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INFLUENCE OF WORKING FROM HOME SCENARIOS ON ANNUAL HEATING ENERGY DEMAND FOR GERMAN RESIDENTIAL BUILDINGS

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Abstract. In this paper, sensitivity analysis is performed for 12 building year classes of German residential buildings to investigate the influence and magnitude of working from home (WFH) scenarios on the annual heating energy demand per specific area (AHED). The analysis contains a variation of user behavior (efficient: S1 and inefficient: S2), insulation standard, zone heating set point, living area of the buildings, and WFH share. For this purpose, 264 simulations are performed for a single-family house (SFH) with 8 zones and a multi-family house (MFH) with 5 zones using reduced-order dynamic building simulation models in Modelica. The simulation models based on the AixLib library were automatically created using the TEASER tool and adapted according to the scenarios. The results show that retrofitting of the building, efficient user behavior scenario, variation WFH share from 100% to 0% for inefficient user behavior scenario, and the reduction of the zone temperature by 1 K had reduced the AHED by a maximum of 82%, 43%, 45%, and 15%, respectively, with the results strongly depending on the year of construction. In contrast, the variation of the living area and the variation of the WFH share in terms of efficient occupant behavior had an insignificant effect on the AHED.

1 Introduction

The strong and short-term shift of the workplace to the home office in the context of the COVID19 pandemic has led to an intensification of the use of private homes as workplace environments. However, the impact and the important influencing factors on energy demand of buildings of this development remain unclear. Dynamic building simulations can help to analyze the influences of changes in occupancy and energy usage patterns and compare it with other measures in different scenarios. To calculate effects that are as realistic as possible and representative of the German building stock, appropriate simplifications, and suitable assumptions for the value ranges of the parameters must be made. This ensures that the computational effort is manageable when creating and parameterizing the models. The parameters building area, building physics, type of energy supply, user behavior [1], can be identified as key influencing variables for the energy demand. Due to the free variation possibility of these parameters, the number of required simulations can be arbitrarily high, which places high demands on the computational effort.

2 Methods

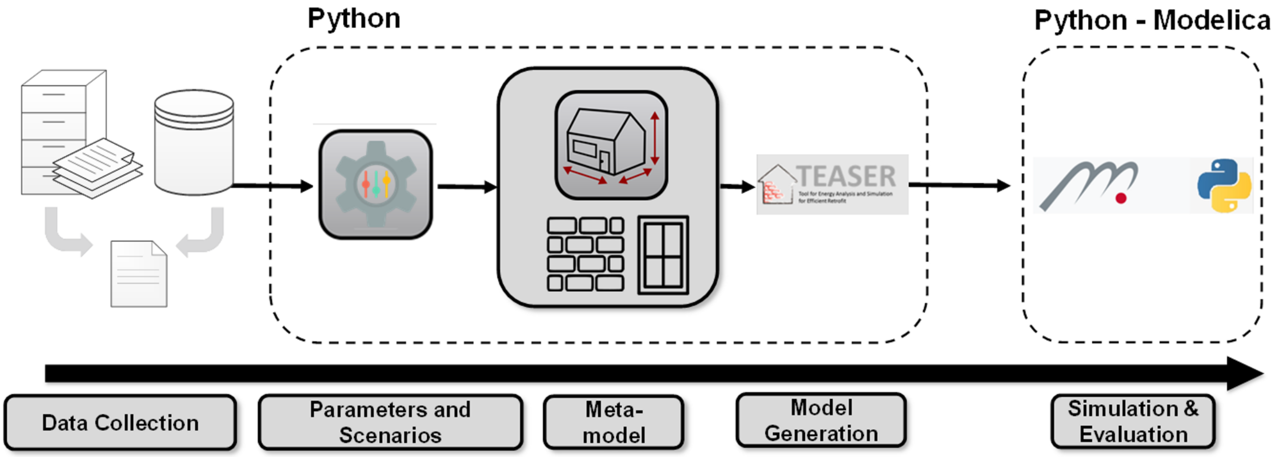

Figure 1. Tool chain for the modelling and simulation process of dynamic building models

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2.1 Tool chain for the modeling and simulation process of dynamic building models

