Developing two benchmark models for post-world war II residential buildings

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ABSTRACT

In the context of the European carbon neutrality targets, building benchmarks are a key issue for the renovation of existing buildings. Although there are various benchmark methods for energy efficiency characterization, their application to the residential sector is still limited. This paper developed two building simulation models for post-world war II houses in Belgium based on data from post-occupancy measurements and field survey campaigns. The study reports the energy characteristics and occupancy profiled of detached single-family houses. An analysis of energy consumption (electricity and natural gas) and a walkthrough survey were conducted between 2016 and 2019. The benchmark model's validity has been further checked against public statistics and verified through model calibration and monthly energy bill comparison. Two reference models representing 633.702 post-WWII single-family houses in Belgium were created and validated. The first archetype has an average energy use intensity of 166 kWh/m²/year and represents detached single-family houses built between 1945 and 1969. The second archetype has an average energy use intensity of 155 kWh/m²/year and represents detached single-family houses built between 1970 and 1990. The paper provides a timely opportunity to evaluate the real performance of post-world war II most common archetypes concerning design assumptions and how building professionals can turn the energy performance gap challenge to their advantage. The findings on energy needs and intensity are useful for creating future renovation scenarios for similar archetypes in Western European countries.

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1. Introduction

Energy use in the residential sector accounts for 20% of the total energy use at the European level [1]. The European Union (EU) states will cut carbon emissions to 55% of 1990 levels by 2030 [2]. To achieve the new carbon reduction targets, member states are required to increase their renovation rate from 2% a year to 3% annually before 2023 before stabilizing at least 2% in 2030 [3]. Conversely, existing households exceed the number of newly built households in Europe [4]. The existing building stock will continue to dominate for the next 30 years. In Belgium, the annual renovation rate of the existing building stock is less than 1% [5]. As shown in Fig. 1, dwellings are responsible for 14% of Belgium's greenhouse gas emissions. Awareness about the carbon emissions reduction potential of existing residential buildings is widespread among European governments, builders, housing associations, and building owners [6].
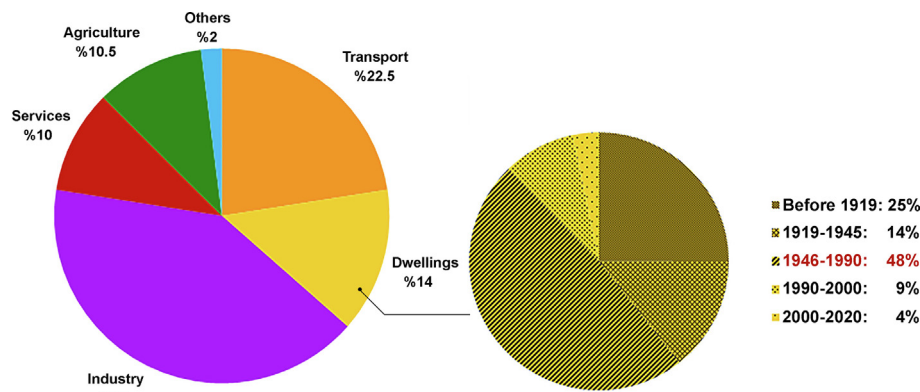
Fig. 1. Greenhouse gas emissions of Belgium in 2018 (%) and the Distribution of Belgian dwellings by the period of construction [7,8].

While in North America and particularly the United States of America (USA), the benchmarking of existing buildings has acquired a consistent tradition [9,10,11,12,13,14], in Europe this research is gaining more and more importance [15]. The TABULA [16] building typology project and the EPISCOPE [17] building monitoring projects are the most structured and central depository of building stock models. Since the Energy performance of buildings directive EPBD [18] came into force in 2003 and was implemented after 2008, member states across Europe had to develop 'reference building' representing their building stock [19]. According to the EU Commission Guidelines accompanying the Commission Delegated Regulation No. 244 (2012) [20], it is recommended that reference buildings are established representing the most typical building in a specific category (e.g., type of use and reference occupancy pattern or floor area or building envelope construction, etc.). However, in Belgium, the creation of representative benchmark models based on field measurements is still in its infancy. The *OCCuPANt* project [21], which developed two post-world war II (WWII) single-family reference models, characterized the energy use intensity of 1328 households (n = 1328). Among other results, more than 85% of occupants are older people, with an average age above 65 years old.

