix C). Adjusting these values would lead to a lower heat loss by infiltration and thermal transmission over the heat bridges. This could, in part, explain the disproportional difference in the space heating demand of SAH 3. A rerun of the SAH 3 simulation in the HRI model could confirm this suspicion.

It should be noted, however, that discrepancies between different simulation programs are not uncommon, as is stated by the VDI 6020, which sets requirements on the calculation methods for building and (heating) system simulations. The VDI 6020 shows that variations in the annual energy demand between common simulation programs can range from 0-50%, [49].

The differences in the calculation methods between the HRI model and the RBM could explain the deviations in the results. The most notable of these differences is the calculation of the thermal storage. The RBM calculates this explicitly by including the heat capacities of the indoor air and building elements, see section 4.5.3. The method of the DIN V 18599 [25] calculates the effect of thermal storage by using a utilisation factor for the heat gains based on the temperature difference between the building's interior and the outside. The utilisation factor is dependent on the construction type (light, medium or heavy). This means that not all heat gains are always used. This calculation method is a simplification that might result in a higher demand for space heating.

For SAH 3 it turns out that the manual addition of all thermal ‘sinks’ and ‘sources’ integrated over the heating period results in a space heating demand of 69 kWh/m^2, instead of the calculated value of 94 kWh/m^{2}by the HRI model. This value of 69 kWh/m^2 without the use of the utilisation factor, is 10 % lower than the result from the RBM. One could conclude that the utilisation factor for internal heat gains is to assumed too low in the HRI model, however further research is necessary to confirm this presumption.

The calculation method for the energy consumption, as used in the RBM, is based on the real time simulation of heat flows through the building, based on the physics of thermal transport. Following a different method, the HRI model uses the DIN V 18599 energy balance method, of heat sinks and sources without modelling the indoor temperature explicitly. Due to these differences, it can thus be assumed that the results obtained from the RBM reflect reality more accurately. This assumption, however, can only be determined by the comparison of the model results with measurement data on actual buildings.

The demand for space heating as calculated by RBM is also in line with actual measured values, as shown in section 3.2. The values range from $Q_h \geq 200\,\mathrm{kWh/m^2 \cdot a}$ for un-renovated buildings built before 1979, to $Q_h \leq 60\,\mathrm{kWh/m^2 \cdot a}$ for buildings based on the EnEV 2009 standard, [39].

When comparing the final energy consumption of the three SAH buildings with actual measurement data, the results start to deviate increasingly from expected values. The German average final energy consumption for space heating in residential homes is 120 kWh/m^2 [79] or 134 kWh/m^2 [48] for natural gas. SAH are expected to have higher values of around 200 kWh/m^2 [74]. Compared to this data, the values from the RBM (with 525 kWh/m^2, 290 kWh/m^2 and 152 kWh/m^2 for SAH 1 to 3 respectively) seem to be to high.

The same conclusion is reached when studying the deviation of the final energy consumption from the demand for space heating. Which can be described by the ratio E_f/HWB and is shown in Table 16. The table depicts E_f, the final energy consumption, and HWB, the demand for space heating.

Building	Ratio E_f/HWB
SAH 1	178 %
SAH 2	180 %
SAH 3	200 %

Table 16: Ratio E_f/HWB for the reference case of SAH 1 to 3 in the RBM.

It is especially surprising that the difference increases for better insulated building with more efficient boilers, which is the case for SAH 3. A possible cause for this deviation could come from the partial model for the heat production system as provided by the Modelica Buildings Library, [51]. Further analysis of the RBM and the heat production partial model could shed some light as to whether or not this is the case.

Building automation retrofits

Scenario 1 Section 5.1.2 shows that scenario 1 BAS retrofits lead to final energy consumption reductions of 10, 11 and 14 % for SAH 1 to SAH 3 respectively. These reductions are smaller than the reductions in the demand for space heating (which are 21, 14 and 17 % for SAH 1 to SAH 3 respectively), which is similar to the reference cases. The BAS retrofits leading to a reduction in the

final energy demand is a welcome result, however, this should not go at the expense of the residents’ comfort. The temperature analysis has shown that under extreme circumstances (during the coldest of the year) the heating system is not able to heat the rooms accordingly, see Figure 41. This is especially the case for room 1F2, which reacts more strongly to changes in the outside temperature than any other room. This can be attributed to the location under the roof and its large area of windows (with a relatively high U-value), which leads to large transmission losses.

Figure 42 shows that during this period the heating system is (almost) running at full capacity. Which indicates that the low room temperatures is not the result of poor temperature regulation, but the result of a boiler that is too small. The nominal capacity of the boiler is designed based on a norm outside temperature of -14 ºC, while the actual outside temperature reaches lows of around -17 ºC during the night of January 30. It it interesting to note that even during temperatures of -5 ºC, the system is not capable of keeping the room set temperature, which indicates that the design heat load is insufficient, according to equation 21.

A further investigation on the design heat load of the heating system has uncovered an error in the value for f_{RH}. In the RBM the value of $f_{RH} = 10$ has been used based on [66], however the DIN EN 12 831 [21] states a value of $f_{RH} = 22$. This would in turn result in a value of Q_{RH} that is a factor 2.2 greater, increasing the total design heat load by 310 W for SAH 1, 330 W for SAH 2 and 321 W for SAH 3. This would result in a faster reacting heating system and more comfortable room temperatures.

Both the reference case and scenario 1 of the BAS retrofits show an increase in the final energy consumption of around 40 %, when including the period outside the heating period (i.e between April 1 and September 30) in the annual final energy consumption calculation. This is surprisingly high for a period where heating is considered unnecessary. This result might be attributed to the heating system that tries to regulate the temperature exactly to the set temperature. These results show that a complete shut down of the heating system during the summer has a great impact on the final energy consumption. Thermostats that have the feature to automatically turn off the heating system (on a season based time schedule) could capitalise on these savings.

Scenario 2a The results for the reference building of scenario 2a show a more realistic view of the manual opening of windows, and the resulting inner room temperature, than those of the standard reference scenario. The standard reference scenario namely assumed a constant low ventilation exchange rate, which can only be achieved by either mechanical ventilation or hinged windows (or 'Klappfenster') that are continuously opened. The results of scenario 2a show for all SAH that even though the room temperature drops rapidly (during opened windows), it is also quickly reheated. The overall controlling of the temperature by the heating system is thus more easily achieved. This is the result of lower thermal heat losses during the periods when the windows are closed.

The results in Figure 44 show different reheating times for the different rooms in the buildings. Having reheating times of thirty minutes for Room GF2B, it can be stated that these times are too long to ensure the comfort of the residents.

The reason that room 1F2 takes longer to reheat is already explained under scenario 1. Room GF2B, or the living room, has twice the amount of ground floor area as the other rooms in the building, which results in a bigger room volume. Since the requirements for the ventilation rate are set based on exchanging this room volume on a half hourly basis, this leads to ventilation losses that are twice as large.

The results of the implementation of regulating thermostat valves in scenario 2a show room temperature curves similar to those in the reference case, with only slightly longer reheating times and slightly lower room temperatures. Since the minimum air exchange is already reached in five minutes, it can thus be concluded that the BAS has no significant negative impact on user comfort. This finding is especially promising since the results, as depicted in Figure 46, are for a cold winter day. The negative impact for user comfort in this scenario is limited, however, the resulting yearly final energy savings are as well, as they only amount to 4 %.

Scenario 2b Scenario 2b is performed in order to see the potential for energy savings when the windows are opened for a prolonged time period. As expected, the effect of the longer opening time of the windows causes a longer reheating time and lower room temperatures during the opening period. The energy savings for this scenario are more substantial than for scenario 2a, with a final energy reduction of 14 % compared to the reference case. These savings are the result of the closed thermostat valves during the window opening period in combination with the fact that this effect is not compensated for in the periods between window opening, as can be seen in Figure 52. Figure 51 shows, however, that this might be only because the heat transmission system reaches maximum output in the reheating period. Fitting a larger heat transmission system in the respective room would result in faster reheating, however, it would also most likely result in a lower energy reduction. In addition, since the simulation of scenario 2b has only been performed for January 29, the final energy savings are in no way representative for the entire year. Further research on the effect of prolonged window opening on the room temperature and heat transmission output is therefore necessary in order to asses the potential for energy savings.

Scenario 1 and 2 combined Figure 53 shows that the implementation of BAS of both scenario 1 and scenario 2 in SAH 3 result in room temperatures that are far below the desired values. This indicates, as concluded before, the need for a proper determination of the design heat load.

5.2 Primary energy saving and CO_2 emission reductions - Results

The primary energy, CO_2emission savings are explicitly calculated for scenario 1 of the BAS retrofits according to the method described in section 4.7. The final energy consumption savings of scenario 1 are summarised in Table 17.

Building	Final energy consumption savings
	Scenario 1 [kWh/a]
SAH 1	7191
SAH 2	4650
SAH 3	3066

Table 17: Annual final energy consumption savings as a result of scenario 1 BAS retrofits on the SAH 1 to 3.

5.2.1 Primary energy consumption

The resulting primary energy consumption savings are calculated by using equation 27 and are shown in the Table 18 below.

Building	Primary energy consumption savings
	[kWh/a]
SAH 1	7910
SAH 2	5115
SAH 3	3373

Table 18: Annual primary energy consumption savings as a result of scenario 1 BAS retrofits on the SAH 1 to 3.

5.2.2 From energy to CO_2-emissions

The resulting CO_2emission savings are calculated according to equation 28 and depend on the type of fuel used. Table 19 shows the potential CO_2emission savings for the 3 SAH when outfitted with a gas burning boiler, and Table 20 for the case that the houses are outfitted with an oil burning boiler.

Building	CO_2 emission savings
	[tCO2/a]
SAH 1	1.582
SAH 2	1.023
SAH 3	0.675

Table 19: CO_2 emission savings for the three SAH with retrofitted scenario 1 BAS and a gas burning boiler.

Building	CO_2 emission savings
	[tCO2/a]
SAH 1	2.057
SAH 2	1.330
SAH 3	0.877

Table 20: CO_2 emission savings for the three SAH with retrofitted scenario 1 BAS and an oil burning boiler.

5.2.3 German wide savings

The German wide savings are based on TABULA data, namely on the building stock composition [46] and the type of space heating systems used in these buildings, [45]. The results are then obtained based on equations 29 to 32, which are depicted in Table 21.

Building	Number of Buildings	% RBS	Total primary energy savings	Total CO_2 savings
			PJ/ a	$MtCO_2$/a
SAH 1	966 000	3.8	28	1.4
SAH 2	1 160 000	5.0	21	1.2
SAH 3	775 000	3.4	9	0.47
Total	**2 901 000**	**12**	**58**	3.1

Table 21: Total annual primary energy savings and corresponding CO_2 emission on the German wide level. Based on the savings as calculated for building SAH to SAH 3 with scenario 1 BAS retrofits. The percentage RBS is the percentage of the residential building stock that the SAH 1 to 3 represent based on their living area.

5.2.4 Discussion

The final energy savings of SAH 1 to 3, as calculated by the model for BAS scenario 1, form an important part of the results. They indicate the possible savings that could be achieved when implementing a time schedule thermostat. These results should be viewed cautiously, as the assumptions and simplifications of the model might lead to distortions of the actual saving achieved. For instance, auxiliary energy consumption of the heating system (e.g. the energy for the circulation pump) have been left out of the RBM.

Section 5.1.3 already pointed out that the final energy consumption for the reference case, as well as for the BAS scenario 1, are considerably larger than actual measured values. One should be aware that this in turn also affects the results on primary energy, costs and CO_2 emissions. The relative effect, compared to the reference case, however (i.e. a reduction of the final energy of 10 %, 11 % and 14 % for SAH 1 to SAH 3 respectively) might still valid. This would result in similar primary energy savings, cost savings and CO_2 emission savings. However this should be investigated further.

Another simplification made in the calculations above is that the final energy consumption for oil burning boilers has been assumed to be identical to those running on natural gas. As described in section 3.2.2 this is not actually the case. For condensing boilers, for instance, the increased efficiency compared to low temperature boilers is three to five percent points less than for the natural gas type. This could result in lower energy savings at partial load, lower CO_2 emission reductions and lower primary energy savings for the total of all SAH 1-3 buildings in the German building stock.

In the calculation for the total savings on the German building stock level it has also been assumed that all the SAH 2 buildings have low temperature boilers and all SAH 3 buildings have condensing boilers. Although these systems are predominant in their building age class they are not exclusive.

Finally it is important to note that the savings described in this section are the maximum achievable amount of energy savings, namely under the assumption that all houses implement the retrofits. The results form an upper boundary that can be used as an guideline for energy saving goals, however they should not be taken as a prediction. The actual achieved savings will form a fraction of the savings as presented here, and moreover the implementation will take time. How long this time frame will be is the result of the implementation rate of these BAS. Which will depend on many different factors, including but not limited to, the economic considerations of the residents and the energy saving policies in place.

6 Conclusion

The goal of this research was to determine the potential for primary energy savings and CO_2reductions of the German residential building stock through retrofit application of Building Automation Systems. To achieve this goal, a Modelica based residential building model (RBM) of a single family house has been developed. The reference buildings as defined in the TABULA building matrix (Appendix B) are representative for the German building stock and their parameters are used as input parameters in the RBM.

Of the 19 reference houses representing all single family houses in the German residential building stock, three reference houses have been modelled over the course of a year using the test reference year *Test Reference Year* climate data. These houses represent stand alone houses (SAH) built between 1860-1918 (SAH 1), 1984-1994 (SAH 2) and 2002-2009 (SAH 3), and represent 12 % of the residential building stock (based on ground floor area).

The RBM is validated by comparing the annual demand for space heating results from the RBM with the DIN V 18599 based HRI model. Simulations on the three different SAHs confirmed the accuracy of the model within 11 % for SAH 1, 10 % for SAH 2 and 23 % for 2002-2009 SAH 3. The three reference houses are subsequently outfitted with the BAS to determine their energy saving potential.

This research focussed on 2 BAS scenarios, which are designed to regulate the heating system, such that the energy consumption is minimised without jeopardising the comfort levels of the residents. Scenario 1 contains the implementation of a time schedule thermostat that automatically reduces the set temperature when the residents are not occupying the building. Implementing these systems for the SAHs would lead to an annual final energy reductions of 10 % for SAH 1, 11 % for SAH 2 and 14 % for SAH 3. The corresponding annual primary energy reduction on the German building stock level results to 58 PJ. This would lead to a corresponding reduction of the CO_2 emissions by 3.1 Mt CO_2 on yearly basis. An overview of these results are shown in Table 22.

Building	Number of Buildings	Final energy savings	Total primary energy savings	Total CO_2 savings
		% compared to ref.case	PJ/ a	$MtCO_2/a$
SAH 1	966 000	10 %	28	1.4
SAH 2	1 160 000	11%	21	1.2
SAH 3	775 000	14 %	9	0.47
Total	**2 901 000**	-	**58**	3.1

Table 22: Total annual primary energy savings and corresponding CO_2 emission reductions on the German building stock level. Assuming an implementation of the BAS in 100 % of the considered houses.Based on the savings as calculated for building SAH 1 to SAH 3 with scenario 1 BAS retrofits.

Scenario 2 contains a self regulating thermostat valve that reduces the heat transmission in the room during manual ventilation over the windows. Due to an insufficient amount of data, the potential for this BAS retrofit has been assessed for SAH 3 only. The annual final energy savings amount to 4 %, under minimal ventilation conditions.

Additional to determining the final energy savings the RBM has been designed to investigate the indoor climate of the buildings. The effects of the design heat load have been tested for the SAH 1 house for BAS scenario 1. It was shown that the design heat load of 2994 Watt (as calculated according to the DIN EN 12831) is insufficient to maintain the indoor set temperature of the rooms at all times. Consequently, the design heat load needs to be adapted, which could possibly lead to lower energy savings by the retrofitted BAS.

7 Discussion

The research set out to determine the potential for primary energy savings and corresponding CO_2 emission reductions as a result of the implementation of BAS in the residential sector. By utilising the TABULA project [47] for the categorisation of the German residential building stock and by creating a RBM in Modelica, it achieved this goal under the limitations set by the scope. Even though the RBM is capable of modelling all 19 SFHs, as described in the TABULA project [47], the final results as presented in this thesis, are only comprised of the results of three SAHs. Generating results with the RBM is constrained by the simulation time. One simulation of a SFH over the course of a year takes between five to ten hours on a regular desktop computer. In comparison, the DIN V 18599 [25] one zone model of the HRI [72] takes only minutes to simulate a single building. The HRI model, however, only calculates the demand for space heating and includes no heating system or the possibility to calculate the final energy consumption. Moreover an added benefit of the RBM is its capability of investigating the effects of the installed heating system on the indoor temperature. This feature is necessary in oder to determine whether the heating regulation system can keep the installed set temperature under all weather conditions. This research has shown that this has not been the case for scenario 1 BAS in SAH 1. A rerun of the simulation with a higher heat load would provide insight on whether the comfort requirements for the residents are reached and, additionally, how this would effect the energy savings.

Model validation

The validation of the RBM is performed by comparing the results of the model to the HRI model based on the DIN V 18599. This method of validation proves the accuracy of the RBM only compared to the theoretical calculations of the DIN V 18599 [25]. Energy measurements on residential homes have shown that the calculation methods like those as the DIN V18599 have limited capacity for predicting actual energy consumptions [48]. Comparing the model results with energy consumption values of actual SFHs would provide a more accurate method for validation. This would in turn give a better indication of the potential for energy savings of BAS retrofits. For the calculation of the final energy consumption, however, the results are not in line with the expected values as obtained from scientific literature. To improve the RBM it is necessary to find the reasons for this discrepancy. Furthermore, the final energy consumption, as calculated in the RBM, does not include auxiliary energy use of the heating system. If BAS retrofits would lead to a higher energy consumption of the pumps, sensors and regulators than in the reference case, than this would affect the final energy savings.

Economic considerations BAS

The possible energy savings as presented in this research represent the maximum achievable savings, as the implementation of the BAS will depend on the economic considerations of the residents. These considerations contain the costs at instalment as well as the saved costs on the gas / oil bill. Determining the payback periods, or the net present value of the BAS in future research, in combination with an implementation rate would lead to more accurate results regarding if and when the energy savings are achieved. Such a method is outside of the scope of this research. A simplified assessment as discussed below, however, shows the potential for the BAS of scenario 1.

Home automation sets for consumers, containing time schedule thermostats, regulating thermostat valves and contact sensors, are available on the market today for around 250 € [71]. The saved annual costs are based on the price of the fuel used and the final energy saved. The annual saved costs are then,

$$Costs_{saved} = C_{fuel} \cdot E_{f,saved} \ [€/a] \tag{33}$$

with C_{fuel} the cost of the fuel [€/kWh] and $E_{f,saved}$ the annual final energy saved [kWh/a].

The cost savings are calculated for the three houses with scenario 1 BAS retrofits and a gas burning boiler. The gas price is of great influence on the result, and for this reason the minimum, average and maximum gas price (in €/kWh) over the last ten years is used to determine the possible savings. The minimum German gas price for consumers over this period was 5.39 €ct./kWh, the average 6.37 €ct./kWh and the maximum 7.04 €ct./kWh, [79]. This results in the savings as depicted in Table 23.

Building	Annual cost savings [€/a]		
	min.	avg.	max.
SAH 1	388	458	506
SAH 2	251	296	327
SAH 3	165	195	216

Table 23: Annual cost savings in euro per year as a result of scenario 1 BAS retrofits on the SAH 1 to 3 with gas burning boilers. Minimum (min.), average (avg.) and maximum (max.) expected values based on the corresponding gas prices for German consumers over the last 10 years.

The resulting annual cost savings, as described in Table 23, imply that implementation of scenario 1 BAS are economically viable. This can be concluded for even the least optimistic scenario with the lowest cost savings, as shown in Table 23, when assuming a payback period of two to three years and an initial investment of around 250 €.