To reduce the computational effort, simplified multi-zone models, so-called "reduced order models" (ROM), are used. ROM is a technique aimed at diminishing the computational complexity and effort required for simulations by reducing dynamic behavior, while maintaining the expected fidelity within an acceptable margin of error. This type of modeling requires a full description of the building for accurate parameterization. The description should encompass details of the building's geometry (both exterior and interior design), its physical properties (such as wall constructions), and boundary conditions (including user behavior). Compared to complex multi-zone models, or "high order models" (HOM), the computation time for single-zone models is significantly shorter without significantly affecting the quality of the results [2]; [3]. For this study, already existing simplified single-zone building models were extended by additional thermal zones. This makes it possible, to control the parameters and conditions of each zone separately resulting in more detailed and realistic simulation outputs. The main advantage of ROM is that the automation potential of the computations can be increased. However, there are drawbacks to this approach, namely that the heat transfer processes between the zones are not fully represented. A tool chain for the entire modelling and simulation process is developed see Figure 1.

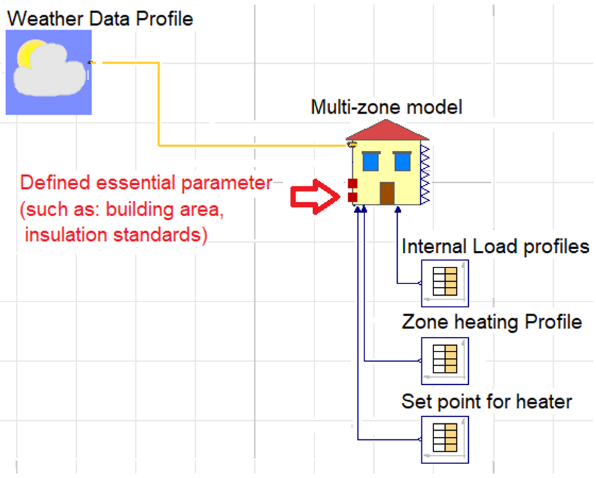

Figure 2 meta-model executed in Modelica in combination with the AixLib library

Based on a literature research, the value ranges for the essential parameters (i.e. typical building area, insulation standard, internal load profiles) are first defined and corresponding user behavior scenario for WFH are created in the form of standardized data sets. Based on these parameters and user behavior scenarios, a so-called meta-model is created for each simulation. From this meta-model, an executable Modelica model is automatically created in a next step using the Teaser software tool [3] in combination with the AixLib library. Figure 2 shows the meta-model executed in Modelica, with predefined internal load profiles, heating profile, and heater set point, along with the essential parameters defined in the multi-zone model.

2.2 Parameters, scenarios and load curves for residential buildings modeling

For the residential buildings, the TABULA database provides representative data of construction type, building materials, window layout and more for the distribution of building types and building age classes, so that in a later evaluation step the energy savings potential can be estimated by scaling to the entire building stock in Germany [4]. In this study, TABULA is used to parameterize the residential building models, the year of construction, the insulation standard and the net floor area. In this study only heating systems are considered as only about one to two percent of German dwellings have cooling systems installed [5].

The consideration of user behavior and the corresponding modeling serves to calculate more realistic energy consumption of buildings [1]. In this study, to evaluate the influence of user behavior, two extreme scenarios for the working from home can be considered. In the first scenario (S1), it is assumed that only the office zone is used and conditioned to a comfort temperature. This leads to lower energy consumption than in the second scenario (S2), where the other zones are used during lunch and coffee breaks and a comfort temperature is maintained for all zones throughout the day. Before and after working hours the behavior is considered to be the same in both scenarios.

Standard load profiles have been used for decades to estimate residential energy demand [6]. The internal heat loads in buildings are mapped in the form of dynamic load profiles, which can be divided into three main loads: mechanical load, lighting load and hot water. These depend on occupancy or user behavior. The procedure for creating dynamic load profiles can be divided into two categories: Bottom-up and top-down models. In bottom-up models, households are mapped in detail, i.e. appliances and occupancy are taken into account, and an overall consumption profile is created from this. Top-down models use aggregated data and determine corresponding influences depending on macro variables such as weather conditions or consumer behavior [7]. In our study, bottom-up models are used to generate lighting and appliance load profiles for working from home scenarios. Devices are identified and assigned based on the corresponding zone, functionality, and daily usage, as shown in Table 1.