In this context, the selection of a building vintage and archetype are particularly crucial. In Belgium, Denmark, France, Germany, the Netherlands, Scandinavian countries, and the United Kingdom (UK), suburbanization after WWII encouraged the dwellers to live in single-family detached houses [22]. As shown in Fig. 2, post-WWII single-family households often have gabled roofs and spacy plans. This large part of the building stock built after WWII did not comply with any energy efficiency requirements and was constructed inefficiently, even after the 1970s energy crisis. Today, post-WWII, traditionalist and baby-boom generations occupying those buildings reached their retirement age. However, the energy efficiency status of those buildings and their future remains unknown [23]. In Belgium, post-WWII households represent 48% of the existing building stock with an ownership rate exceeding 78% (see Fig. 1) [22]. Understanding the root causes of the performance gap across the post-WWII building stock improves the future renovation programs and increases their renovation potential.

Therefore, this study aims to accelerate post-WWII single-family houses' renovation by creating two validated benchmark models representing those buildings. Describing 633.702 households and characterizing their energy efficiency and their occupant behavior offers a valuable foundation. The aging of the existing occupants provides an opportunity to renovate those buildings with the ownership transfer. However, without accurate and granular data collected about single-family post WWII houses, renovation policies and strategies won't be effective [24]. The current study follows a cross-sectional study design where field surveys and auditing for more than 1320 households. The research directly engaged occupants who completed self-reported surveys and shared their energy bills compiled in a dataset about their buildings. The research methodology combines mixed research methods involving qualitative (e.g., literature review) and quantitative empirical and modeling (e.g., walkthrough audits, building performance simulation, calibration) research. Our study approach and methodology is similar to the work of Touchi et al. [25], Kragh, and Wittchen and Attia et al.[26,27] aiming to develop two simulation reference models based on monitoring and analyzing 1320 households. The building performance simulation models are implemented in EnergyPlus energy simulation program. A systematic and replicable approach for measurement and verficiation based on ASHRAE Guidline 14 was used to calibrate the building performance simulation models [28].

The study provides robust evidence of the extent of energy intensity use and the influence of occupant behavior of post-WWII single-family housing in a temperate climate. The calibrated simulation models provide an operationally accurate virtual representation of buildings' energy performance. The calibrated models can allow to develope retrofit scenarios, calculate the potential energy-saving, and transform post-WWII buildings into energy-neutral buildings [29]. At the same time, its methodology and findings can be useful across Western Europe. The relationship between occupancy profiles and energy use represents one of the most extensive national studies that characterize a remarkable residential building stock sector. The building energy models were created using a multizonal modeling approach distinguishing living areas, sleeping areas, and short presence spaces. On these bases, the paper presents a fundamental construct of two building energy models and their occupancy profiles that represent residential buildings to predict future renovation potential. Finally, the recommendations of future work renovation roadmap milestones that lead to an accelerated renovation rate are discussed.

2. Methodology

The research methodology is based on creating representative reference models for post-WWII detached single-family housing in Belgium. As shown in Fig. 3, the methodology implemented in this paper followed a hybrid approach involving empirical monitoring and modeling techniques. The literature review and field visits of more than a thousand dwellings allowed creating a database of WWII detached single-family housing. The analyses

Fig. 2. Distribution of Belgian dwellings by period of construction.

allowed selecting two representative reference houses, determining their energy consumption, and characterizing their building performance systems and occupant's behavior. A full energy audit and four years of energy monitoring allowed generating high-quality data. This data was then analyzed and used to create two building performance models. The model was calibrated and validated based on the monitored data. The methodology followed in this research is similar to other recent international energy modeling and benchmarking studies [26]. The methodology is similar to the approach of Tereci (2013) [30], who defined a reference building and calculated their energy use for different German archetypes; and Ghajarkhosravi (2020), who developed an energy benchmark models for multi-unit residential buildings (MURBs) in Toronto, Canada [31]. The following sections describe in detail the steps undertaken in this research.