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A Sankey diagram of the German final energy consumption

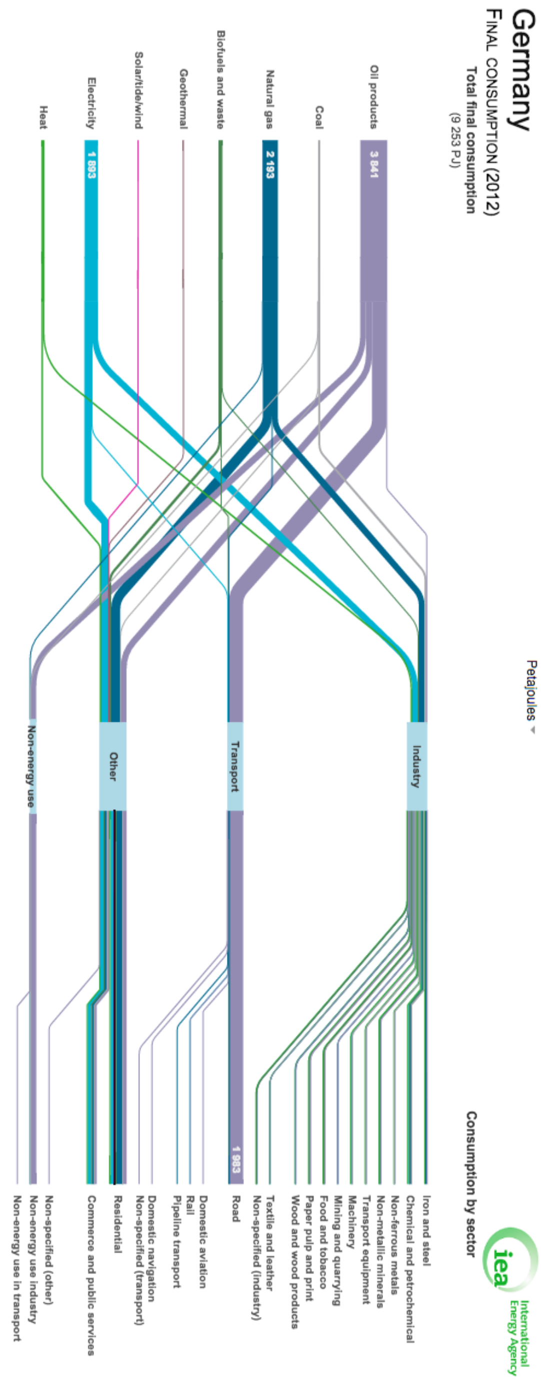


Figure 54: Final energy consumption of Germany in 2012, represented in a Sankey diagram in PJ. Total: 9253 PJ, based on data from the IEA [42].

B German building type matrix - TABULA

Figure 55: German residential building type matrix as defined by the TABULA project, standard building types and exceptional cases ("Sonderfälle"), [52].

Important to note is that the TABULA categories differ in name compared to the definitions in this research. The TABULA name EFH/SFH corresponds to the definition SAH and RH/TH corresponds to LH as defined in this research.

C TABULA input data

This appendix lists all the input values as provided by the TABULA project [47] for the three modelled houses.

C.1 SAH 1

Variable		Value	Unit	Description
$A_{c,ref}$		141	$[m^2]$	Complete floor area of the building (all storeys combined)
$V_{building}$		595	$[m^3]$	Total building volume (all storeys combined)
U_{WB}		0.1	$[W/m^2 \cdot K]$	Surcharge heat transfer coefficient for thermal bridges
T_{set}		20	[ºC]	Set room temperature during standard operation
g		0.75	$[-]$	Solar energy transmission factor of the window
Floor	$F_{x,floor}$	0.5	$[-]$	Temperature correction factor
	A_{floor}	78.3	$[m^2]$	Area of the ground floor
	U_{floor}	1.02	$[W/m^2 \cdot K]$	Overall heat transfer coefficient
Roof	$F_{x,roof}$	1	$[-]$	Temperature correction factor
	A_{roof}	83.1	$[m^2]$	Area of the roof
	U_{roof}	1.3	$[W/m^2 \cdot K]$	Overall heat transfer coefficient
Wall_N	$F_{x,wall,N}$	1	$[-]$	Temperature correction factor
	$A_{wall,N}$	48.51	$[m^2]$	Area of the wall
	$A_{window,N}$	1.4	$[m^2]$	Area of the all windows combined
	$A_{door,N}$	2	$[m^2]$	Area of the door
	$U_{wall,N}$	1.7	$[W/m^2 \cdot K]$	Overall heat transfer coefficient of the wall
	$U_{window,N}$	3.5	$[W/m^2 \cdot K]$	Overall heat transfer coefficient of the window
	$U_{door,N}$	3	$[W/m^2 \cdot K]$	Overall heat transfer coefficient of the door
Wall_E	$F_{x,wall,E}$	1	$[-]$	Temperature correction factor
	$A_{wall,E}$	48.51	$[m^2]$	Area of the ground floor
	$A_{window,E}$	7.65	$[m^2]$	Area of the all windows combined
	$U_{wall,E}$	1.7	$[W/m^2 \cdot K]$	Overall heat transfer coefficient of the wall
	$U_{window,E}$	3.5	$[W/m^2 \cdot K]$	Overall heat transfer coefficient of the window
Wall_S	$F_{x,wall,S}$	1	$[-]$	Temperature correction factor
	$A_{wall,S}$	48.51	$[m^2]$	Area of the ground floor
	$A_{window,S}$	5.6	$[m^2]$	Area of the all windows combined
	$U_{wall,S}$	1.7	$[W/m^2 \cdot K]$	Overall heat transfer coefficient of the wall
	$U_{window,S}$	3.5	$[W/m^2 \cdot K]$	Overall heat transfer coefficient of the window
Wall_W	$F_{x,wall,W}$	1	$[-]$	Temperature correction factor
	$A_{wall,W}$	48.51	$[m^2]$	Area of the ground floor
	$A_{window,W}$	7.65	$[m^2]$	Area of the all windows combined
	$U_{wall,W}$	1.7	$[W/m^2 \cdot K]$	Overall heat transfer coefficient of the wall
	$U_{window,W}$	3.5	$[W/m^2 \cdot K]$	Overall heat transfer coefficient of the window

Table 24: Input data for the RBM as provided by the TABULA project, [47]. SAH 1.

C.2 SAH 2

Variable		Value	Unit	Description
$A_{c,ref}$		150	$[m^2]$	Complete floor area of the building (all storeys combined)
$V_{building}$		514	$[m^3]$	Total building volume (all storeys combined)
U_{WB}		0.1	$[W/m^2 \cdot K]$	Surcharge heat transfer coefficient for thermal bridges
T_{set}		20	$[^oC]$	Set room temperature during standard operation
g		0.75	$[-]$	Solar energy transmission factor of the window
Floor	$F_{x,floor}$	0.5	$[-]$	Temperature correction factor
	A_{floor}	75.3	$[m^2]$	Area of the ground floor
	U_{floor}	0.51	$[W/m^2 \cdot K]$	Overall heat transfer coefficient
Roof	$F_{x,roof}$	1	$[-]$	Temperature correction factor
	A_{roof}	123	$[m^2]$	Area of the roof
	U_{roof}	0.4	$[W/m^2 \cdot K]$	Overall heat transfer coefficient
Wall_N	$F_{x,wall,N}$	1	$[-]$	Temperature correction factor
	$A_{wall,N}$	52.8	$[m^2]$	Area of the wall
	$A_{window,N}$	2.1	$[m^2]$	Area of the all windows combined
	$A_{door,N}$	2	$[m^2]$	Area of the door
	$U_{wall,N}$	0.5	$[W/m^2 \cdot K]$	Overall heat transfer coefficient of the wall
	$U_{window,N}$	3.5	$[W/m^2 \cdot K]$	Overall heat transfer coefficient of the window
	$U_{door,N}$	3	$[W/m^2 \cdot K]$	Overall heat transfer coefficient of the door
Wall_E	$F_{x,wall,E}$	1	$[-]$	Temperature correction factor
	$A_{wall,E}$	52.8	$[m^2]$	Area of the ground floor
	$A_{window,E}$	7.4	$[m^2]$	Area of the all windows combined
	$U_{wall,E}$	0.5	$[W/m^2 \cdot K]$	Overall heat transfer coefficient of the wall
	$U_{window,E}$	3.5	$[W/m^2 \cdot K]$	Overall heat transfer coefficient of the window
Wall_S	$F_{x,wall,S}$	1	$[-]$	Temperature correction factor
	$A_{wall,S}$	52.8	$[m^2]$	Area of the ground floor
	$A_{window,S}$	12.7	$[m^2]$	Area of the all windows combined
	$U_{wall,S}$	0.5	$[W/m^2 \cdot K]$	Overall heat transfer coefficient of the wall
	$U_{window,S}$	3.5	$[W/m^2 \cdot K]$	Overall heat transfer coefficient of the window
Wall_W	$F_{x,wall,W}$	1	$[-]$	Temperature correction factor
	$A_{wall,W}$	52.8	$[m^2]$	Area of the ground floor
	$A_{window,W}$	7.4	$[m^2]$	Area of the all windows combined
	$U_{wall,W}$	0.5	$[W/m^2 \cdot K]$	Overall heat transfer coefficient of the wall
	$U_{window,W}$	3.5	$[W/m^2 \cdot K]$	Overall heat transfer coefficient of the window

Table 25: Input data for the RBM as provided by the TABULA project, [47]. SAH 2.

C.3 SAH 3

Variable		Value	Unit	Description
$A_{c,ref}$		146	$[m^2]$	Complete floor area of the building (all storeys combined)
$V_{building}$		479	$[m^3]$	Total building volume (all storeys combined)
U_{WB}		0.05	$[W/m^2 \cdot K]$	Surcharge heat transfer coefficient for thermal bridges
T_{set}		20	$[^oC]$	Set room temperature during standard operation
g		0.6	$[-]$	Solar energy transmission factor of the window
Floor	$F_{x,floor}$	0.5	$[-]$	Temperature correction factor
	A_{floor}	79.8	$[m^2]$	Area of the ground floor
	U_{floor}	0.28	$[W/m^2 \cdot K]$	Overall heat transfer coefficient
Roof	$F_{x,roof}$	1	$[-]$	Temperature correction factor
	A_{roof}	85.9	$[m^2]$	Area of the roof
	U_{roof}	0.25	$[W/m^2 \cdot K]$	Overall heat transfer coefficient
Wall_N	$F_{x,wall,N}$	1	$[-]$	Temperature correction factor
	$A_{wall,N}$	47.2	$[m^2]$	Area of the wall
	$A_{window,N}$	3.12	$[m^2]$	Area of the all windows combined
	$A_{door,N}$	2	$[m^2]$	Area of the door
	$U_{wall,N}$	0.3	$[W/m^2 \cdot K]$	Overall heat transfer coefficient of the wall
	$U_{window,N}$	1.4	$[W/m^2 \cdot K]$	Overall heat transfer coefficient of the window
	$U_{door,N}$	2	$[W/m^2 \cdot K]$	Overall heat transfer coefficient of the door
Wall_E	$F_{x,wall,E}$	1	$[-]$	Temperature correction factor
	$A_{wall,E}$	47.2	$[m^2]$	Area of the ground floor
	$A_{window,E}$	3.94	$[m^2]$	Area of the all windows combined
	$U_{wall,E}$	0.3	$[W/m^2 \cdot K]$	Overall heat transfer coefficient of the wall
	$U_{window,E}$	1.4	$[W/m^2 \cdot K]$	Overall heat transfer coefficient of the window
Wall_S	$F_{x,wall,S}$	1	$[-]$	Temperature correction factor
	$A_{wall,S}$	47.2	$[m^2]$	Area of the ground floor
	$A_{window,S}$	17.3	$[m^2]$	Area of the all windows combined
	$U_{wall,S}$	0.3	$[W/m^2 \cdot K]$	Overall heat transfer coefficient of the wall
	$U_{window,S}$	1.4	$[W/m^2 \cdot K]$	Overall heat transfer coefficient of the window
Wall_W	$F_{x,wall,W}$	1	$[-]$	Temperature correction factor
	$A_{wall,W}$	47.2	$[m^2]$	Area of the ground floor
	$A_{window,W}$	3.94	$[m^2]$	Area of the all windows combined
	$U_{wall,W}$	0.3	$[W/m^2 \cdot K]$	Overall heat transfer coefficient of the wall
	$U_{window,W}$	1.4	$[W/m^2 \cdot K]$	Overall heat transfer coefficient of the window

Table 26: Input data for the RBM as provided by the TABULA project, [47]. SAH 3.

D Model parts - Modelica

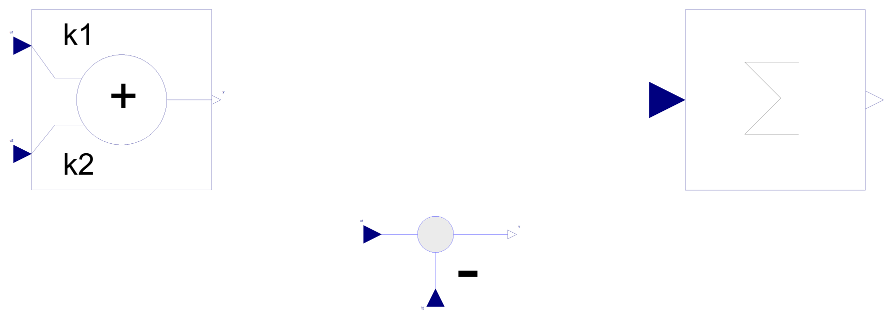
D.1 Basic Modelica building blocks

Icons for two heatports. A heatport transfers two variables, the temperature T and the heatflow Q_{flow}. Both ports are identical in their properties, apart from their color which helps distinguishing the direction of heatflow and the connection to other models. Basic building blocks of Modelica.

Icons for a Real input $left$ and a Real output $right$. These ports transfer values of type Real and are basic building blocks of Modelica.

Icons for a Integer input $left$ and a Integer output $right$. These ports transfer values of type Integer and are basic building blocks of Modelica.

Icons for a Boolean input $left$ and a Boolean output $right$. These ports transfer values of type Boolean and are basic building blocks of Modelica.



Icons for the addition of two Real inputs *left* the sum of any number of Real inputs *right* and the subtraction of two Real inputs *middle*. These ports are basic building blocks of Modelica.

Icons for the product of two Real inputs *left* and the devision of two Real inputs *right*. These ports are basic building blocks of Modelica.

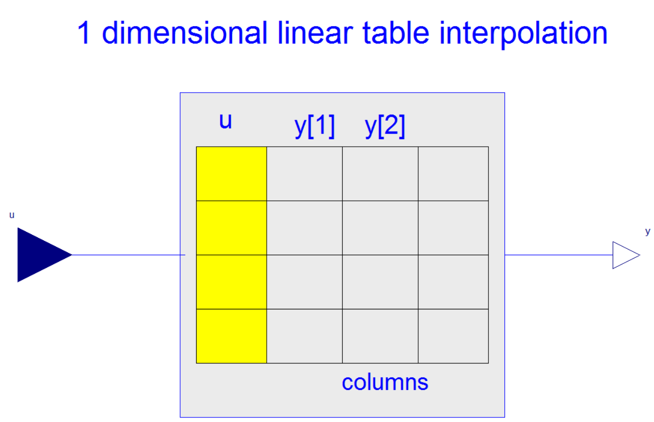


Figure 56: Icon for an input Table. Based on Real input u it looks up the corresponding stored value in the table and delivers it as output y. Where necessary it interpolates between two table entries .Basic building block of Modelica.

D.2 Constructed partial models - reference building

D.2.1 Outside wall

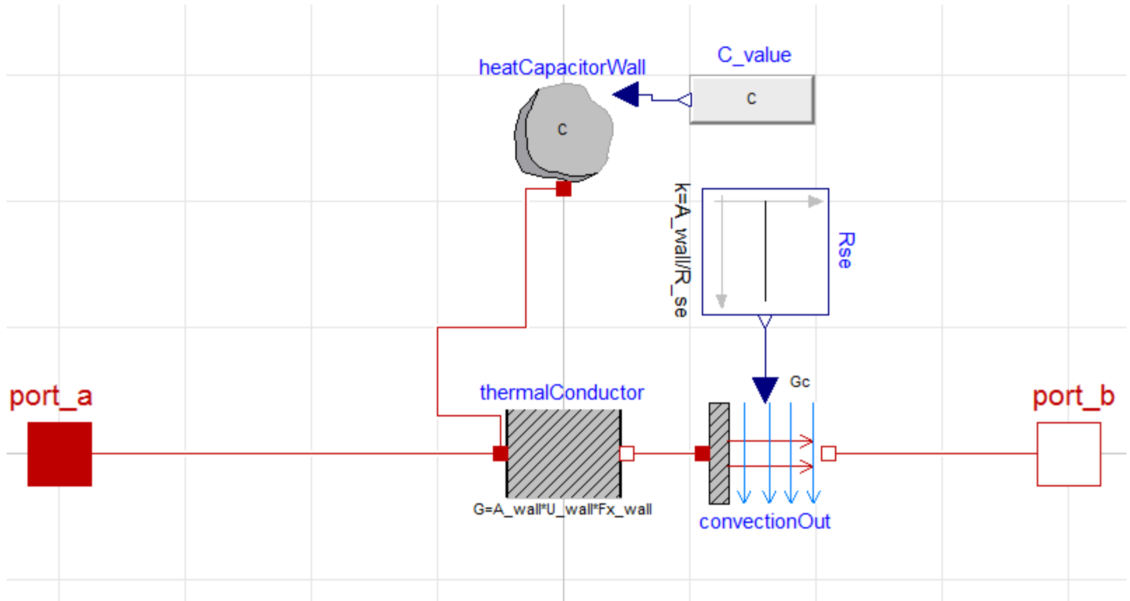


Figure 57: Representation of the partial model for an outside wall. Picture as taken from the final version of the Modelica model.

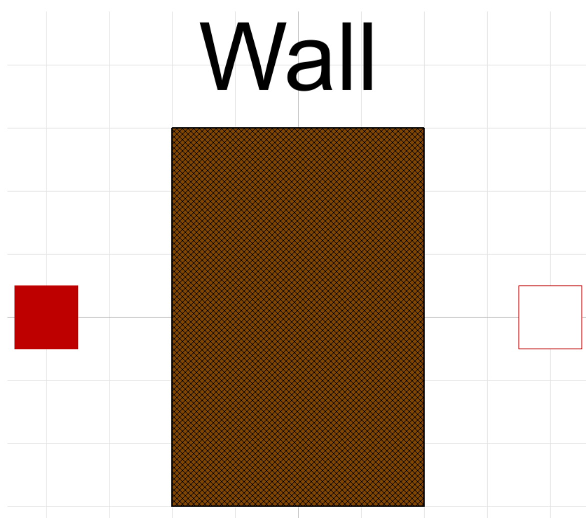


Figure 58: Icon of the partial model for an outside wall as shown in the previous picture. Picture as taken from the final version of the Modelica model.

D.2.2 Window

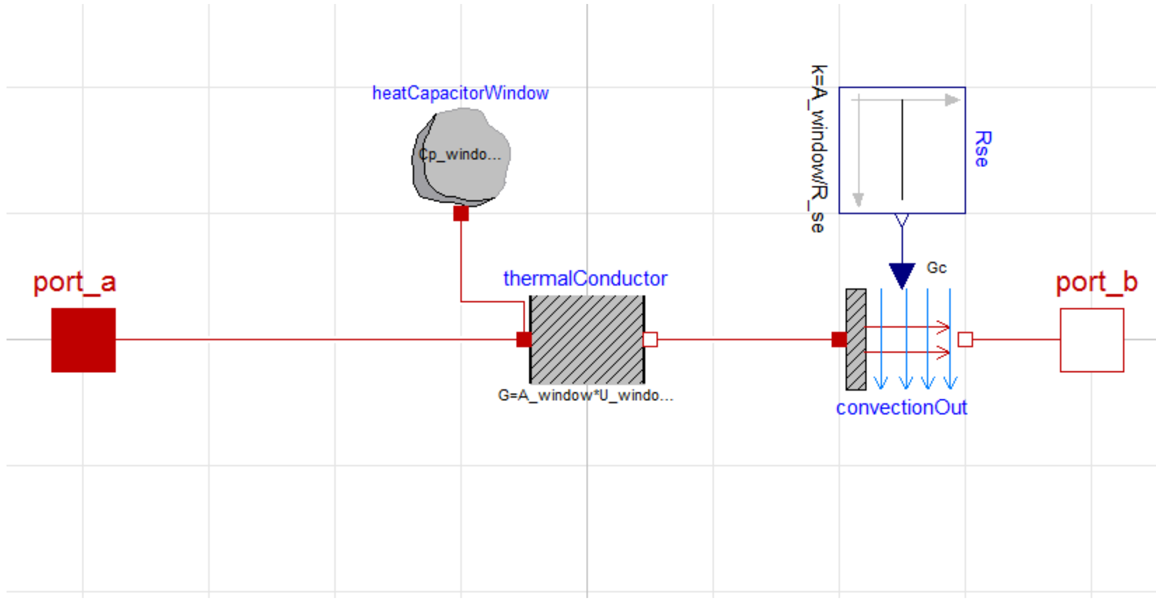


Figure 59: Representation of the partial model for a window. Picture as taken from the final version of the Modelica model.