Table 1 Household appliances with allocation by zone, duty cycle and hours of use

Device	Zone	Duty cycle	Hours of use in day
			h
Coffee maker	Kitchen	100%	2-3
Dishwasher		100%	
Refrigerator		33%	
Freezer		33%	
Microwave		100%	
Stove		100%	

Oven		100%	
Washing machine		100%	
Kettle		100%	
Laptop	Home office	100%	8
Printer		100%	
LCD/LED	Living room	100%	2-3
TV		100%	
Game console		100%	

Table 1 shows that the kitchen contains most of the appliances that are used daily (refrigerator, freezer, stove, oven, and coffee maker), which has a strong impact on the load profiles for the scenarios. For the working from home scenarios, the office zone loads are second highest due to computers and monitors being used for 8 hours. Home appliances are divided into full load and partial load based on the type of appliance. Refrigerators and freezers operate in the partial load range, a typical duty cycle for a freezer is 33%, and for a refrigerator the best duty cycle is between 30% and 50% [8]; [9]. In this work, it is assumed that the duty cycle for the refrigerator and freezer is 33%, while the other appliances operate at full load during the operating period and the standby current is neglected.

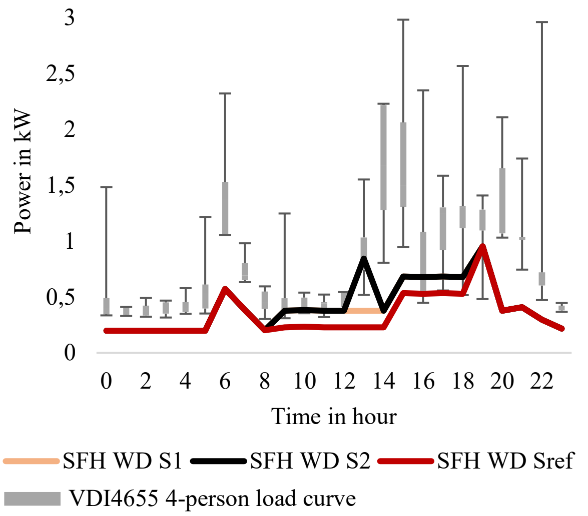

Figure 3 comparison between generated profiles by bottom up method with standard profile from VDI4655 for 4-person household

In VDI 4655, aggregated reference electricity load profiles for residential buildings are provided. According to the guideline, the daily load profiles are divided into working days (WD) and Sundays, with a distinction made with regard to cloudy and clear days. The annual electric energy demand for single-family dwellings is determined as a function of the number of people living in the dwelling. The annual electrical energy demand is given in terms of household electricity demand including auxiliary electricity demand for circulation pumps and control of the heating system as well as ventilation systems [10]. In this study, a comparison between standard profiles from VDI4655 is applied for validation of the bottom-up model generated for a 4-person SFH household for different scenarios and is shown in Figure 3.

In Figure 3, the orange, black and red lines representing the generated bottom-up load profiles for S1, S2 and reference scenario without WFH (Sref). The grey box plots represent variants of the VDI4655 4-person load curve representing cloudy and clear working days in Germany. The generated Sref and reference load profiles have the same pattern. The results also show that the annual electrical energy demand for appliances from the generated load curve is 13% to 35% lower than the annual electrical energy demand from VDI 4655. This difference may be due to the inclusion of additional auxiliary power demand for circulation pumps and heating and ventilation control in VDI 4655. For S1, an increase in load is observed during working hours, with additional peaks added to S2 for kitchen and living room usage during lunch and break times. The same load pattern is maintained before and after working hours for all scenarios.

2.3 Sensitivity analysis

To determine the impact of WFH on the energy demand of buildings in Germany, a large number of simulations is necessary to accurately represent the currently existing building types with their different parameters and usage scenarios. An exemplary full-factorial study with 4 weather profiles for representative locations in Germany, 12 building age classes, 3 occupancy scenarios each, 5 model types, 2 refurbishment states, 2 usage scenarios and 6 scenarios for the share of WFH in residential buildings results in approximately 100,000 simulations.