2.1. Literature review

A literature review was conducted, including international publications that aimed to develop energy performance benchmarks for post-world war residential buildings. More than sixty publications were reviewed in the Belgian content concerning residential building benchmarking and energy efficiency characterization. The review included residential benchmarking reports that were developed as part of the EU cost-optimality approach for the three regions of Belgium; Brussels [32], Flanders [33], and Wallonia [34]. An exhaustive list of the reviewed studies and their content analysis can be found in this study's technical report [21]. Moreover, vital international studies on benchmarking were reviewed

and summarized in the introduction. The review focused on state-of-the-art benchmark model creation approaches [19] and their calibration techniques for model validation [35]. The study also covered the most well-known building archetype databases, such as the US Department of Energy's archetypes database for residential buildings [13] and the European Projects TABULA EPI-SCOPE [17] that aim to provide reference buildings for the European building stock.

2.2. Selection, mapping, and geolocalisation of post-WWII single-family houses

A mapping study followed the literature review to select one of the most representative building archetypes in Belgium. The selection criteria of the archetype and construction vintage for benchmark model creation involved four main aspects. First, a high numerical representation of the selected archetypes for the existing building stock. Focusing on representative archetypes is a priority strategy for deep renovations [36] because it stimulates the standardization and cost reduction of renovation packages resulting in remarkable renovation increase [37]. Second, a low EPC rating of the chosen archetypes, based on elements including the building materials, its airtightness, and the building services installed. A poor EPC rating suggests low energy efficiency, which makes the renovation potential high [38]. Thirdly, an archetype with a geometry can allow for an external renovation without restrictions on appearance changes or being listed as monuments [39]. Fourth, owner-occupied single-family detached houses. Mixed ownership complicated the renovation decision, and private
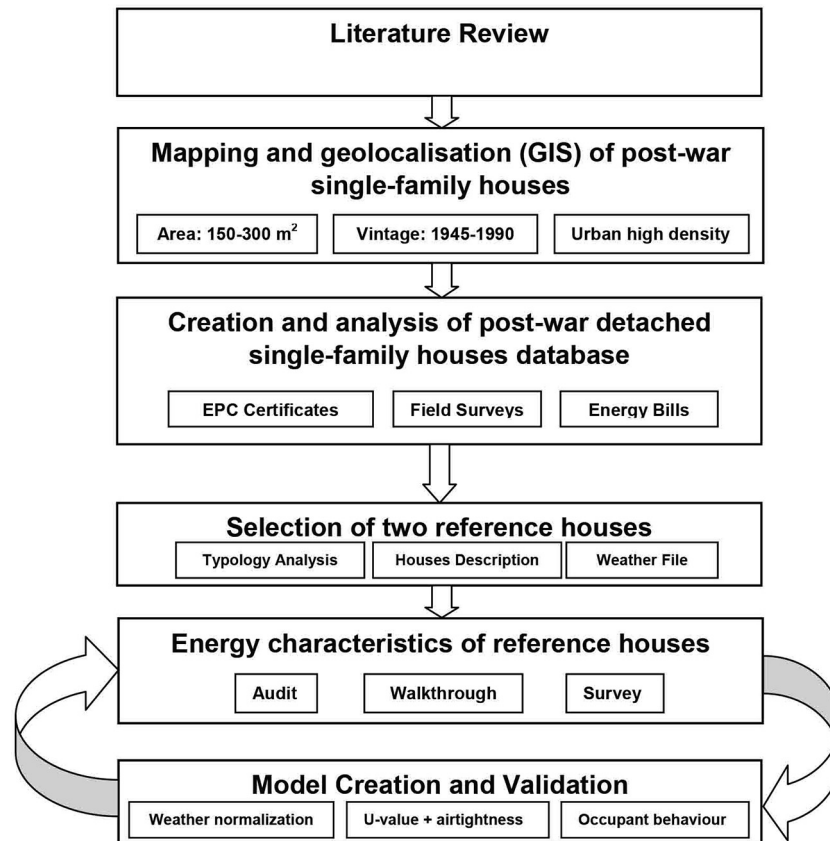
Fig. 3. Conceptual framework for the study methodology.