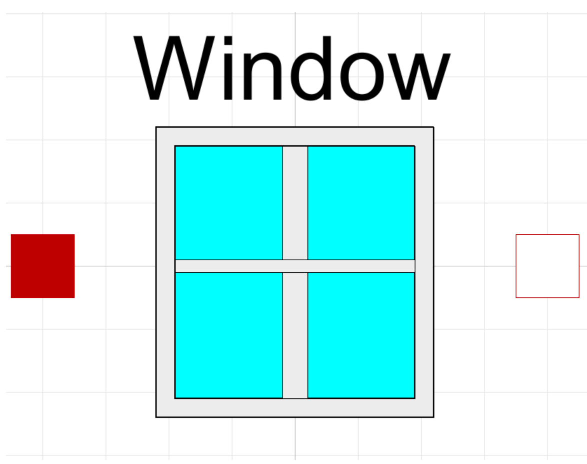


Figure 60: Icon of the partial model for a window as shown in the previous picture. Picture as taken from the final version of the Modelica model.

D.2.3 Thermal bridges

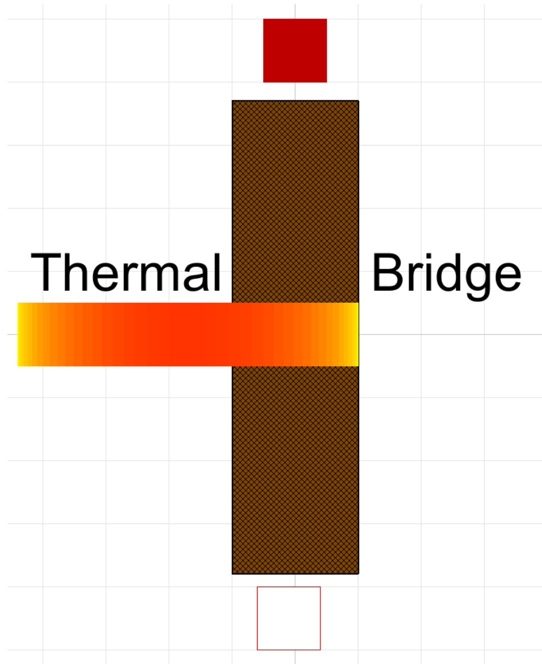


Figure 61: Icon of the partial model for thermal bridges. Picture as taken from the final version of the Modelica model.

D.2.4 Outside wall combined

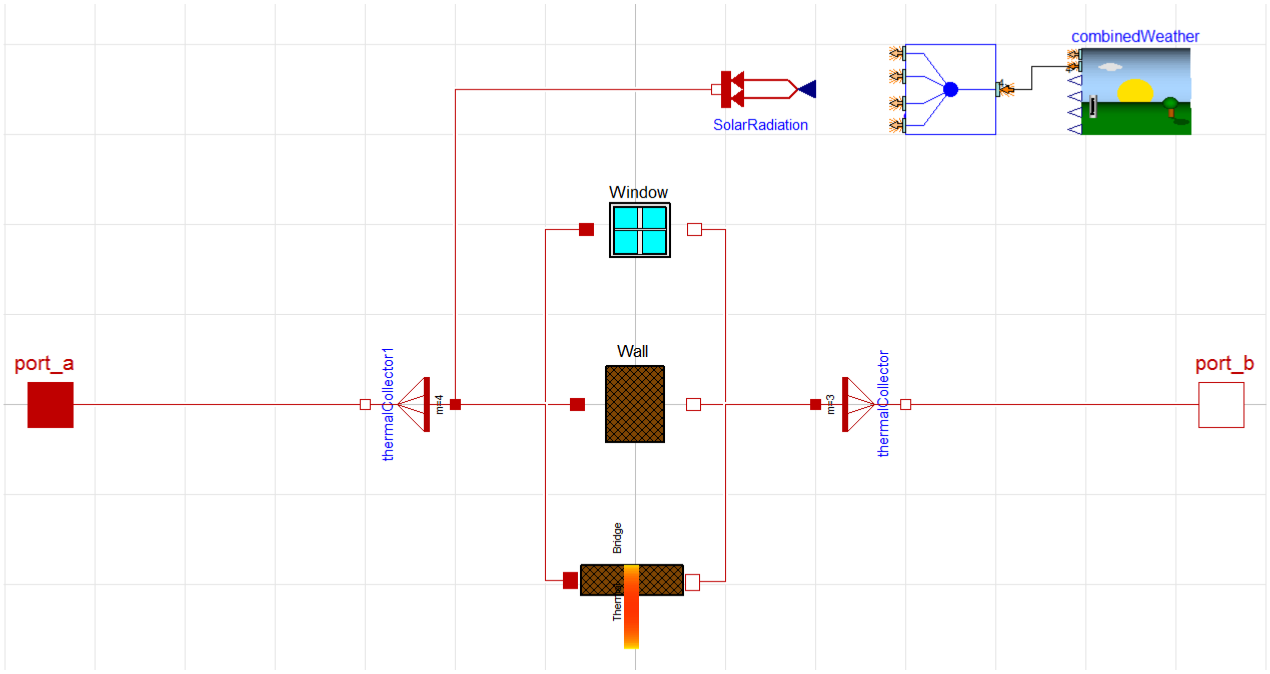


Figure 62: Representation of the partial model that combines the outside wall, window and heat bridges partial models. Picture as taken from the final version of the Modelica model.

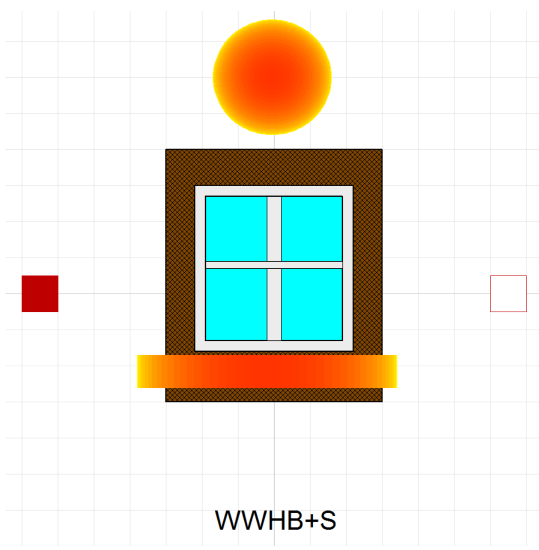


Figure 63: Icon of the partial model that combines the outside wall, window and heat bridges partial models, as shown in the previous picture. Picture as taken from the final version of the Modelica model.

D.2.5 Roof

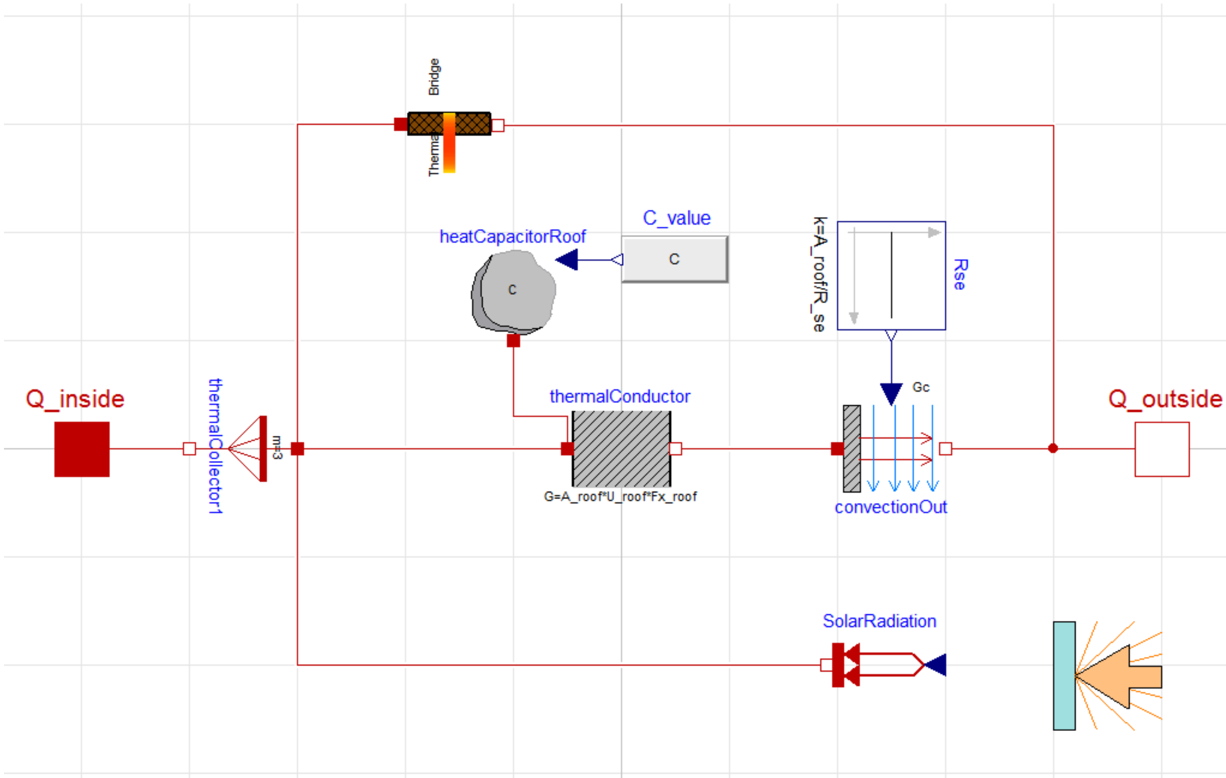


Figure 64: Representation of the partial model for a roof. Picture as taken from the final version of the Modelica model.

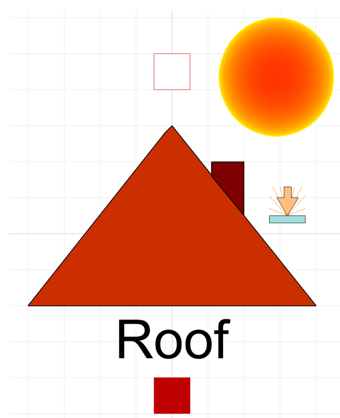


Figure 65: Icon of the partial model for a roof as shown in the previous picture. Picture as taken from the final version of the Modelica model.

D.2.6 Floor

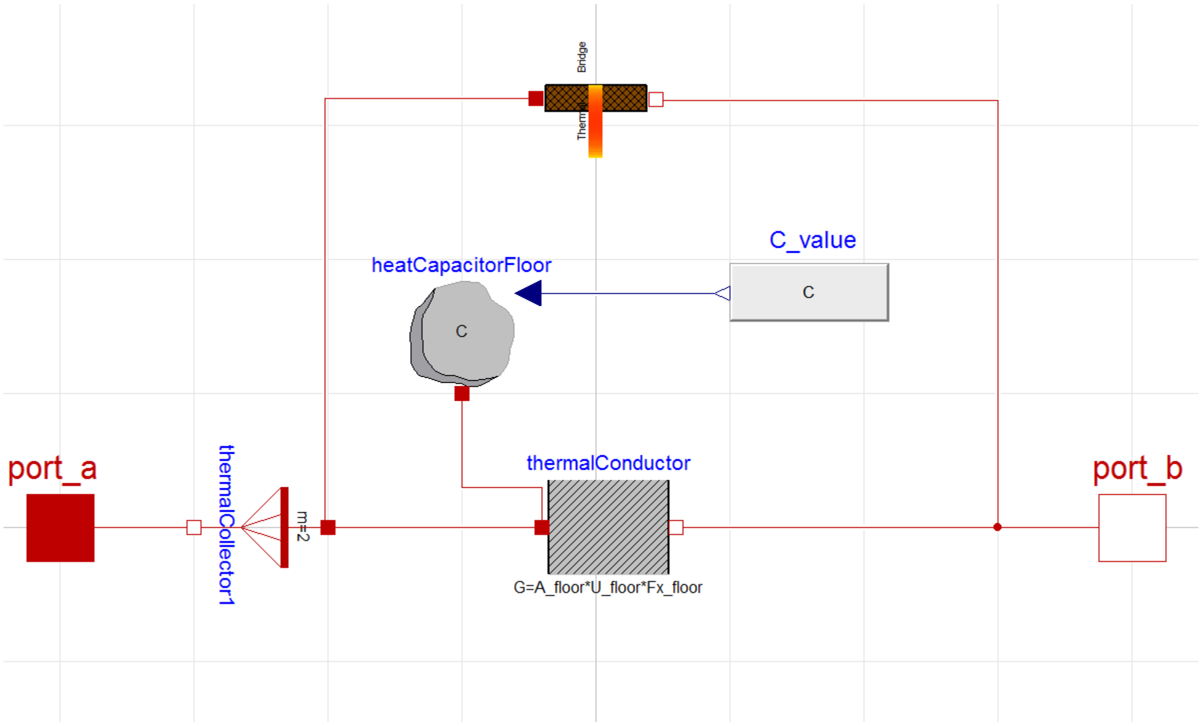


Figure 66: Representation of the partial model for a floor. Picture as taken from the final version of the Modelica model.

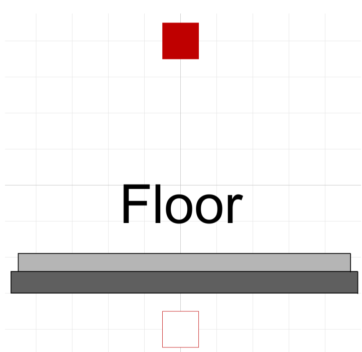


Figure 67: Icon of the partial model for a floor as shown in the previous picture. Picture as taken from the final version of the Modelica model.

D.2.7 Door

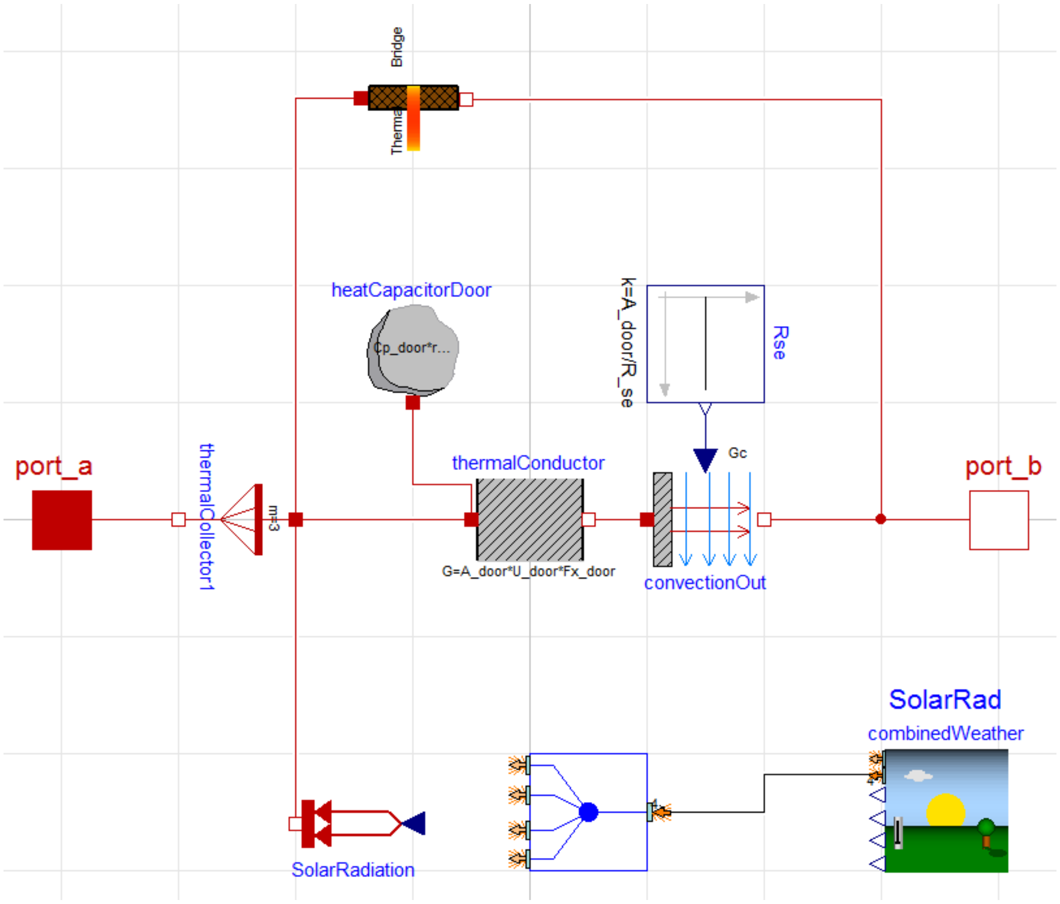


Figure 68: Representation of the partial model for a door. Picture as taken from the final version of the Modelica model.

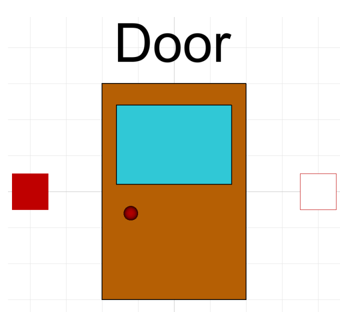


Figure 69: Icon of the partial model for a door as shown in the previous picture. Picture as taken from the final version of the Modelica model.

D.2.8 Interior wall

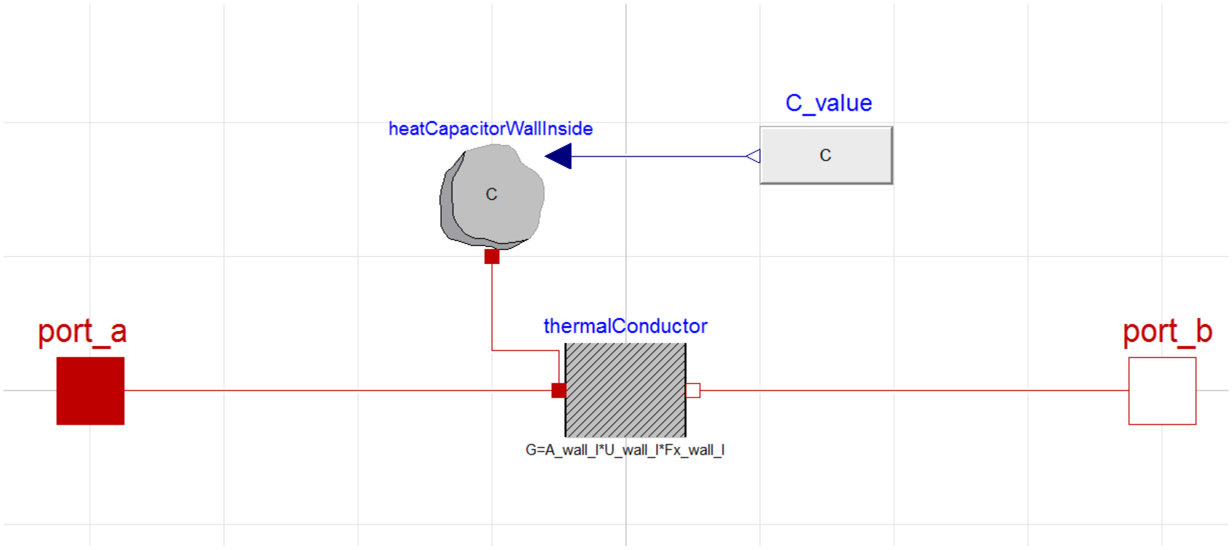


Figure 70: Representation of the partial model for an interior wall. Picture as taken from the final version of the Modelica model.

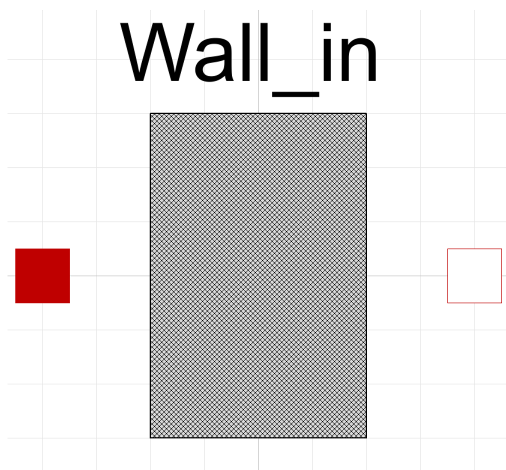


Figure 71: Icon of the partial model for an interior as shown in the previous picture. Picture as taken from the final version of the Modelica model.