Table 2 Division of residential buildings into zones.

Building Type	Zone	Number of Zones	Number of Persons
SFH	Living-room	1	up to 4
	Kitchen	1	
	Bath-room	2	
	Home-office	1	
	Bed-room	3	
MFH	Living room	1	up to 4
	Home office		
	Kitchen	1	
	Bed-room	2	
	Bath-room	1	

To reduce this high number of required simulations, a sensitivity analysis is performed. This involves determining the effects of different scenarios and

Table 3 Overview of variation parameters for sensitivity analysis including applied levels and overall number of required simulations

Variation parameter	Usage behavior	Retrofit condition	Area calculation	Set temperature		WFH Share	Number of simulations
				Present	Absent		
Usage behavior	Efficient (S1); Inefficient (S2)	Standard	Constant	21 °C 21 °C	15 °C 21 °C	100%	24
Retrofit condition	Efficient (S1)	Standard; Retrofit	Constant	21 °C	15 °C	100%	24
Area assumption	Efficient (S1)	Standard	Constant ; Area according to TABULA	21 °C	15 °C	100%	24
Set temperature	Efficient (S1)	Standard	Constant	20 °C 21 °C 22 °C	15 °C	100%	36
Reference case (weighting HO share)	Efficient (S1)	Standard	Constant	21 °C	15 °C	0%	24
						Number of models	2
						Total	264

parameters on AHED. If the effect on AHED is large, the scenarios and parameters are included in the main simulation; if the effect is small, they can be neglected. In a first step, the sensitivity analysis is applied to two residential building models: a SFH with 8 zones and a 3-room apartment in a MFH with 5 zones. Table 2 shows the breakdown of the building models, the integrated zones and the number of people living in them.

The sensitivity analysis for residential buildings is carried out to determine the influence of efficient and inefficient user behavior scenarios, the insulation standard (standard and refurbished), a 1 K variation in the zone heating set-point, the building area typical of the building age compared to an average building area on the AHED in kWh/m², and a variation in the WFH share with respect to user behavior. A total of 264 simulations were conducted to assess its influence.

Table 3 shows the number of simulations for each sensitivity analysis with respect to construction year variants, occupant behavior, and WFH share. The following parameters or boundary conditions are kept constant. Only one weather profile was used: Aachen, Germany, for the year 2021, obtained from the German Weather Service. For the occupancy, a load profile with 4 persons (2 adults and 2 children) with presence both during the week and on weekends is used. According to TABULA, the year of construction can be divided into 12 classes, which are also used in this analysis. The ventilation is currently mapped in a simplified way using a basic infiltration and correction values for summer and winter depending on the outdoor temperature. To generate the machine and lighting profiles, the bottom-up method from Section 2.2 is used. The floor height is 2.5 meter, and the building floor area is assigned with typical values according to the year of construction. To better represent user behavior, four vacation weeks are considered in the residential building models, using only the base load of the appliances (e.g. refrigerator in the kitchen) and a temperature set point of 15 °C for all zones.

According to IEA EBC Annex 53, one of the factors influencing the energy consumption of buildings is user behavior [11]. In this study, the influence of user behavior is investigated with the help of two scenarios as mentioned in section 2.2. For S1 and S2 temperature profile for each zone depends on the occupant presence as shown in Table 3. For S1, during working hours, the lighting and specific devices are active only in the zone where work is being done. In the remaining zones, only the base load of the appliances is considered. In S2, the additional appliance loads (e.g. kitchen) are taken into account in the break time.

For all further simulations carried out in this study, only S1 is used with regard to the user behavior. According to TABULA, the wall constructions of standard buildings differ depending on the year of construction, e.g., building walls built before 1958 are constructed of solid brick, from 1958 to 1994 of concrete, and after 1995 of concrete and insulation [12]. Retrofit helps to improve the energy efficiency of a building by installing new technologies. In TEASER, retrofitting a building means adding two layers of insulation to the existing building walls, a top layer of insulation and an insulating plaster. This study investigates the retrofit condition to demonstrate its impact on the AHED.