ownership allows easier access to renovation subsidies [40]. Thus, owner-occupied housing remains having a high potential for energy savings [41], and the ownership has a positive influence on the renovation decision [42].

As a consequence, post-WWII single-family detached houses were selected. Post-WWII single-family detached houses are generally speaking less homogenous than pre-war buildings [4]. In Belgium, most of those archetypes fall under the EPC label F or G. They are fastly built using low-quality materials. They are poorly insulated at the time of construction. Therefore, they show a relatively high need for renovation.

Next, all existing detached residential buildings were mapped on the Belgian Cadastral Parcel Data (BCPD). The BCPD is a vectorial polygon map representing the cadastral parcels of the entire Belgian territory made available by the Land Registry Administration of Belgium [43]. The Geographical Information Systems (GIS) cadaster maps provide information about each building in Belgium, such as construction data, building use, number of floors, etc. [44]. Using construction date and building use, we extracted all residential buildings built before 1991 and after 1945 with an area $\geq$ of 55 m^2 and $\leq$ 350 m^2. We limited our mapping to detached single-family houses built before 1990 because energy efficiency regulations became only effective in Belgium in 1991.

In terms of regulations, thermal insulation for new buildings was introduced in 1984 in the Walloon Region [45] and in 1992 in the Flemish Region [46]. The regulatory energy efficiency requirements applicable to new housing were only strengthened after the 1990s in the three regions (Flanders, Wallonia, and Brussels).

Table 1 list the portion of extracted buildings before 1945 and between 1945 and 1990. Table 1 demonstrates that most of the extracted buildings have been built between 1945 and 1990 (more than 70%). Consequently, this study focuses on all residential-detached buildings in Belgium constructed between 1945 and 1990.

The entire Belgium was divided into grids to conduct our field audits and surveys; each represents one ha (100mx100m). Each grid has been assigned a density index, which represents the number of buildings within the grid. Eighty-two grids distributed over Belgium were selected. They contain about 1500 buildings. Data were geo-processed with the help of a selection algorithm to rasterize and aggregate the vector data. The chosen sample represents 72% (633.702 households) of single-family detached houses built before 1991 in Belgium. According to [47], a sample size of 1000 can be considered an excellent representation of the study's phenomena. The developed mapping approach allowed identifying single-family detached houses grouped by hectare. The aim of identify the detached houses by hectare is to reduce the number of field visits and facilities the audits. Each selected hectare represents about fifteen houses, as shown in the results Section 3.1.

2.3. Creation and analysis of post-WWII single-family houses database

An initial database of 1500 households was created and updated based on the input from different regional databases

Table 1
Distribution of single-family detached houses in Belgium.

	Num of buildings	Percentage
Before 1945	245.070	27.89
1945–1969	**275.915**	**31.40**
1970–1990	**357.787**	**40.71**
Total (before 1990)	878.772	100

(Brussels, Flanders, and Wallonia), field audits, and self-reported occupants' surveys. It included several details on each building such as the location, construction age, area, information on the architecture, type of materials, airtightness, heating system, ventilation system, renovation, occupancy, electrical appliances used, comfort in the home etc. The EPC databases in the three regions were consulted. Fortunately, the EPC details of all houses located in the Brussels Region were identified from the open-access Brussels Environment Database [48]. With the help of real estate websites, the EPC labels and EPB audits were retrieved for hundreds of houses. In this initial stage, this initial stage allowed us to compile the database and prepare for the following stage of field visits and audits.