D.2.9 Ceiling

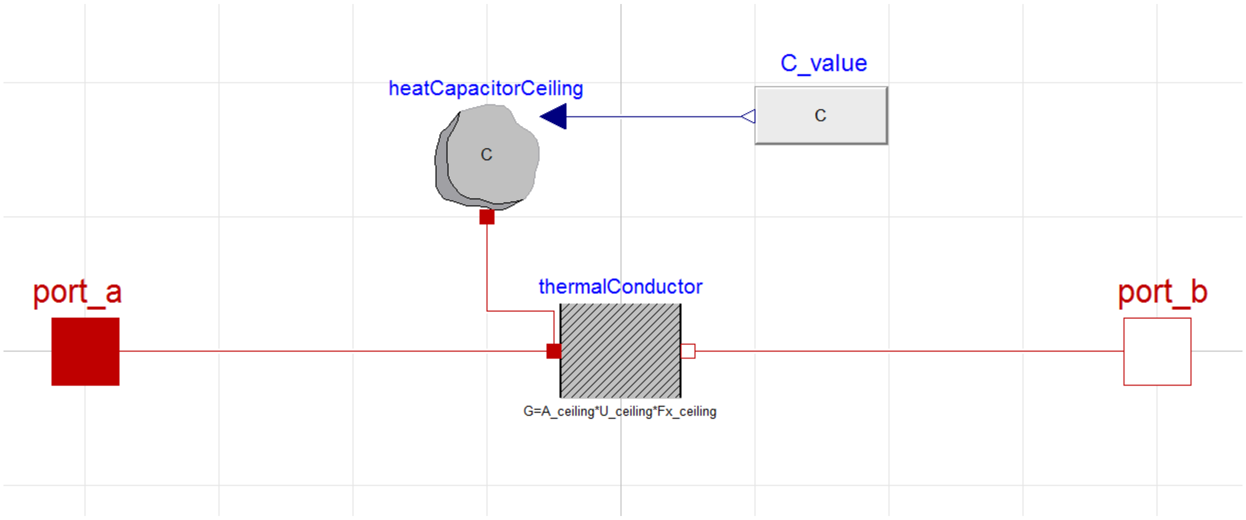


Figure 72: Representation of the partial model for an interior wall. Picture as taken from the final version of the Modelica model.

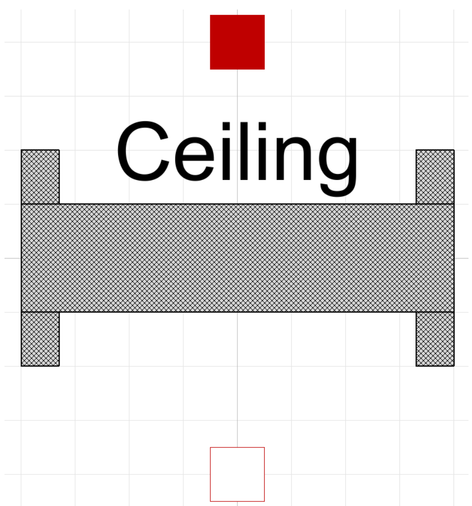


Figure 73: Icon of the partial model for an interior as shown in the previous picture. Picture as taken from the final version of the Modelica model.

D.2.10 Infiltration & ventilation

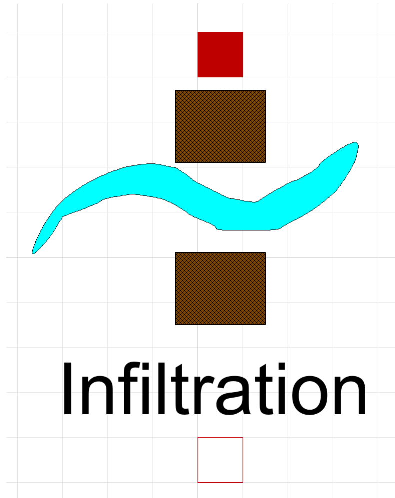


Figure 74: Icon of the partial model for infiltration. Picture as taken from the final version of the Modelica model.

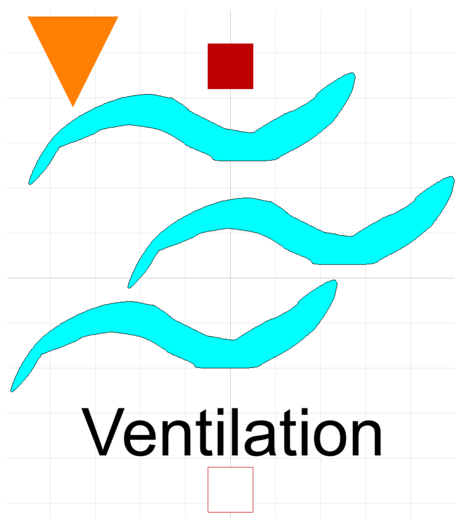


Figure 75: Icon of the partial model that combines infiltration and ventilation partial models. Picture as taken from the final version of the Modelica model.

D.2.11 Infiltration & ventilation combined

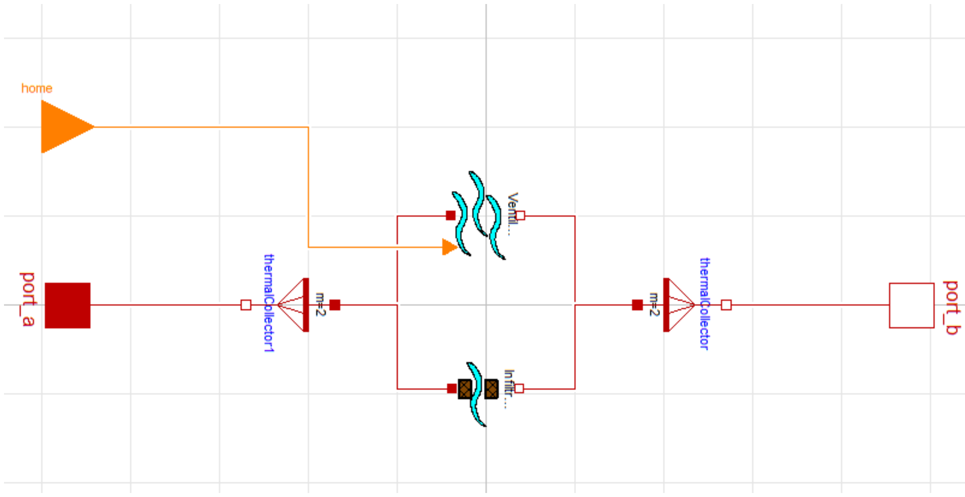


Figure 76: Representation of the partial model that combines infiltration and ventilation partial models. Picture as taken from the final version of the Modelica model.

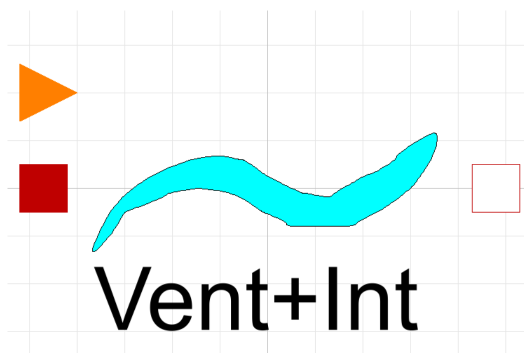


Figure 77: Icon of the partial model that combines infiltration and ventilation partial models, as shown in the previous picture. Picture as taken from the final version of the Modelica model.

D.2.12 Internal heat gains

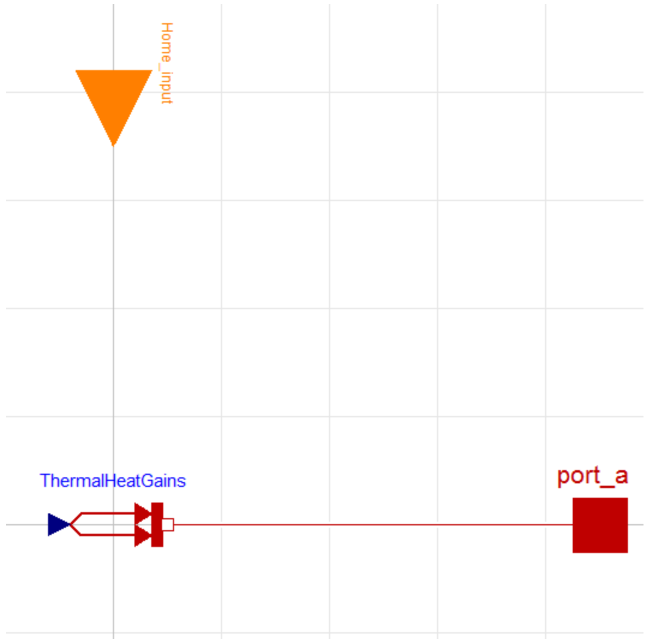


Figure 78: Representation of the partial model for internal heat gains. Picture as taken from the final version of the Modelica model.

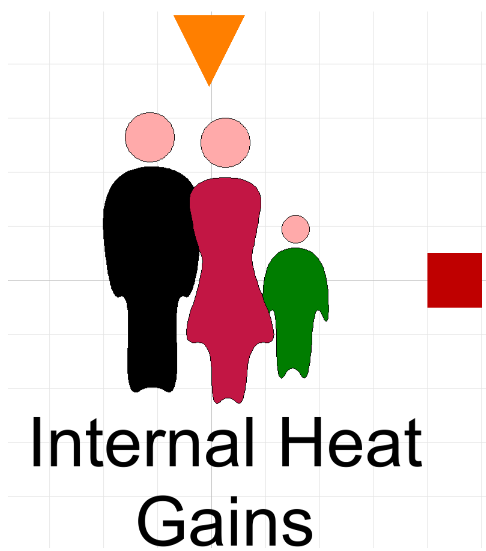


Figure 79: Icon of the partial model for internal heat gains, as shown in the previous picture. Picture as taken from the final version of the Modelica model.

D.2.13 Radiation exchange (small zone)

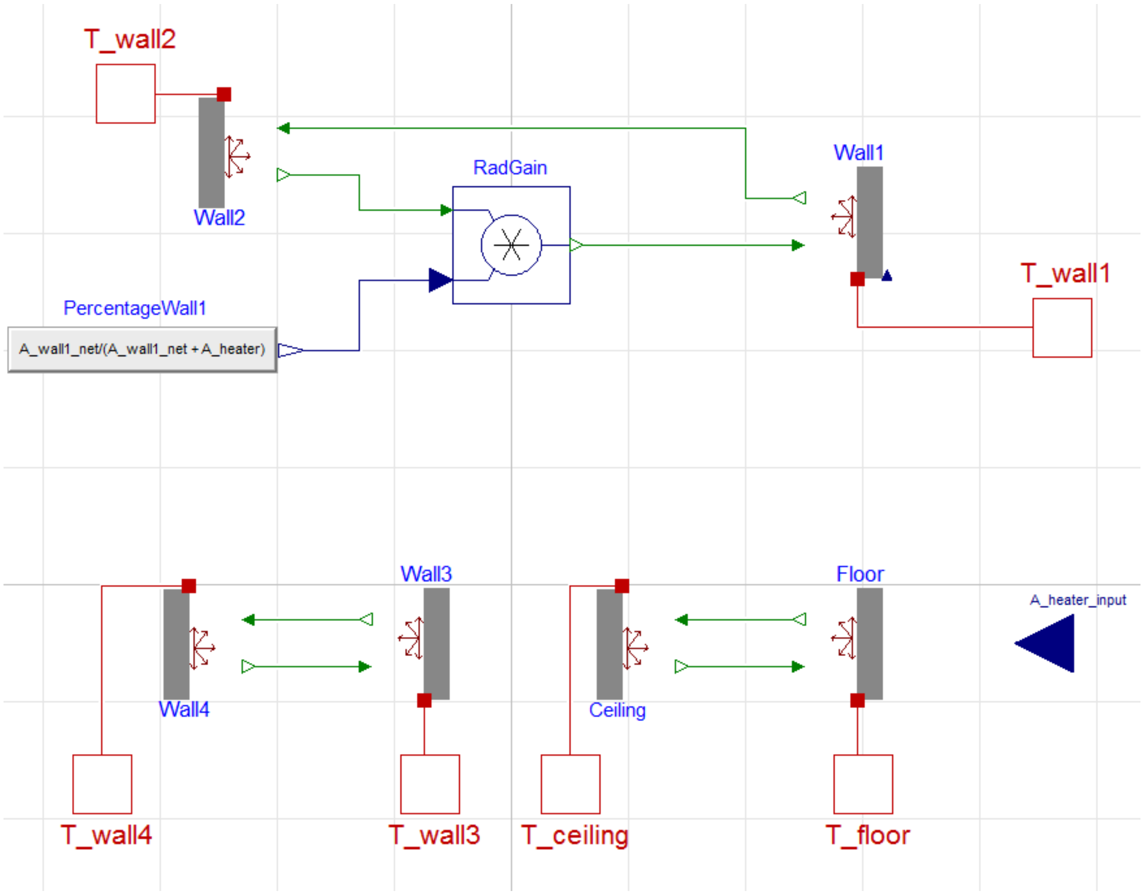


Figure 80: Representation of the partial model for radiation exchange between the walls, floor and ceiling of the room. Picture as taken from the final version of the Modelica model.

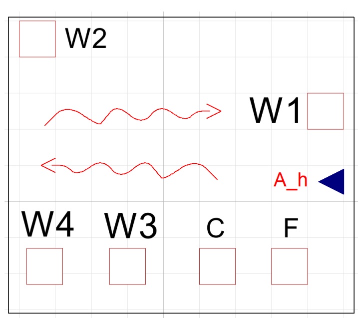


Figure 81: Icon of the partial model for radiation exchange between the walls, floor and ceiling of the room, as shown in the previous picture. Picture as taken from the final version of the Modelica model.

D.2.14 Radiation exchange (big zone)

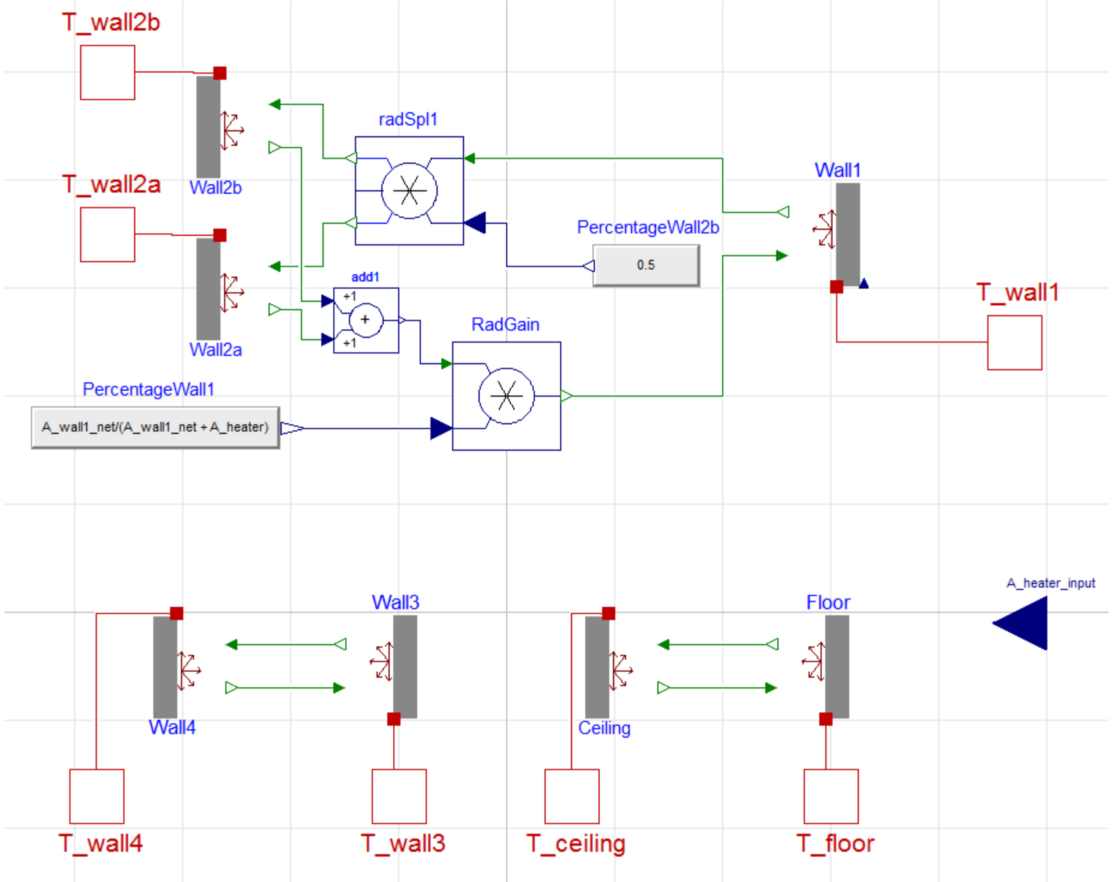


Figure 82: Representation of the partial model for radiation exchange between the walls, floor and ceiling of the room (Big zone model). Picture as taken from the final version of the Modelica model.

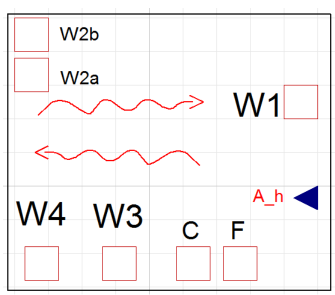


Figure 83: Icon of the partial model for radiation exchange between the walls, floor and ceiling of the room (Big zone model), as shown in the previous picture. Picture as taken from the final version of the Modelica model.