According to TABULA, for each year of construction class, an average building area is recorded for German residential buildings, e.g. from 1860 to 1918 the average building area of SFH is 111 m². Another example is the period from 2002 to 2009, where the average building area is 139 m² [12]. In this case, the sensitivity analysis refers to the impact of a change in building area on the AHED in kWh/m². This study explores the effects of varying building area, considering both the average building area for each building year class and an overall average area for all building year classes, as referred to as constant in Table 3 for the AHED.

According to DIN 16789-1, the indoor thermal comfort temperature ranges from 16 to 28 °C for residential buildings[13]. In this study, sensitivity analysis is performed with a variation of 1 K inside the thermal comfort zone to investigate the influence of this variation on AHED.

In 2022, approximately one-quarter of the German workforce was engaged in remote work, with nearly 15% of these individuals working from home on a daily basis or for the majority of their work hours. An additional 9.5% occasionally worked from home on less than half of their workdays. This marked a significant increase compared to pre-COVID-19 levels [14]. To evaluate the effect of WFH share, simulations are performed with 100% WFH for S1 and S2, and scenario without WFH (reference scenario) for SFH and MFH.
Interpolation can be used to calculate any proportions. Equation 1 shows the equation for the AHED for x% WFH share.

$$Q_{HO}(x) = x\, Q_{\mathrm{S1|S2}} + (100\% - x)Q_{\mathrm{Sref}} \tag{1}$$

Where Q is the AHED, x represents the WFH share, S1 is scenario 1, S2 is scenario 2 and Sref is reference scenario.

3 Results

3.1 User behavior scenarios

Figure 4 shows the effects of user behavior on the heating energy demand for SFH. The higher the absolute AHED, the greater the influence of the depicted user behavior on the absolute demand. Due to the high transmission losses, heating all zones in older (non-refurbished) buildings leads to significantly higher demands than is the case for newer buildings with higher thermal insulation requirements. For buildings constructed between 1850 and 1948, the AHED for S1 is 185 kWh/m² and for S2 approximately 265 kWh/m², a relative increase of 43%. From 1969 onwards, a decrease in AHED can be observed, from 107 to 28 kWh/m² for S1 and from 149 to 35 kWh/m² for S2, with the difference between S1 and S2 ranging from 41 to 7 kWh/m² during this annual period. For buildings constructed from 2002 onwards, the influence of user behavior is very small in absolute terms, but corresponds to an increase of 25% for the youngest buildings relative to S1.

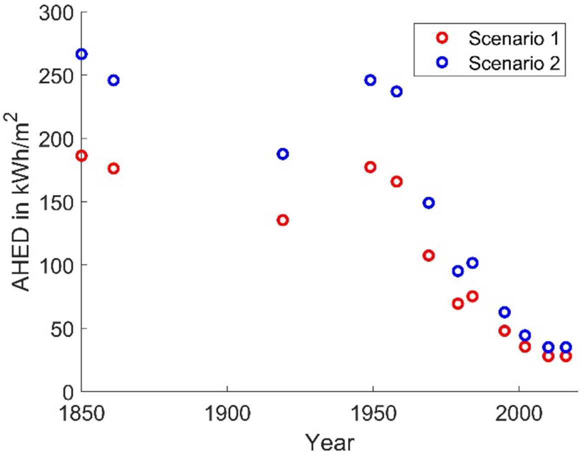

Figure 4 Effect of the investigated scenarios of user behavior on the AHED for SFH (8 zones): Scenario 1 "presence-based, partially heated", S2 "fully heated".

Figure 5 shows the effects of user behavior on the heating energy demand for the MFH. In general, the same effects are found as for the SFH. For buildings constructed before 1850, the AHED for S2 is 244 kWh/m² higher than for S1 with 64 kWh/m², which corresponds to a relative increase of 26%. From 1919 on, there is also a decrease in AHED from 115 kWh/m² to 13 kWh/m² for S1 and from 160 kWh/m² to 17 kWh/m² for S2. The difference between S1 and S2 is between 45 and 3 kWh/m². The relative decrease due to user behavior corresponds to 23% for the youngest buildings.

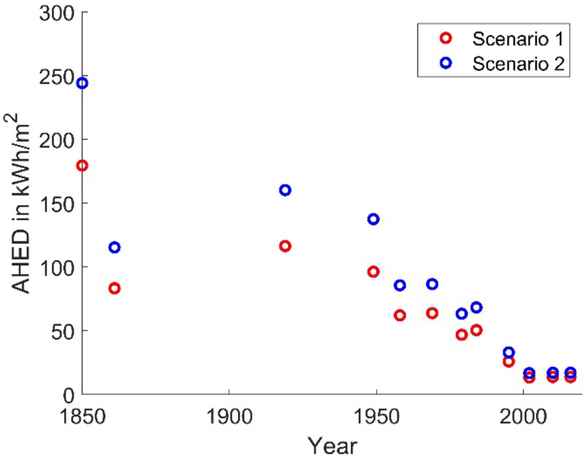

Figure 5 Effect of the investigated scenarios on user behavior on the AHED for MFH (8 zones): S1 "presence-based, partially heated", S2 "fully heated".

3.2 Insulation standard

Figure 6 shows the results for the SFH, Figure 7 for the MFH. The retrofit of the building has a large impact on the reduction of energy consumption. For the SFH, the largest reduction of 151 kWh/m² is observed for buildings built before 1850, and for the MFH, the largest reduction of 85 kWh/m² is also observed for buildings built before 1850. The AHED after renovation is almost constant depending on the year of construction. For SFH and MFH, the average AHED is 29 kWh/m² and 12 kWh/m2, respectively. It should be noted that the very low values result from additional insulation of already insulated buildings, which is of no significance in practice.

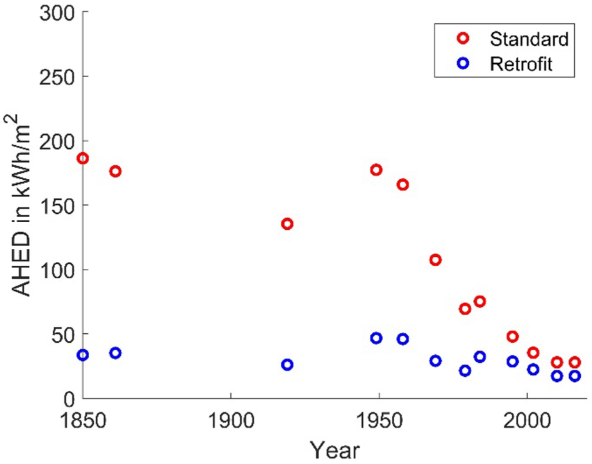

Figure 6 Effect of insulation standard (standard, refurbished) on AHED for SFH (8 zones)

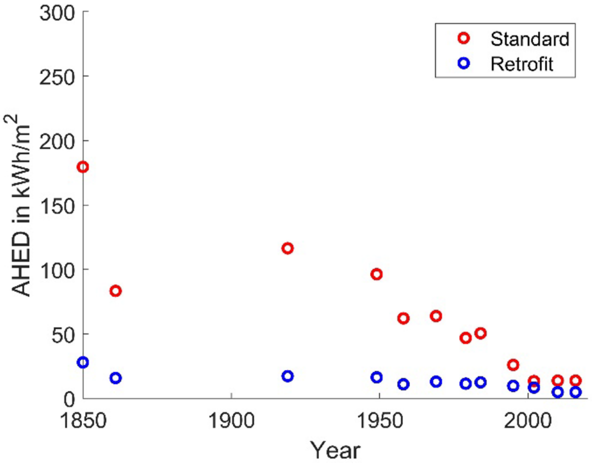

Figure 7 Effect of insulation standard (standard, refurbished) on AHED for MFH (5 zones).

3.3 Variation of the living area of the buildings

Figure 8 shows the results for the SFH, the effect of the variation of the building area on the AHED is therefore negligible as shown in the following figures, the same effect is observed for the MFH model.

3.4 Variation in the zone heating set point

Figure 9 shows the results for the SFH and Figure 10 for the MFH. For a temperature change of 1 K, the AHED varies by an average of 15% for the SFH and 12% for the MFH. For SFHs and MFHs built in 1850, the variation is 13% and 12%, respectively, reaching 19% and 21% for buildings built in 2016. The absolute AHED of new buildings is low compared to old buildings, which leads to low absolute changes of AHED by changing the set temperature.