D.2.15 Heat production system

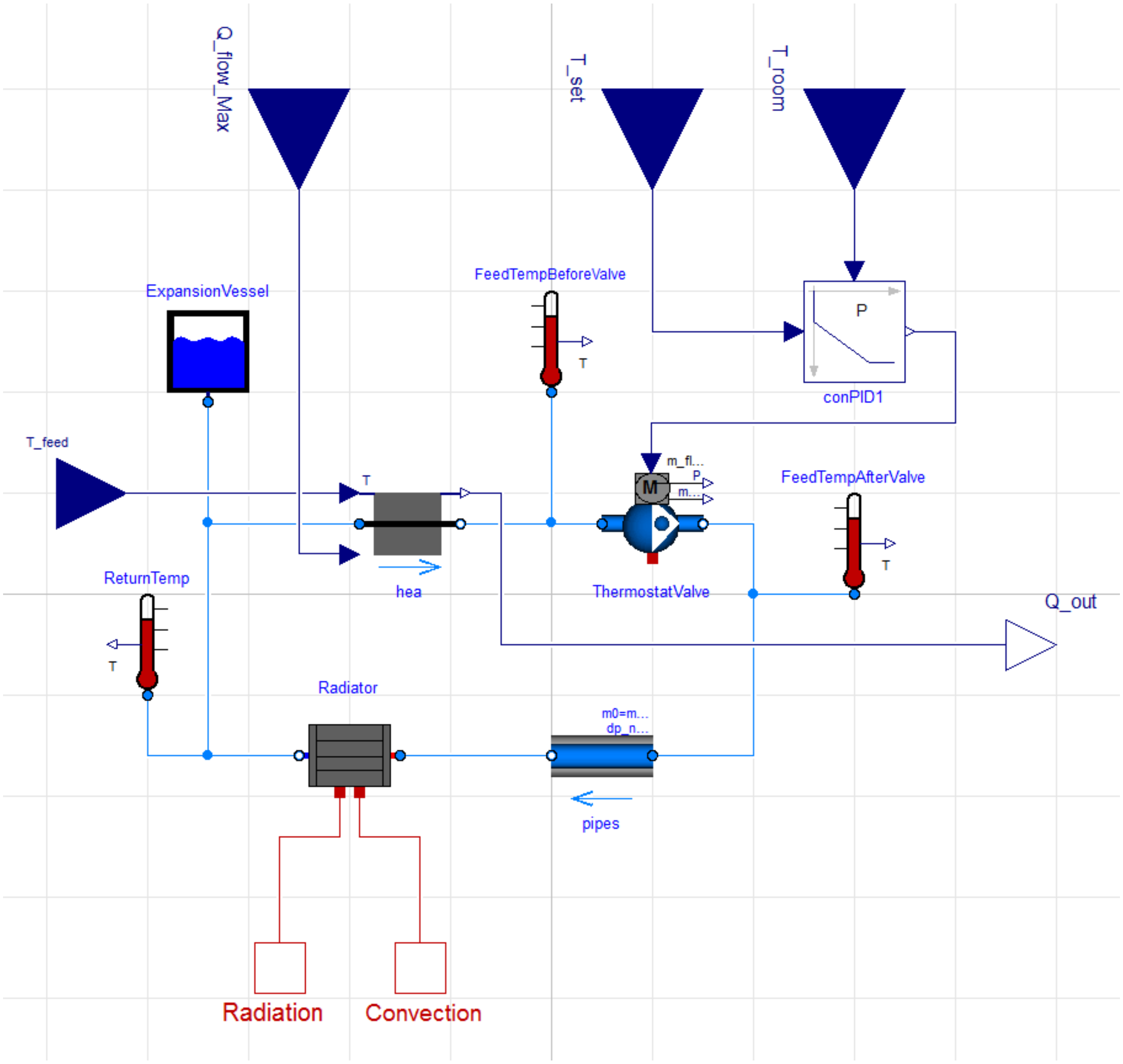


Figure 84: Representation of the "heat production system" partial model that simulates the boiler, the thermostat valve and the radiator. Picture as taken from the final version of the Modelica model, based on partial models as provided by the Modelica buildings library [51]

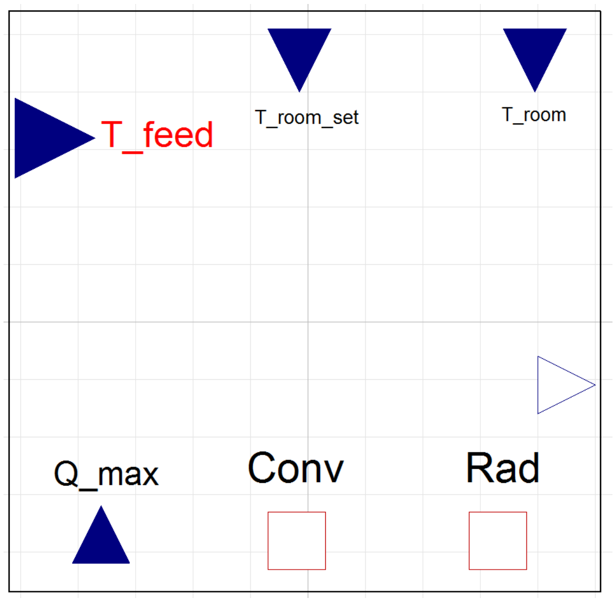


Figure 85: Icon of the partial model "heat production system", as shown in the previous picture. Picture as taken from the final version of the Modelica model.

D.2.16 Heat transmission system

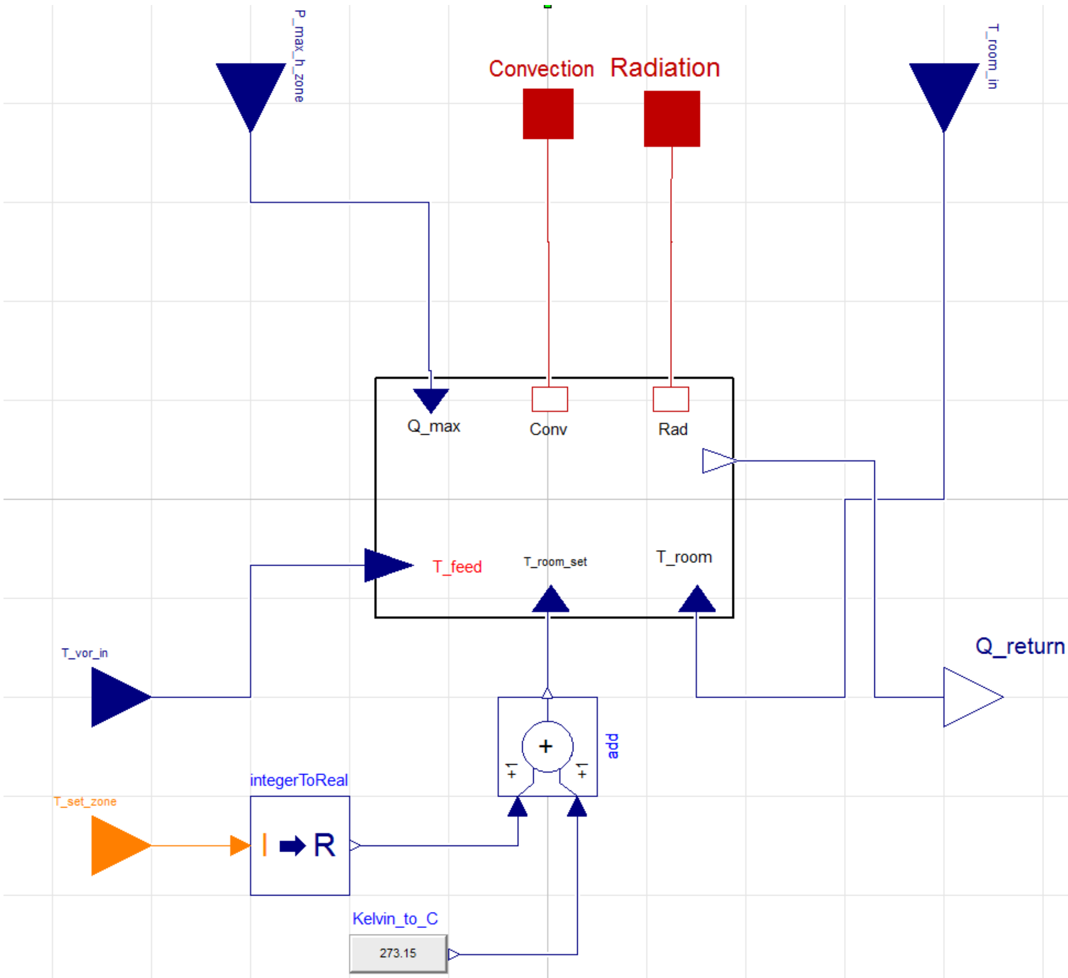


Figure 86: Representation of the partial model for the heat transmission system. Which includes the partial model. Picture as taken from the final version of the Modelica model.

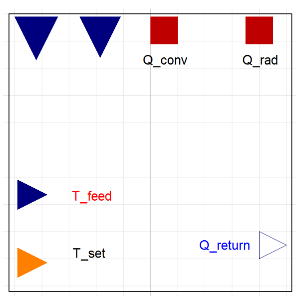


Figure 87: Icon of the partial model for the heat transmission system, as shown in the previous picture. Picture as taken from the final version of the Modelica model.

D.2.17 Indoor air

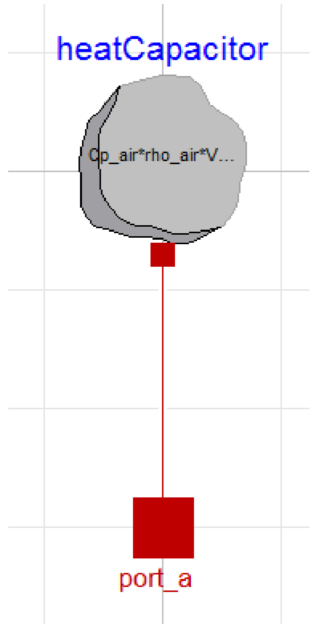


Figure 88: Representation of the partial model for the indoor air. Picture as taken from the final version of the Modelica model.

Figure 89: Icon of the partial model for the indoor air, as shown in the previous picture. Picture as taken from the final version of the Modelica model.

D.2.18 Combined zone model (small)

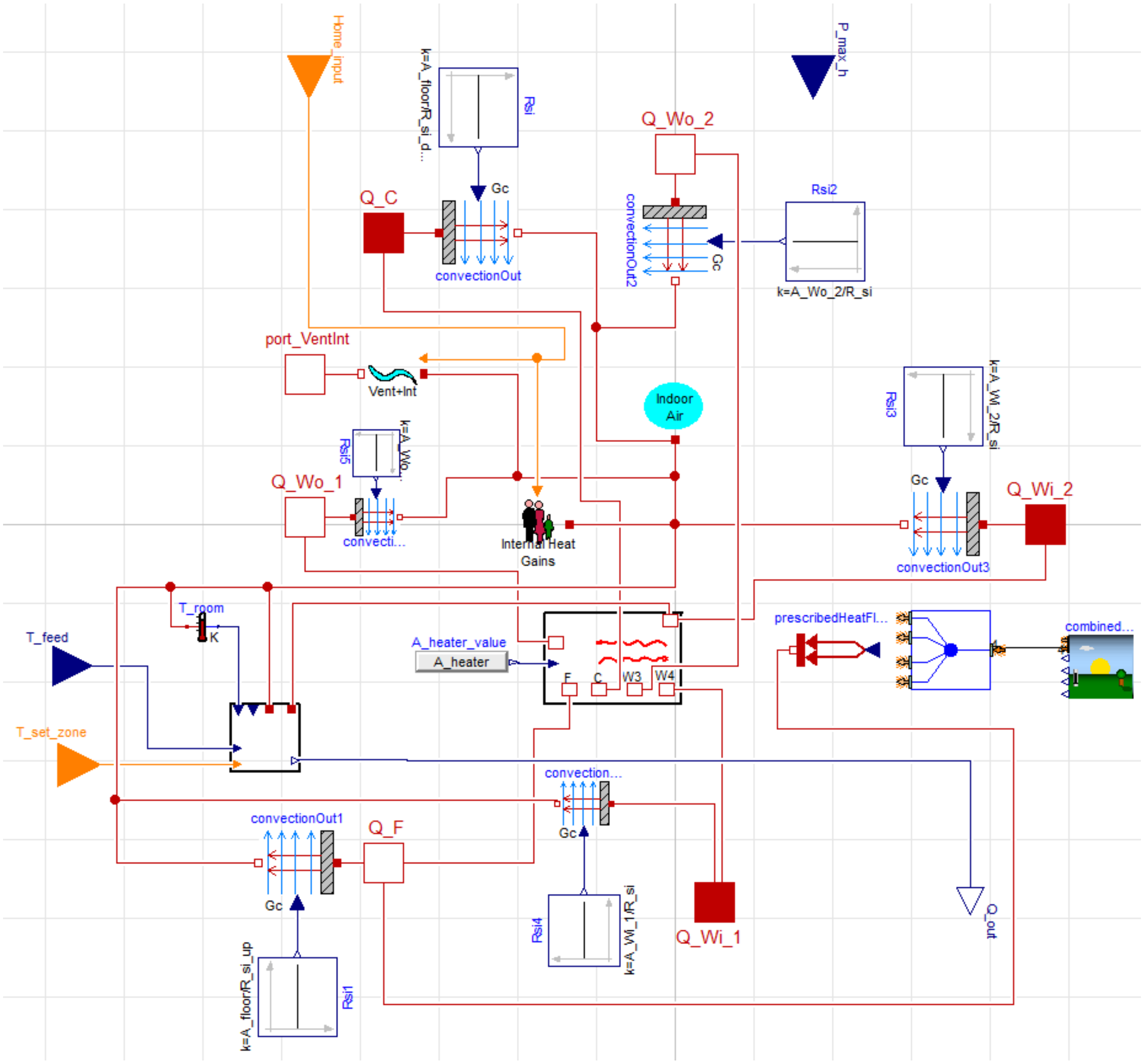


Figure 90: Representation of the partial model for a complete zone/room. Picture as taken from the final version of the Modelica model.

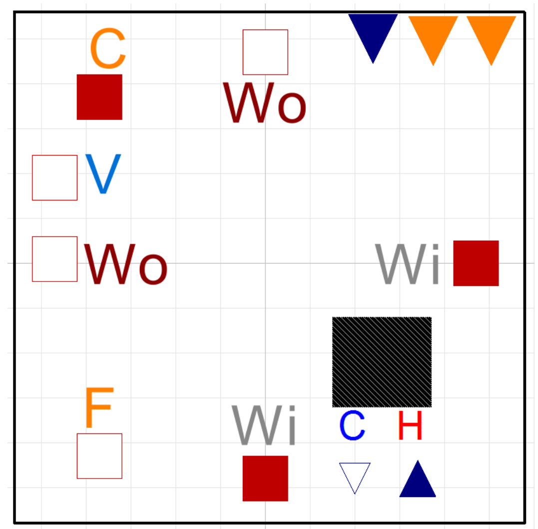


Figure 91: Icon of the partial model for a complete zone/room, as shown in the previous picture. Picture as taken from the final version of the Modelica model.

Combined zone model (big)

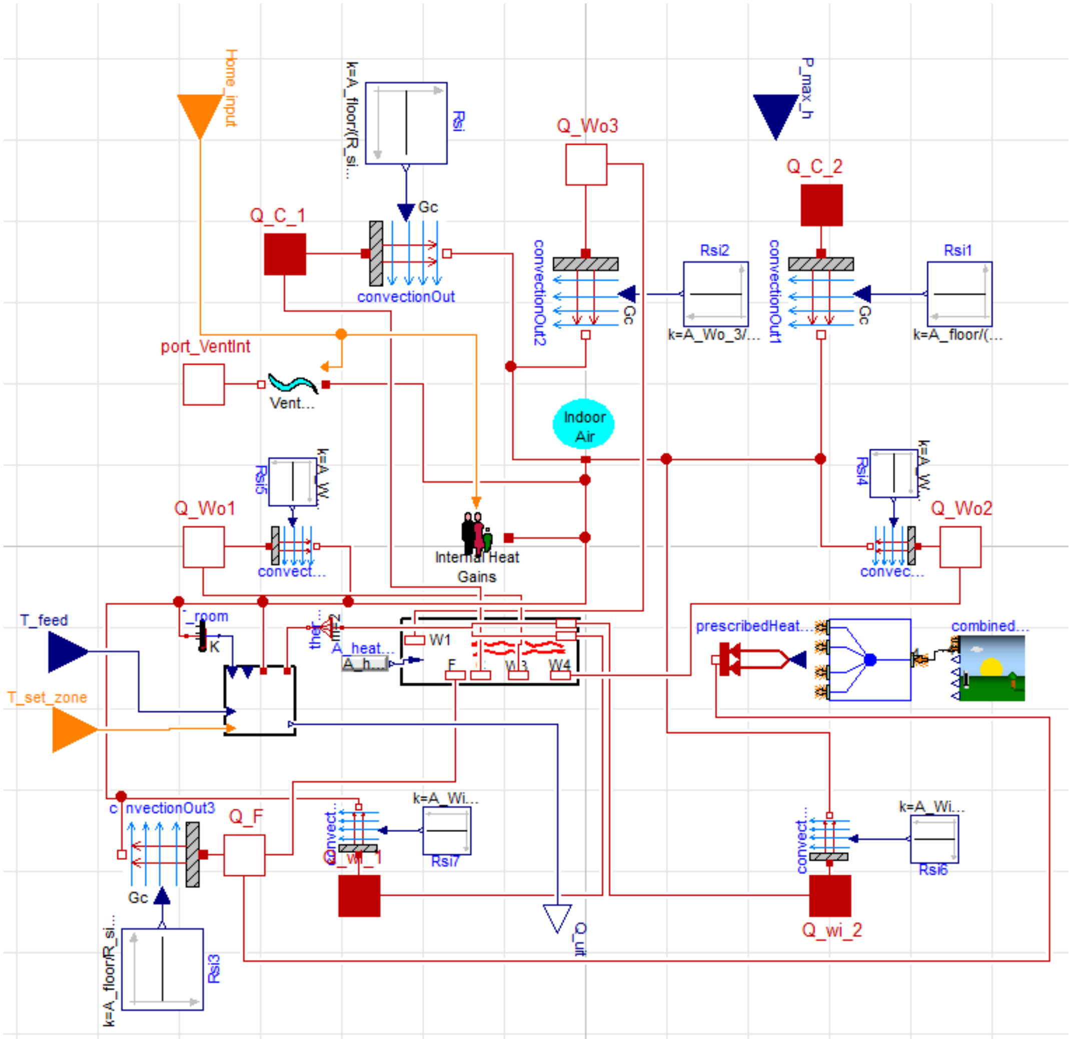


Figure 92: Representation of the partial model for a complete zone/room (Big). Picture as taken from the final version of the Modelica model.

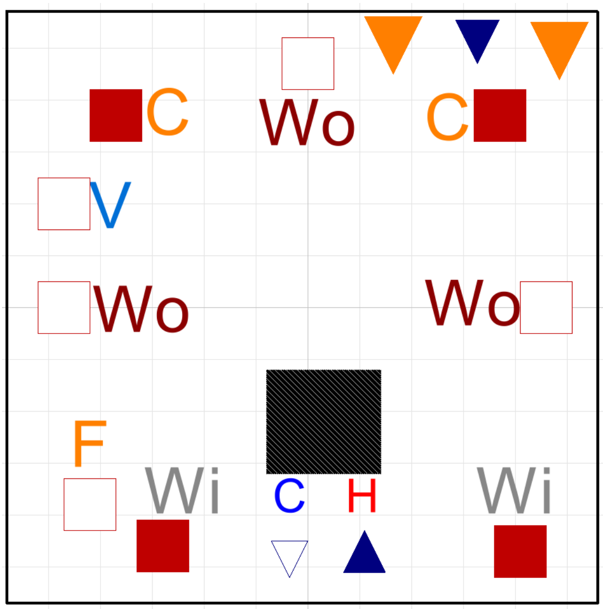


Figure 93: Icon of the partial model for a complete zone/room (big), as shown in the previous picture. Picture as taken from the final version of the Modelica model.

D.2.19 Outside temperature

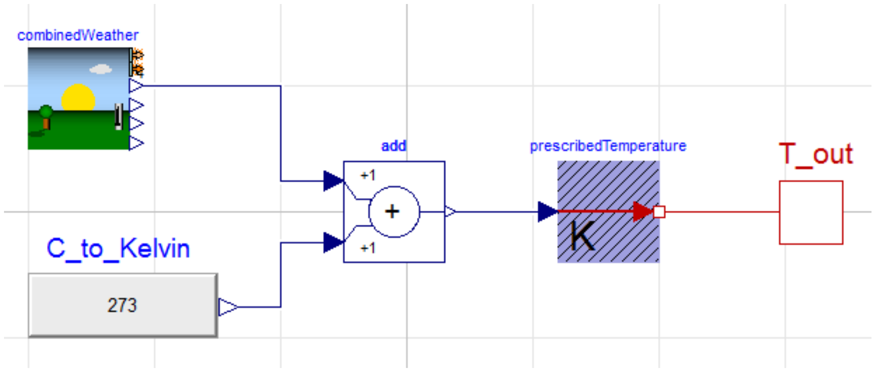


Figure 94: Representation of the partial model that provides the model with the outside temperature based on the combinedWeather file. Which incorporates the "Heizkurve" model which regulates the feed-in temperature based on the outside temperature. Picture as taken from the final version of the Modelica model.

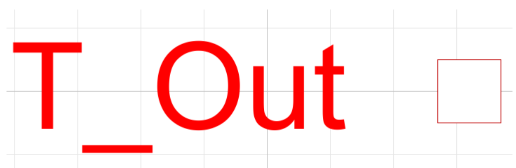


Figure 95: Icon of the partial model for the outside temperature, as shown in the previous picture. Picture as taken from the final version of the Modelica model.

D.2.20 Heating curve

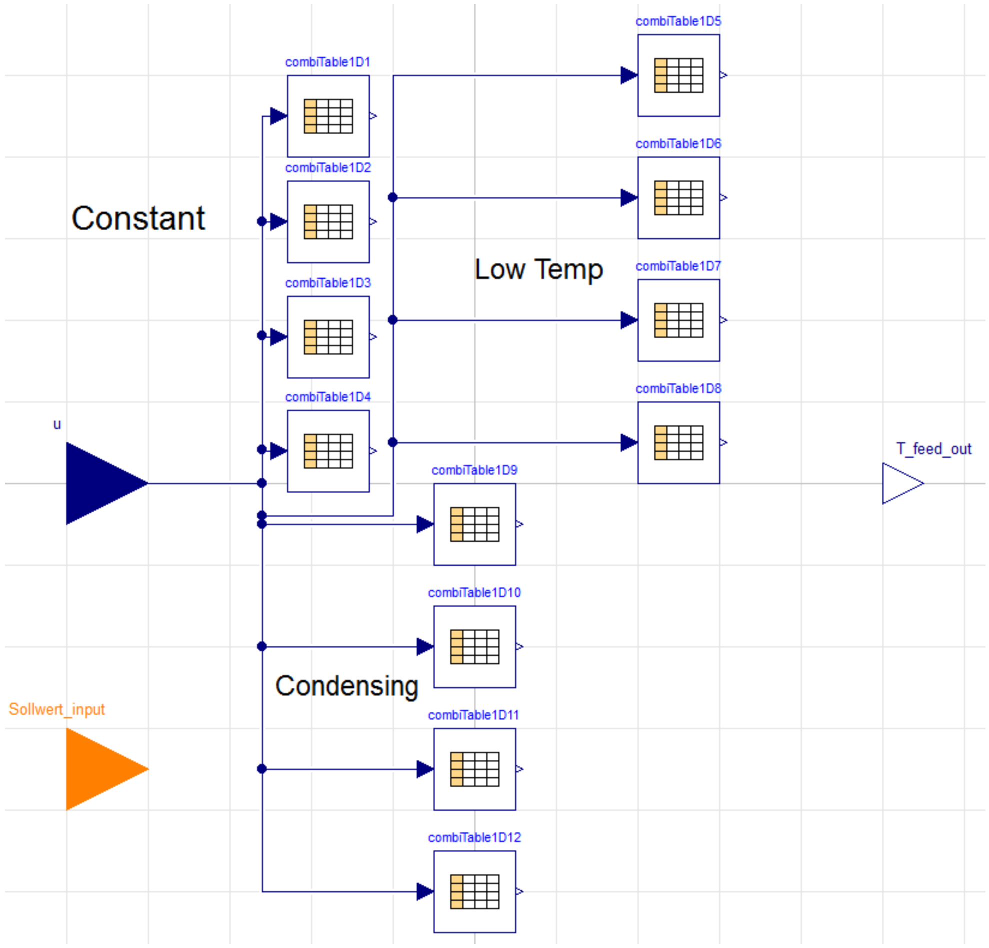


Figure 96: Representation of the partial model "Heizkurve" that provides the heating curve data for the different boilers. Which incorporates the "Heizkurve" model which regulates the feed-in temperature based on the outside temperature. Picture as taken from the final version of the Modelica model.

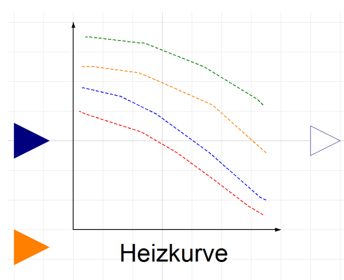


Figure 97: Icon of the partial model "Heizkurve", as shown in the previous picture. Picture as taken from the final version of the Modelica model.

D.2.21 Feed-in temperature regulation

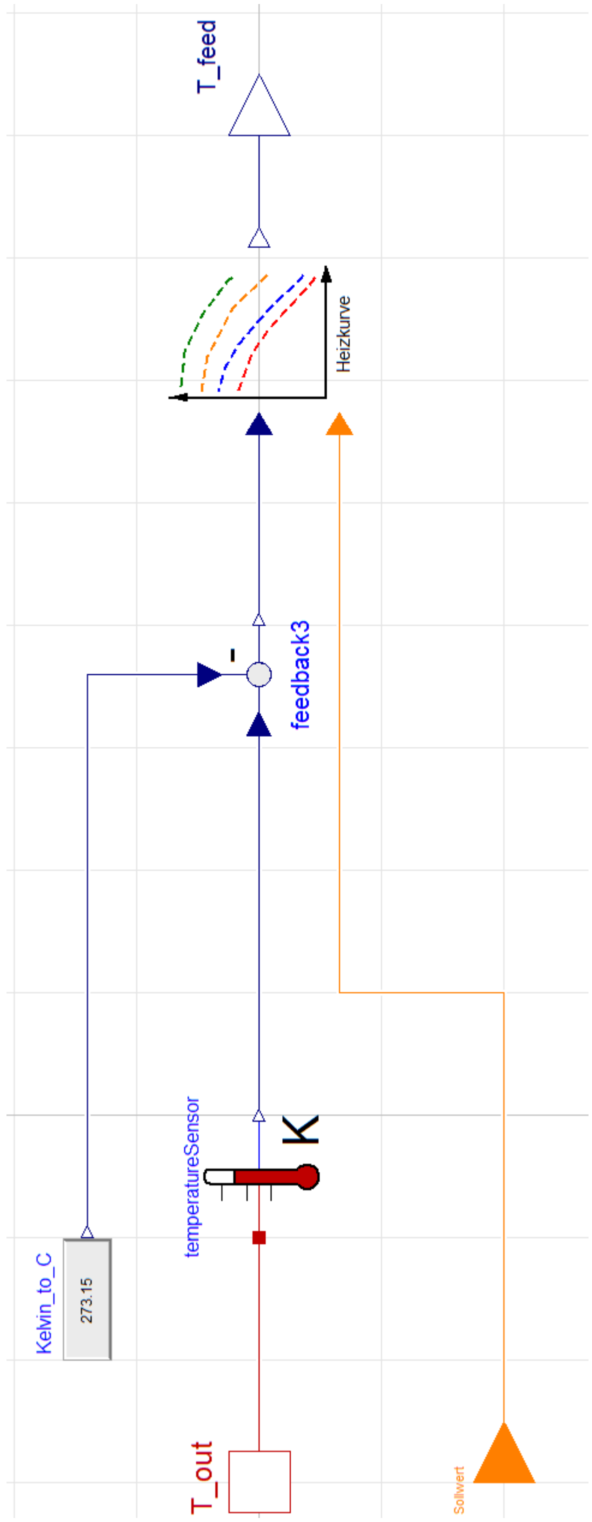


Figure 98: Representation of the partial model "HeatProd". Which incorporates the "Heizkurve" model which regulates the feed-in temperature based on the outside temperature. Picture as taken from the final version of the Modelica model.

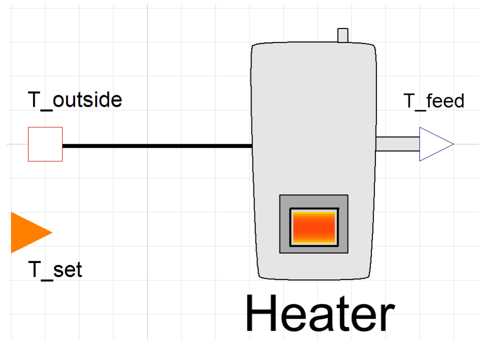


Figure 99: Icon of the partial model "HeatProd", as shown in the previous picture. Picture as taken from the final version of the Modelica model.

D.2.22 Efficiency curves ("Heizungskennlinie")

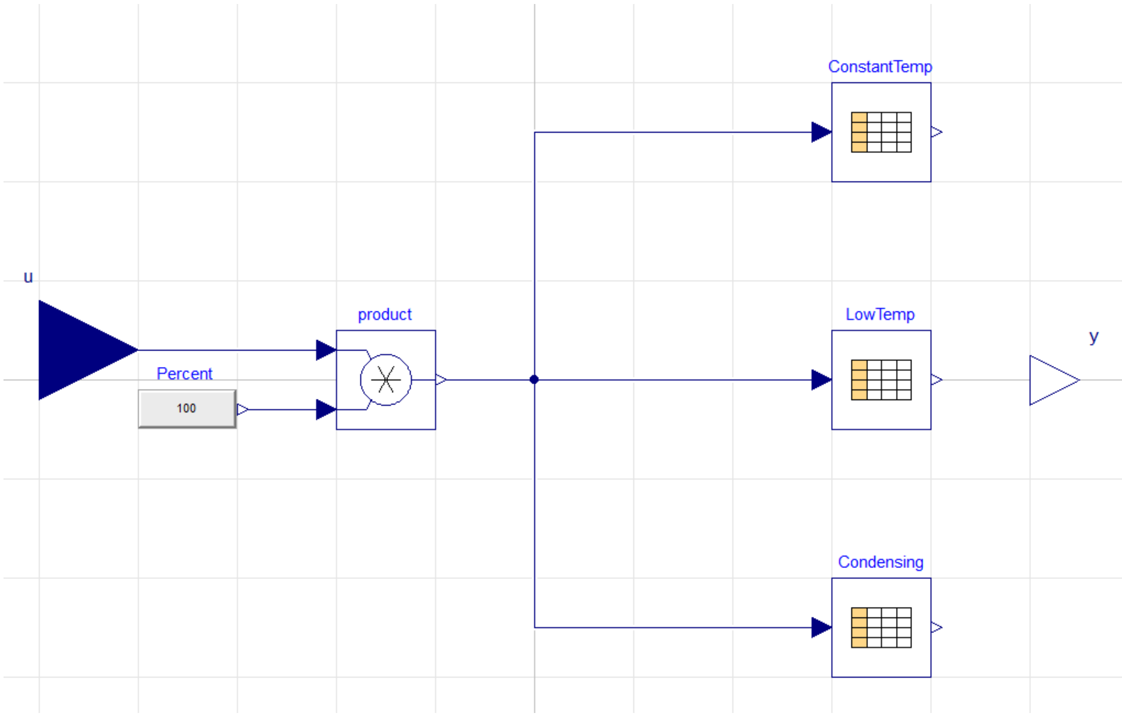


Figure 100: Representation of the "HeizungsKennlinie" partial model. Which provides the data for the efficiency of the boilers as a function of the load. Picture as taken from the final version of the Modelica model.

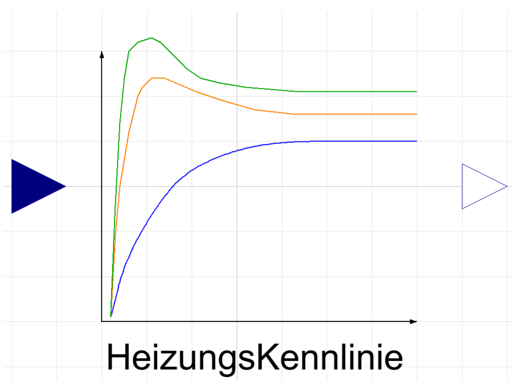


Figure 101: Icon of the partial model of the "HeizungsKennlinie", as shown in the previous picture. Picture as taken from the final version of the Modelica model.

D.2.23 Combined heat production system

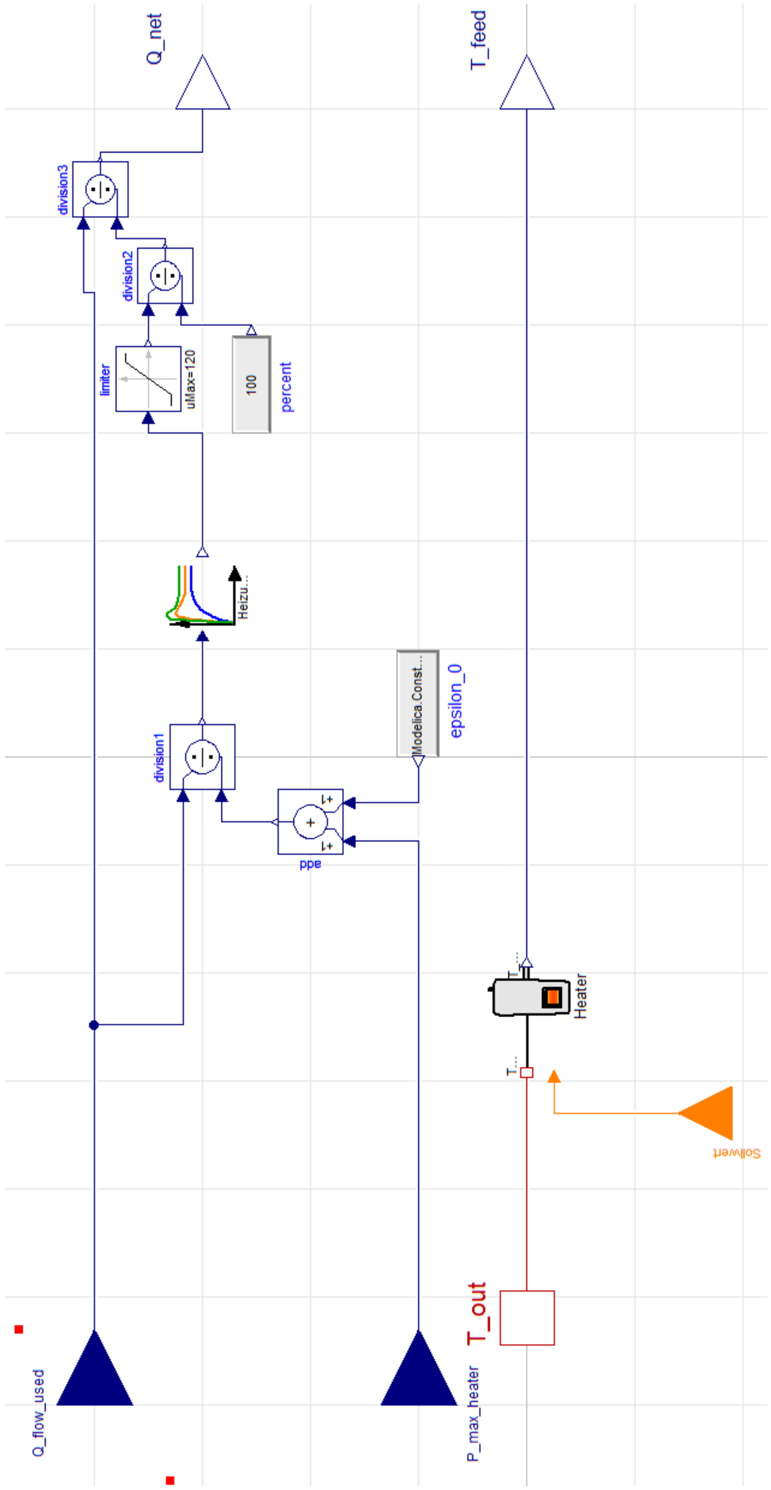


Figure 102: Representation of the combined heat production system partial model that combines the "HeizungsKennlinie" and "HeatProd" partial models. Picture as taken from the final version of the Modelica model.

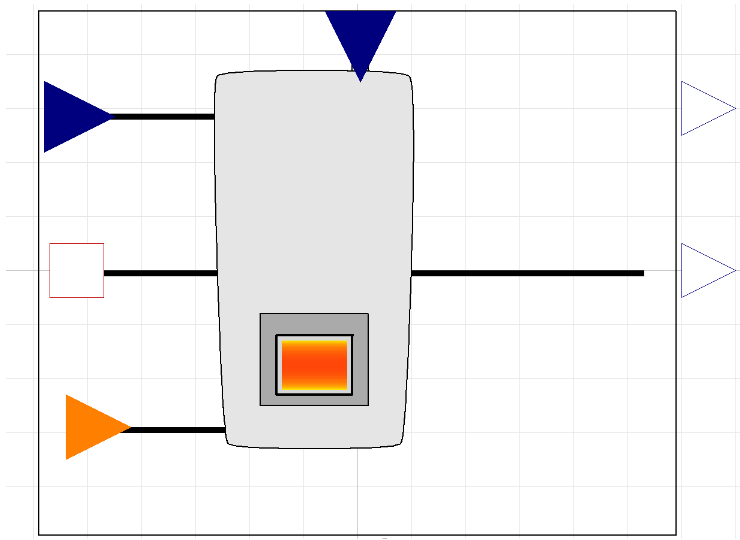


Figure 103: Icon of the partial model for the combined heat production system, as shown in the previous picture. Picture as taken from the final version of the Modelica model.

D.2.24 Two storey SAH - complete model - overview

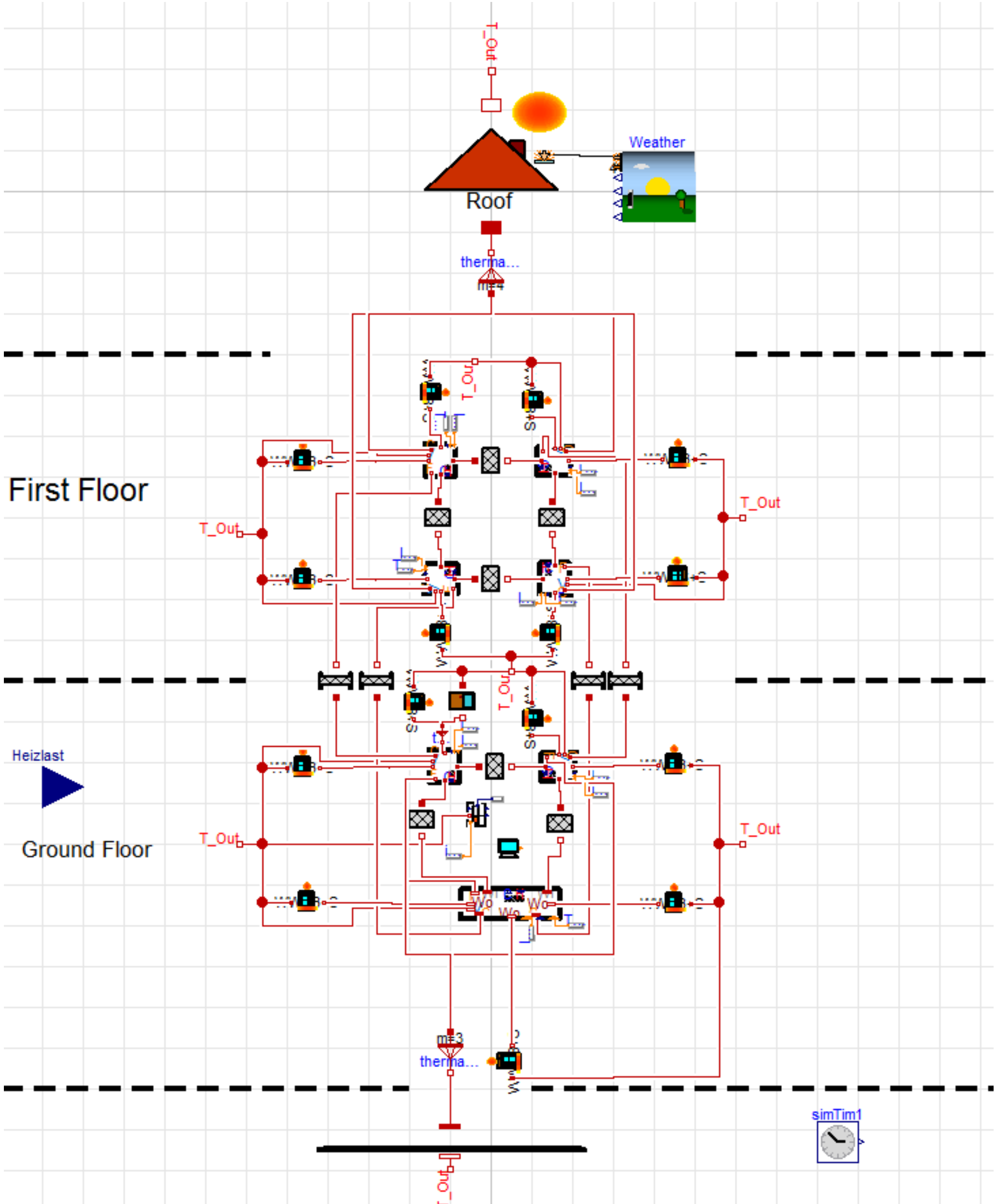


Figure 104: Representation of the two storey SAH. This complete model contains all the other partial models as described above.