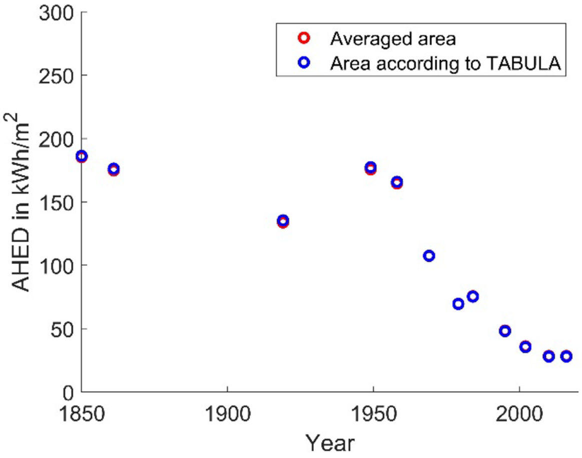

Figure 8 Effect of using an average area and the specified area according to TABULA on the AHED for the SFH (8 zones).

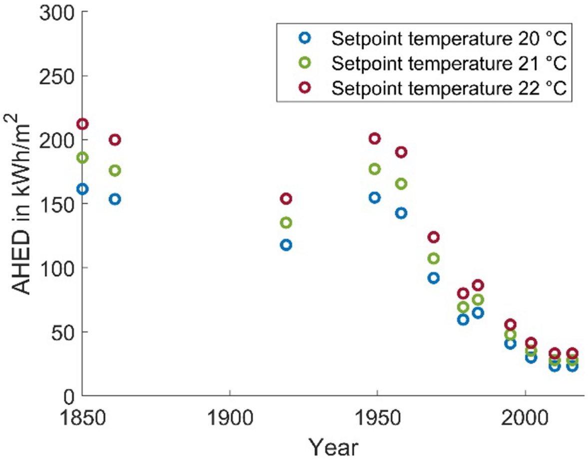

Figure 9 Effect of 1 K variation in the zone heating set point on AHED for SFH (8 zones).

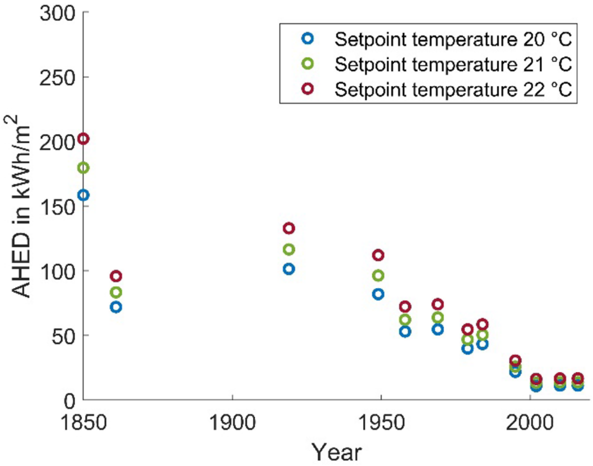

Figure 10 Effect of 1 K variation in the zone heating set-point on AHED for MFH (5 zones).

3.5 Variation in the WFH share with respect to user behavior

Figure 11 and Figure 12 show the effect of varying the WFH share with respect to user behaviors S1 and S2 on the AHED for SFH. For the efficient user behavior scenario (S1), the average increase in AHED for a 20%

increase in WFH share is less than 1%. For inefficient user behavior (S2), the average increase in AHED for a 20% increase in WFH share is 7.5%. In MFH scenarios the same effects are observed for the efficient user behavior scenario (S1), the average increase in AHED for a 20% increase in WFH share is less than 1%. For inefficient user behavior (S2), the average increase in AHED for a 20% increase in WFH share is 6.5%.