D.2.25 Two storey SAH - complete model - GF

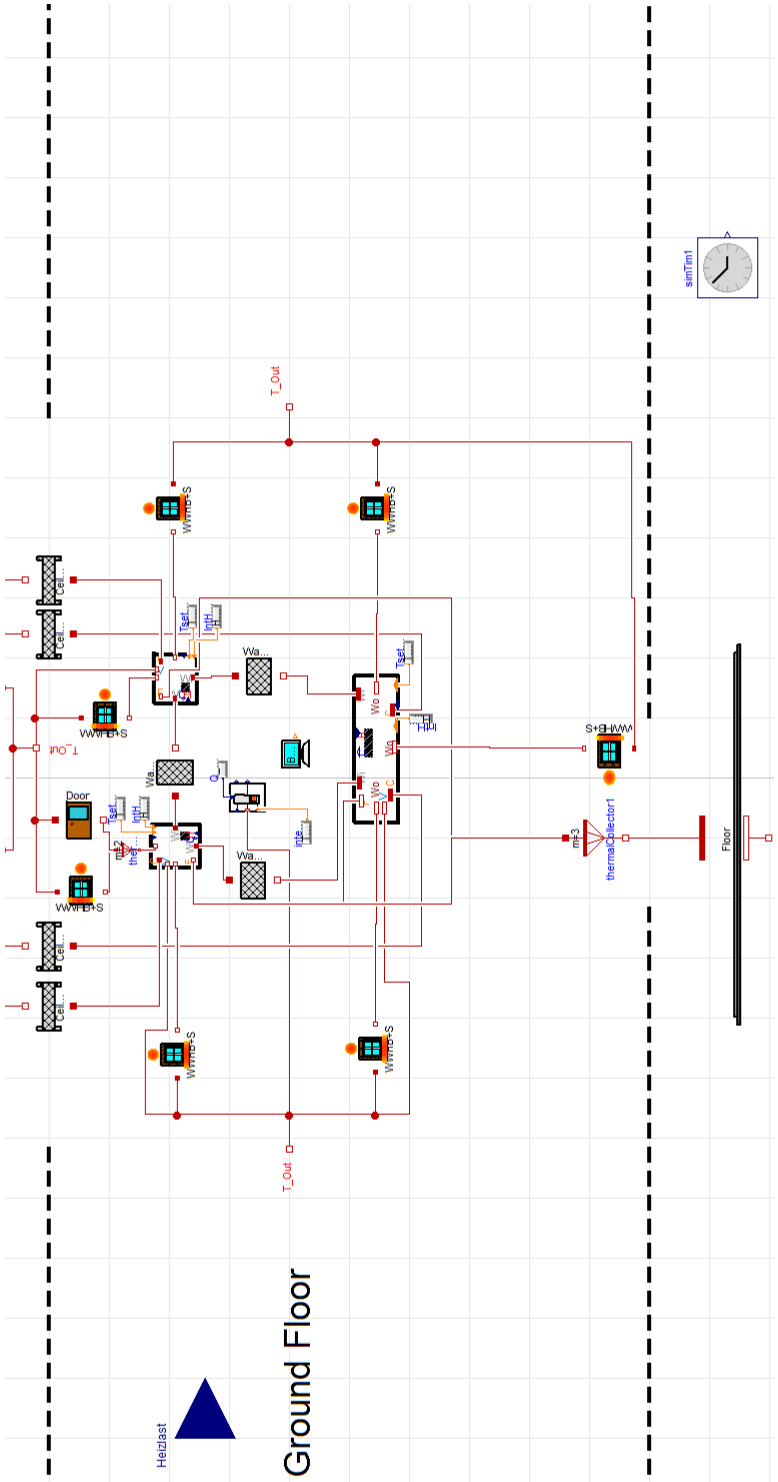


Figure 105: Representation of the two storey SAH. Zoomed picture ground floor (GF).

D.2.26 Two storey SAH - complete model - 1F

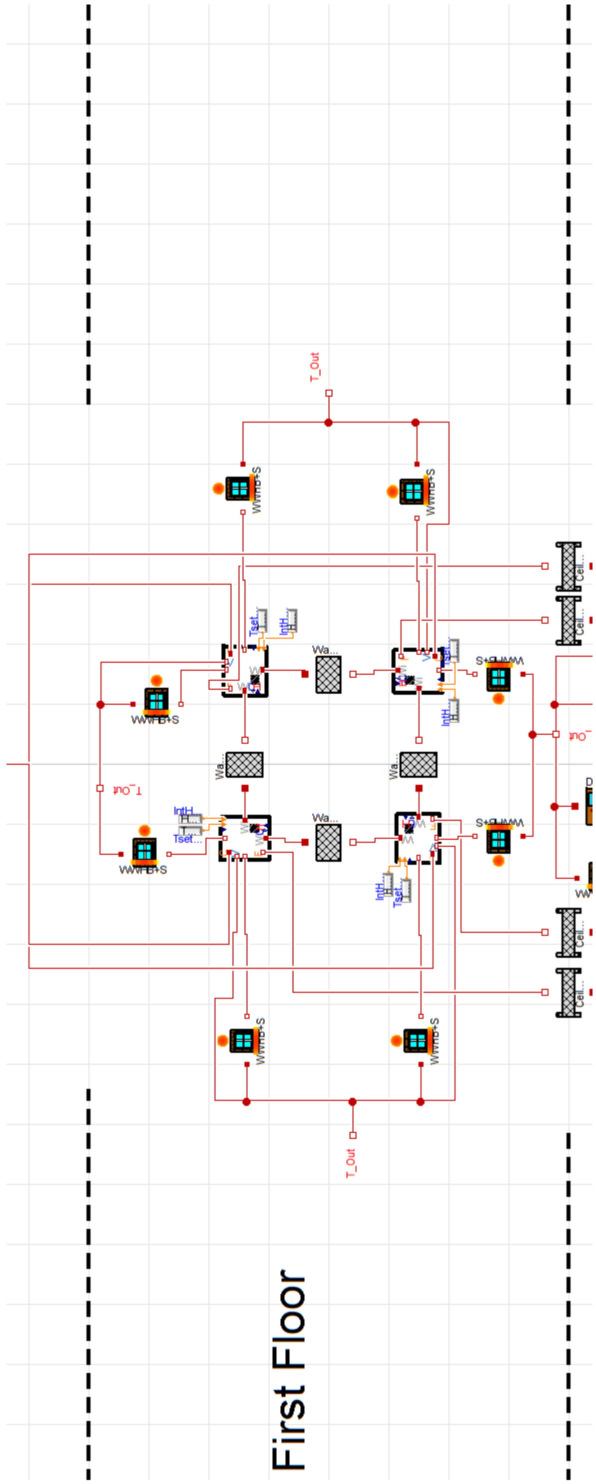


Figure 106: Representation of the two storey SAH. Zoomed picture ground floor (1F).

D.2.27 Two storey SAH - complete model - Roof

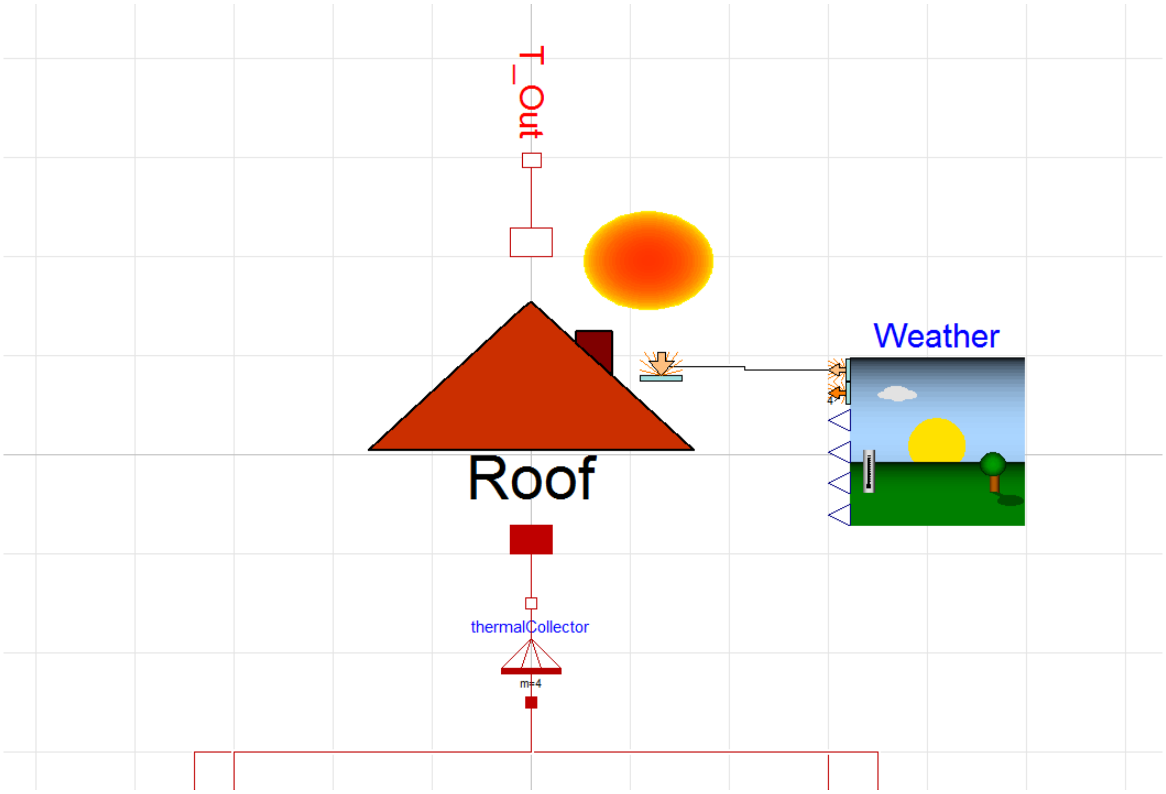


Figure 107: Representation of the two storey SAH. Zoomed picture Roof

D.2.28 Two storey TH - complete model

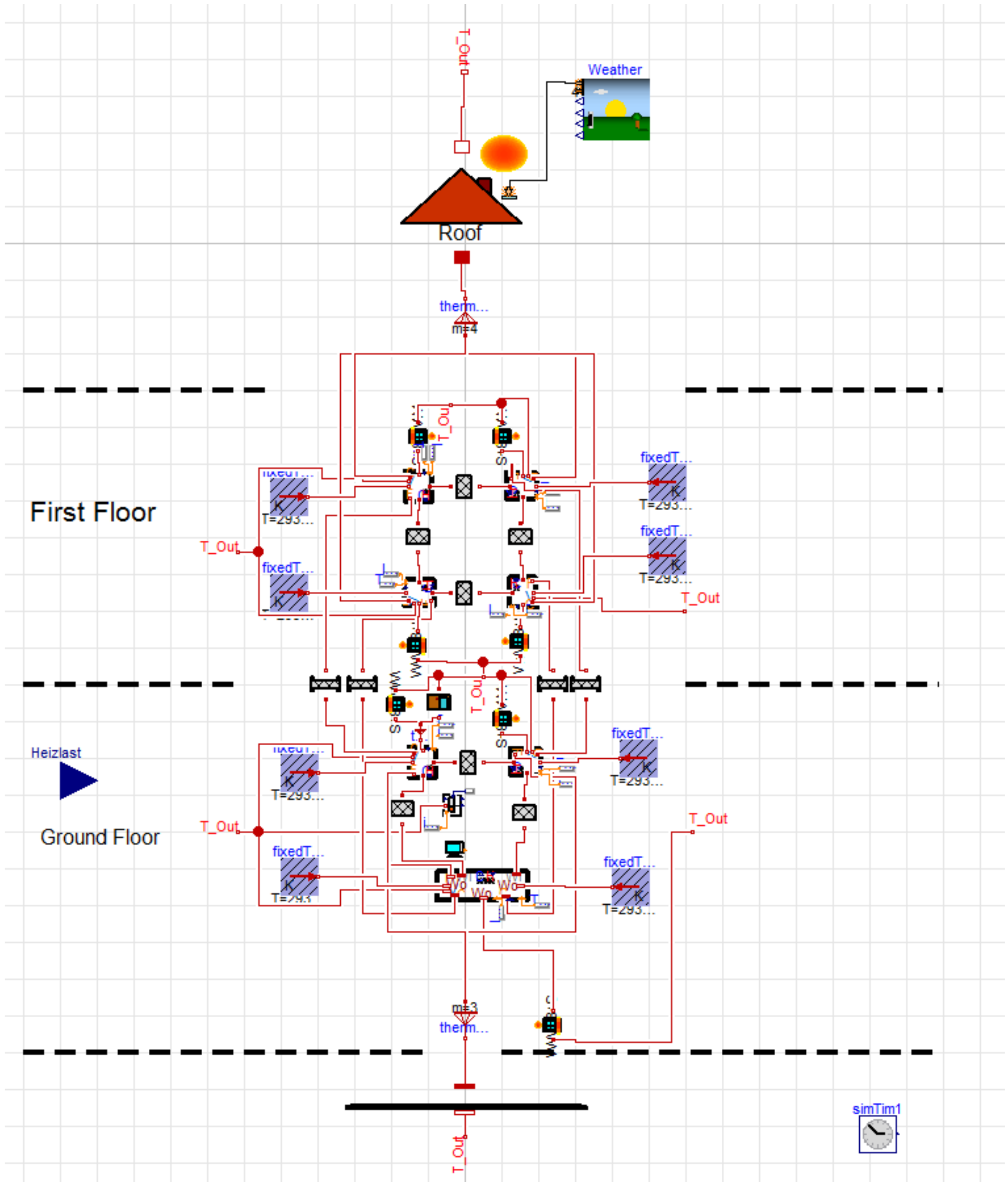


Figure 108: Representation of a two storey TH.

D.2.29 Three storey SAH - complete model

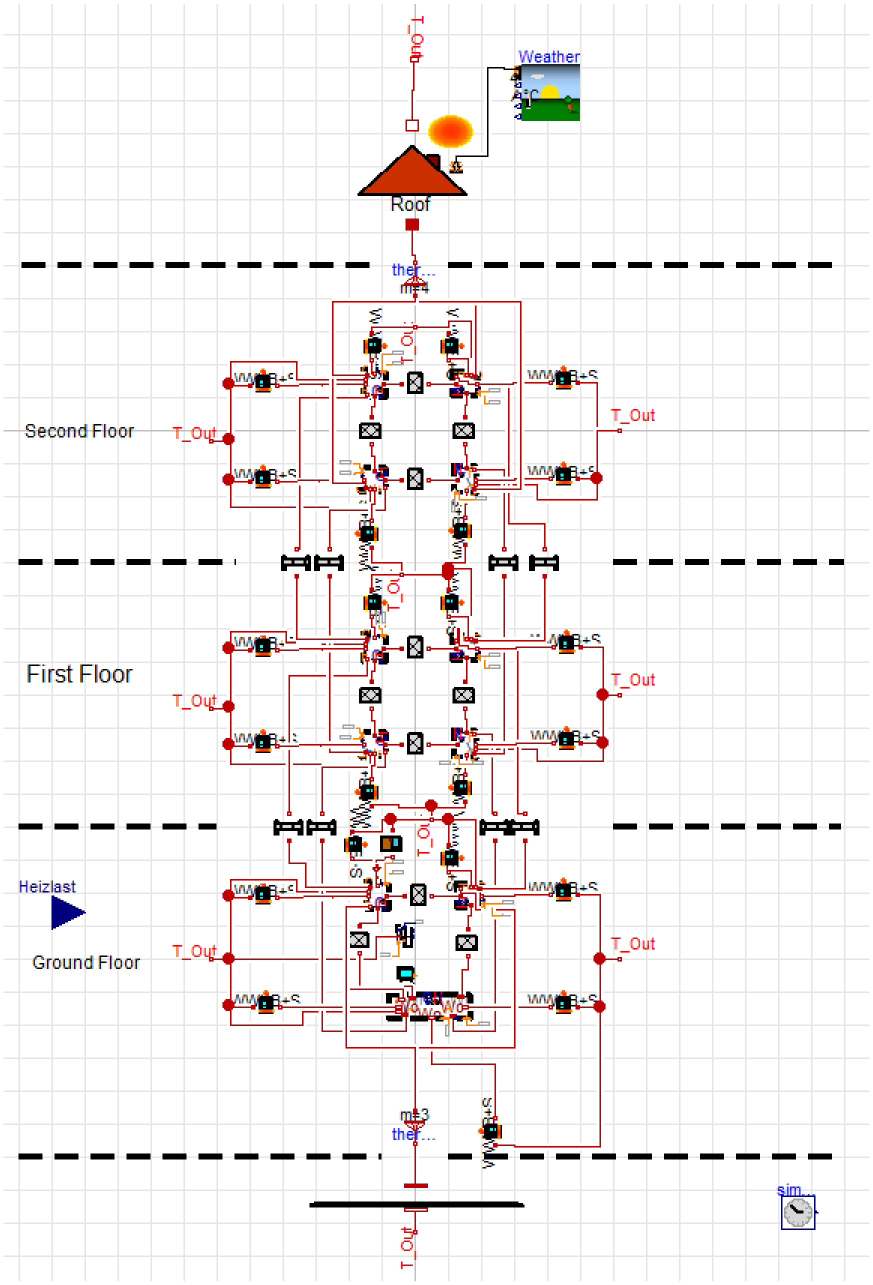


Figure 109: Representation of a three storey SAH. Zoomed picture Roof

D.2.30 U-value correction

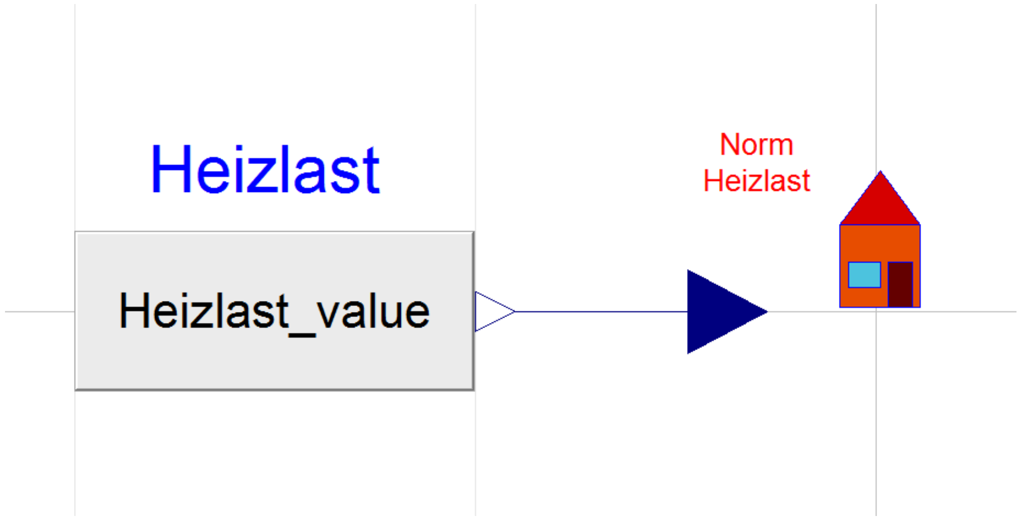


Figure 110: This model entails one of the previously described entire building models (the 2 Storey SAH or TH or the 3 Storey SAH). It corrects for the U-value as described in section 4.5.4 and it calculates the design heat load.

D.3 Constructed partial models - building with BAS

D.3.1 Programmable thermostat

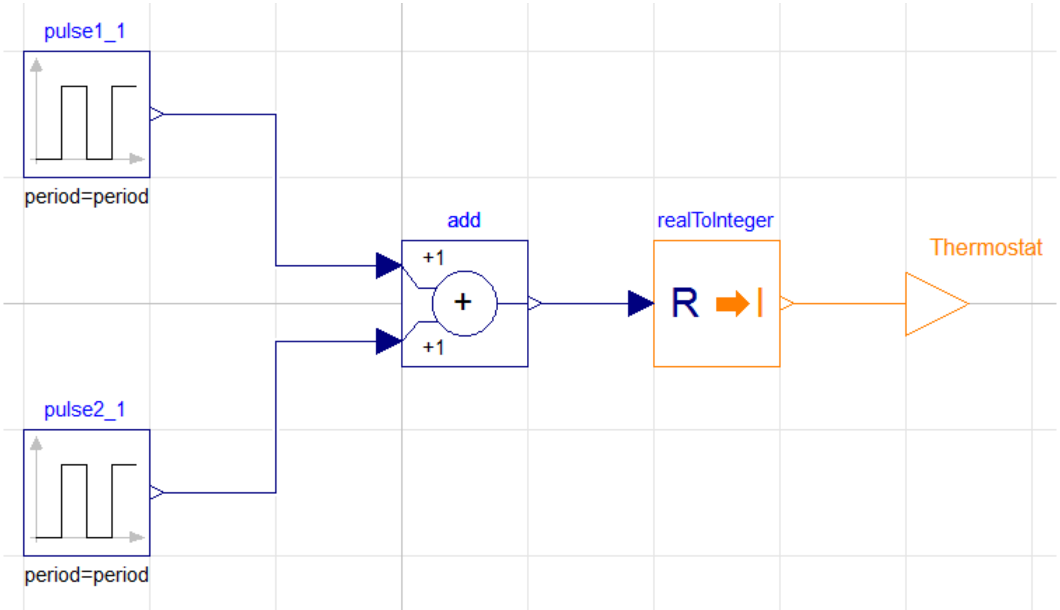


Figure 111: Representation of the partial model for the programmable thermostat. It's output indicates whether the residents are at home and whether the heating system should be on. Picture as taken from the final version of the Modelica model.