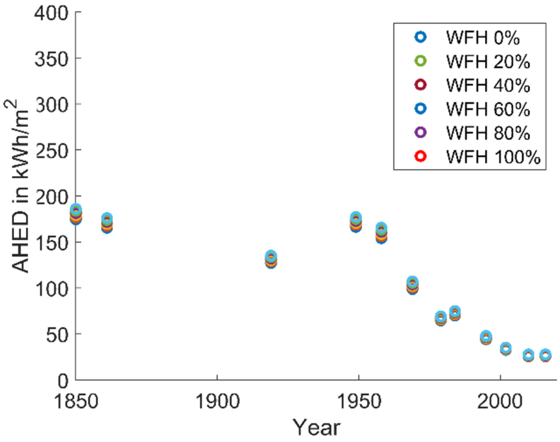

Figure 11 Effect of variation in WFH share in respect to user behavior S1 on AHED for SFH (8 zones)

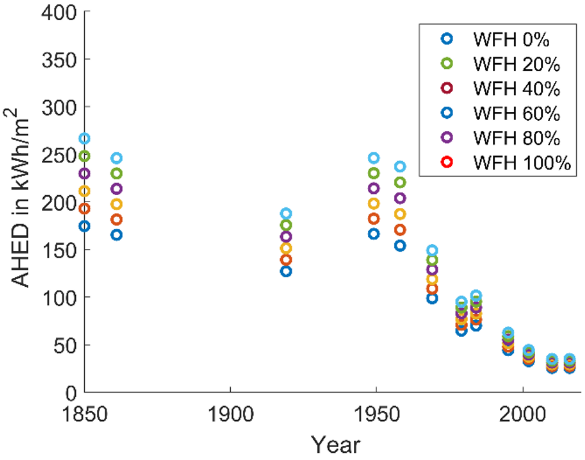

Figure 12 Effect of variation in WFH share in respect to user behavior S2 on AHED for SFH (8 zones)

4 Discussion

For all the analyses conducted, regarding the year of construction, a consistent pattern emerges in terms of its influence on AHED. This pattern can potentially reduce the building simulation complexity to less than 12 classes. Both maintaining a constant area and reducing the building construction class can significantly reduce the number of simulations required to assess the impact of working from home usage on the AHED of residential buildings.

The analysis applied to user behavior, insulation standard, 1 K variation in the zone heating set point, and variation WFH share from 100% to 0% for inefficient user behavior revealed a significant impact on AHED. The influence is most noticeable in older construction and gradually diminishes with newer construction, ultimately reaching a point where it becomes negligible in newly constructed buildings.

The concerned variations in building area indicated a negligible impact, accounting for less than 1% of AHED, however the variation of building area was small. A comprehensive assessment that considers both the minimum decrease and maximum increase in area would help ascertain the full extent of this influence.

The variation of the WFH share showed that the adjustment of the user behavior would lead to a significant reduction of the AHED. The study showed that moving from the efficient scenario (S1), which assumes that only the office zone is used and conditioned to a comfort temperature to inefficient scenario (S2), which assumes that other zones are used and a comfort temperature is maintained for all zones throughout the day, results in an increase in the AHED for a 20% increase WFH share from less than 1% to 7.5% for the SFH and from less than 1% to 6.5% for the MFH.

5 Conclusions and outlook

The results demonstrate that retrofitting buildings resulted in significant reductions in AHED, averaging 94 and 65 kWh/m² for pre-1995 buildings and 11 and 8 kWh/m² for post-2000 buildings in SFH and MFH, respectively. Shifting from inefficient (S2) to efficient (S1) user behavior scenarios resulted in an average decrease in AHED of 50 and 30 kWh/m² for pre-1995 buildings and 8 and 4 kWh/m² for post-2000 buildings in both SFH and MFH, respectively. Shifting the WFH share from 100% to 0% for the inefficient scenario (S2), resulted in an average AHED reduction of 61 and 32 kWh/m² for pre-1995 buildings and 11 and 2 kWh/m² for post-2000 buildings in SFH and MFH, respectively. In addition, a 1 K reduction in zone temperature resulted in an average AHED reduction of 26 and 11 kWh/m² for pre-1995 buildings and 7 and 3 kWh/m² for post-2000 buildings in SFH and MFH, respectively. In conclusion, our study shows that significant reductions in AHED resulting from building retrofits, transitioning to efficient user behavior scenarios, and reducing the proportion of working from home for the inefficient scenario (S2) further contributed to AHED reduction, especially in older buildings. Conversely, variations in living area and work-from-home share for the efficient scenario (S1) had negligible impacts on AHED. For the same project, future work will analyze this influence on energy demand through dynamic building simulations of the German building stock, which can be used to determine the energy effects of working from home use for both residential and non-residential buildings.

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