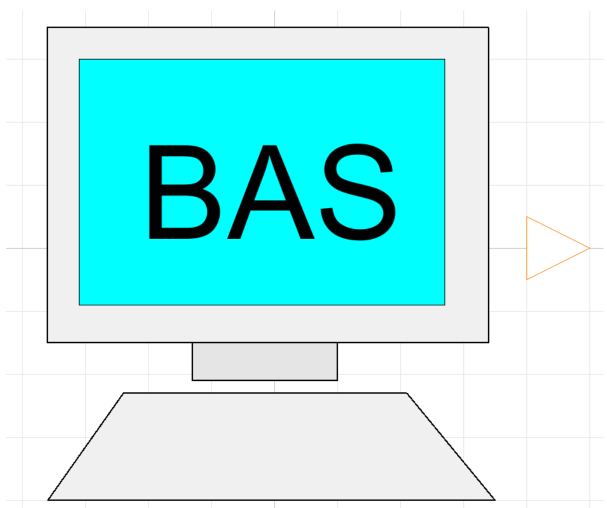


Figure 112: Icon of the partial model for the programmable thermostat, as shown in the previous picture. Picture as taken from the final version of the Modelica model.

D.3.2 Window opening

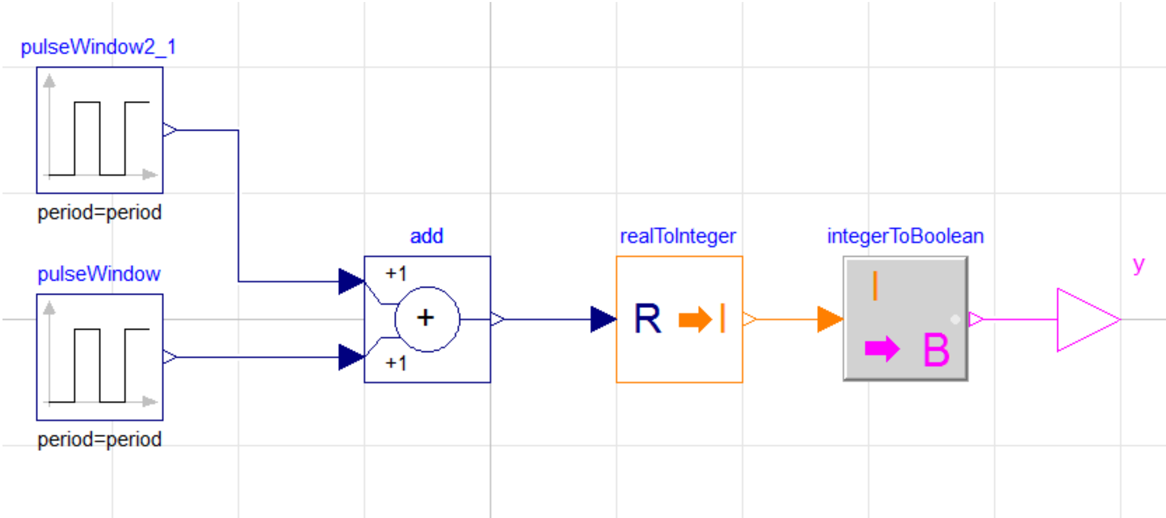


Figure 113: Representation of the partial model for the intermittent opening of the windows. It's output indicates whether a window is open "true" or closed "false". Picture as taken from the final version of the Modelica model.

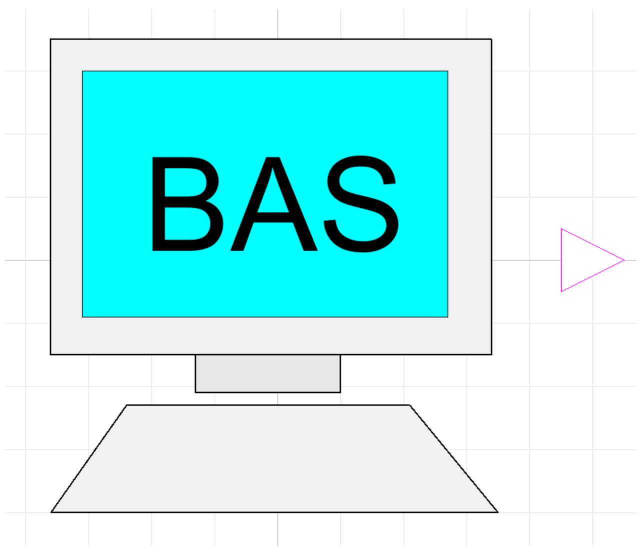


Figure 114: Icon of the partial model for the intermittent opening of the windows, as shown in the previous picture. Picture as taken from the final version of the Modelica model.

D.3.3 Intermittent ventilation

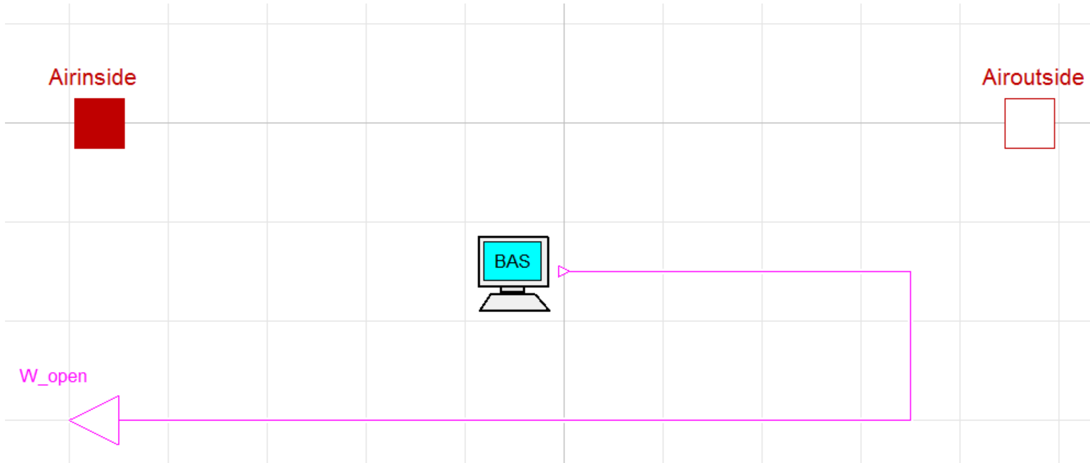


Figure 115: Representation of the partial model for the intermittent ventilation heat losses as a result of opened windows. Picture as taken from the final version of the Modelica model.

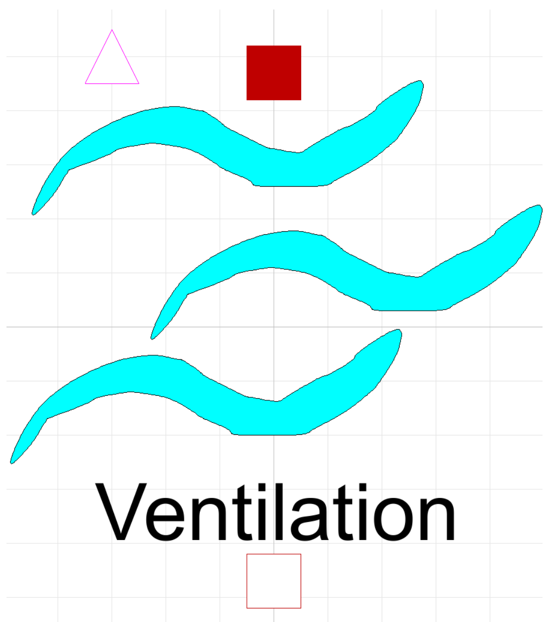


Figure 116: Icon of the partial model for the intermittent ventilation, as shown in the previous picture. Picture as taken from the final version of the Modelica model.

D.3.4 Infiltration & intermittent ventilation

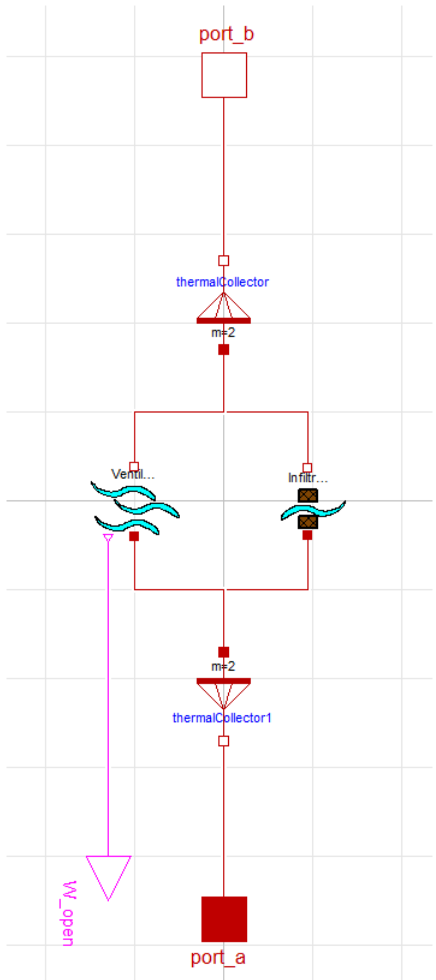


Figure 117: Representation of the partial model that combines infiltration and intermittent ventilation. This model replaces the old infiltration & ventilation model as present in the reference building. Picture as taken from the final version of the Modelica model.

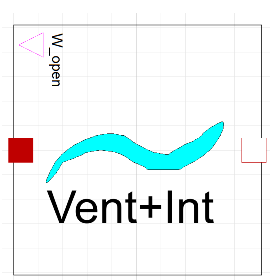


Figure 118: Icon of the partial model that combines infiltration and intermittent ventilation, as shown in the previous picture. Picture as taken from the final version of the Modelica model.

D.3.5 Heat transmission system incl. BAS

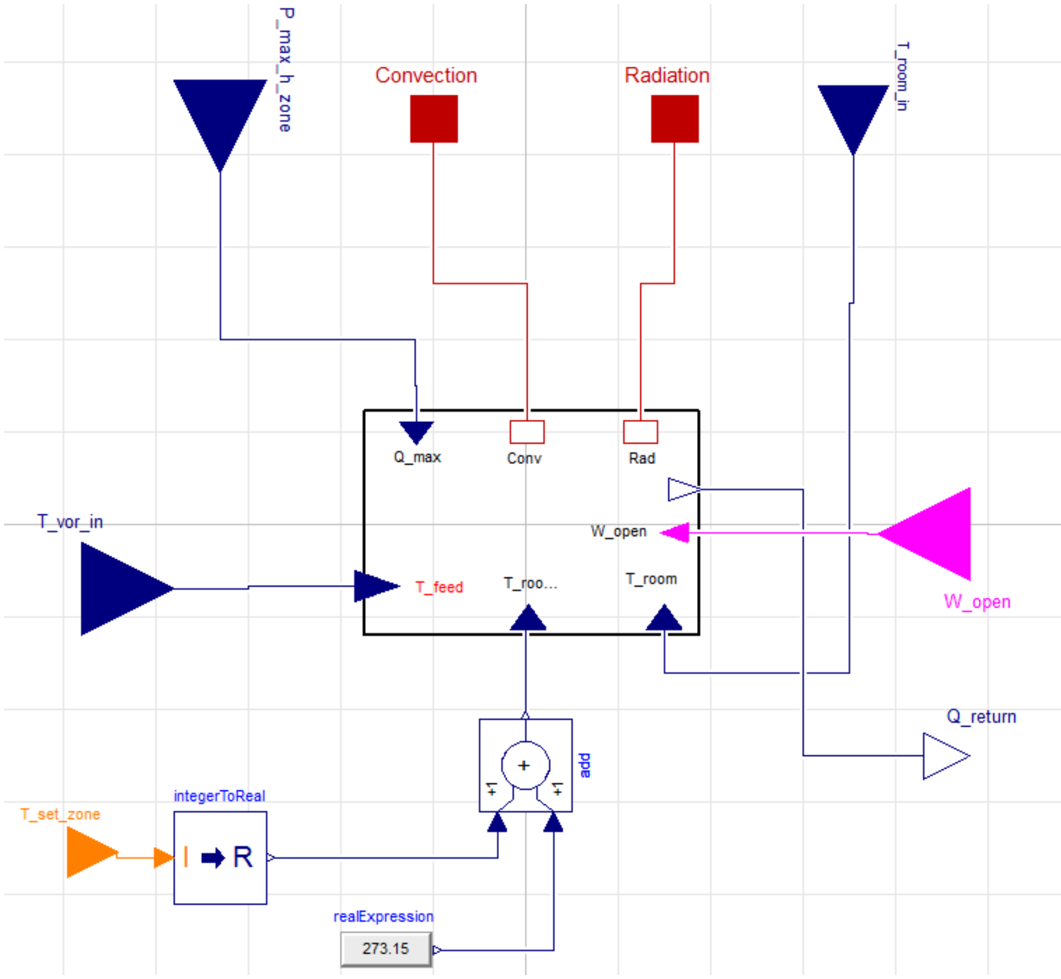


Figure 119: Representation of the partial model for the controllable heat transmission system. When the windows in the room/zone are opened the thermostat valve is automatically closed, which interrupts the flow of hot water to the heat transmission system.Picture as taken from the final version of the Modelica model.

D.3.6 Combined zone model incl. BAS

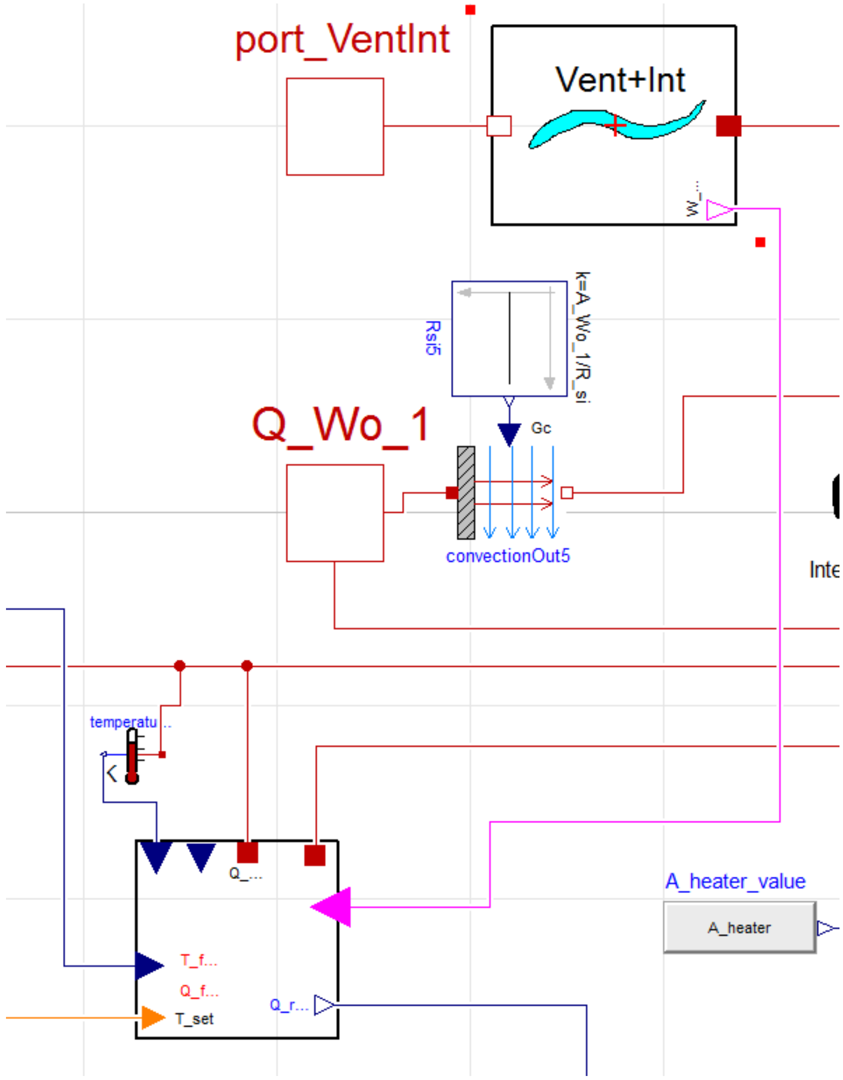


Figure 120: Representation of the altered part of the partial model for a complete zone/room. It displays the changed partial model for ventilation and infiltration and its connection to the partial model for the heat transmission incl. BAS. This change to the zone model applies to both the small and the big zone partial model. Picture as taken from the final version of the Modelica model.

D.4 Existing model of the HRI

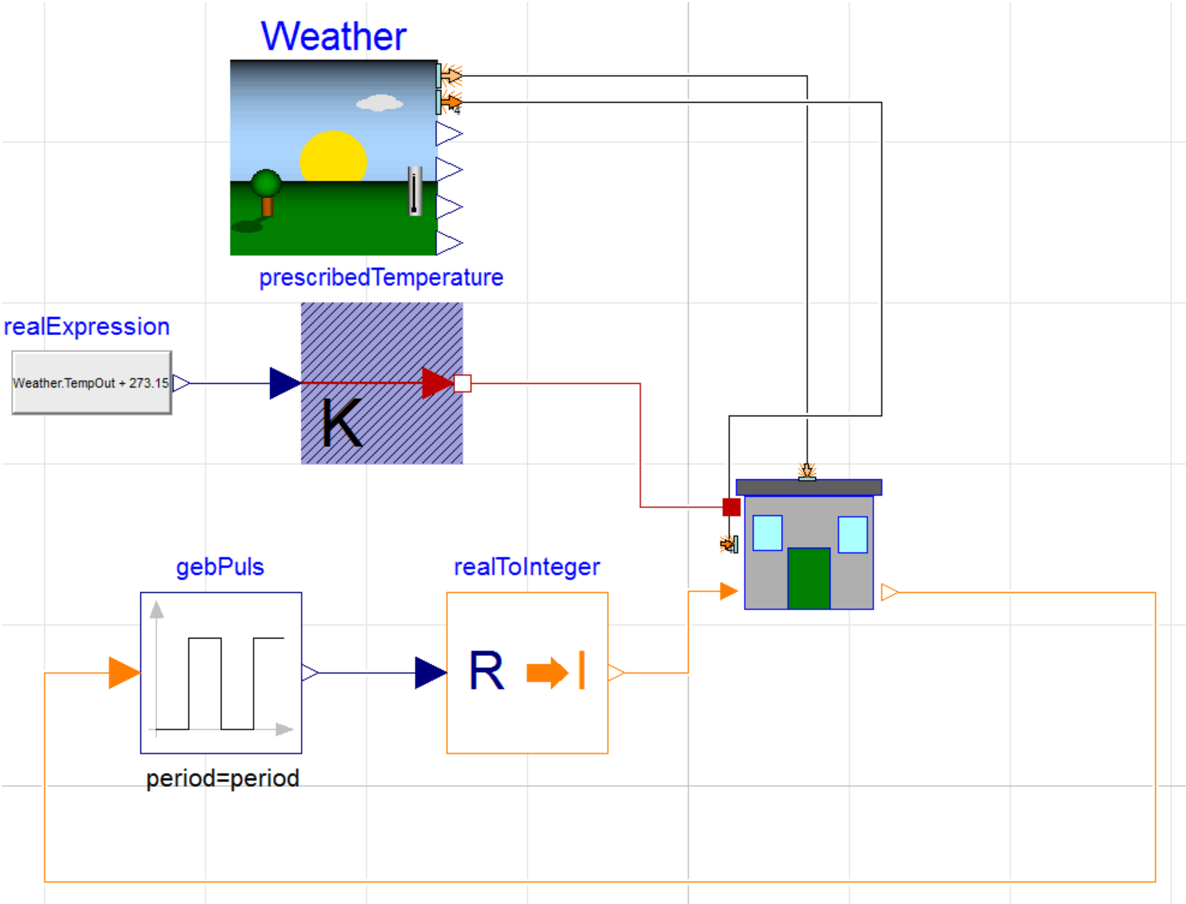


Figure 121: Representation of the DIN V 18599 model as developed at the Hermann-Rietschel Institut by Bahar Saeb-Gilani, [72]

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