Field visits were organized to visit the 82 ha representing the 1500 households between 2017 and 2021. All houses were visually inspected to assess the building envelope characteristics. The field surveys also enabled identifying and characterizing the energy systems (air and water heating systems, ventilation, lighting, smart meter, etc.) of individuals who could submit the survey by mail or online. Households' occupants were invited to sign a consent form to share their electricity and fuel bills (gas or fuel oil) via their energy providers. Once signed, it was possible to access their bills via the energy suppliers. Also, occupants were invited to fill in an online or paper survey that characterizes their building's energy efficiency. The consent form and survey content covered the building characteristics, domestic hot water, energy systems, and occupant behavior. Logbooks were also distributed to owners so that they could indicate their monthly consumption. In some dwellings, data loggers were installed to record consumption. Access to the forms and surveys can be found in the project report [21]. Finally, neighborhood organizations could also be contacted directly as it was often easier to convince people to communicate their bills through the local community.

Moreover, walkthrough audits were organized in more than 160 households voluntarily. Detailed energy audits involving blower door tests, u-value monitoring, energy system inspection, and occupancy behavior characterization were performed. Finally, the database was compiled, and missing information was completed to include 1050 households. The data collection process, analysis, and storage were done in line with the European Union General Data Protection Regulation, which was applied retrospectively [49].

2.4. Selection of two representative reference houses

A typology analysis took place for the 1328 houses to select two representative building configurations. The architectural and energy characteristics of the buildings have been analyzed concerning the building vintage. The analysis indicated a strong divide between the two vintages of post-WWII households.

First, (archetype A) detached houses built late 1940s throughout the 1969s had similar geometry, surface area, building materials, and occupant density. After WWII, it was necessary to house the population and rebuild the country. Under the federal law proposed by minister De Taeye, a new law allowed for the construction of 100,000 detached houses from its entry into force in 1954 [50] and reached 285,166 detached houses by 1969. Taeye's law resulted from a compromise between two great movements: the socialist and catholic movements [51]. Taeye's law was the fruit of a campaign by Christian Democrats wishing to promote low-cost construction [52] of private dwellings outside the cities [53]. At that epoch, the Law of 1939 started to get implemented and made it mandatory to submit building permit applications accompanied by plans drawn up by an architect [54]. Consequently,

many house owners resisted hiring an architect and opted to select identical house designs found in catalogs offered by architects for reduced fees. We interviewed several house owners from this epoch who confirmed this information. Contractors offered limited design alternatives of architectural designs against reduced costs for reproduction.

Consequently, typical De Taeye-archetype houses emerged with red bricks and ceramic roof tiles (see Result Section 3.2) [55]. Another point of similarity was construction materials. Single-family houses were constructed with inner walls of Ytong and were covered with external walls of traditional bricks [56]. Floors were built with lightweight concrete [57]. Other influential factors that lead to grouping single-family houses built between 1945 and 1969 under one archetype to represent a vintage were demographics and household surface area. Our field studies revealed that houses built before 1970 exceeded the 200 m^2 area threshold and homeowners had an average of three to four children per household. Between 1945 and 1969, birth rates boomed in Belgium [58]. On the opposite, households built between 1970 and 1990 were less than 200 m^2 and witnessed a decline in birth rate per household, reaching on average two children.

Second, (archetype B) detached houses built between the 1970s throughout 1990s had similar geometry, surface area, building materials, and occupant density. Despite this archetype's geometrical similarity, the facades and envelope cladding became more heterogeneous [59]. There has been an evolution in lightweight concrete for walls, from infills principally to loadbearing walls [56]. A proliferation of insulation materials and systems occurred. Norms and regulations evolved, and the BBRI published several technical reports on the insulation of flat roofs. The BBRI promoted construction standards and published the 'General specifications for the execution of private buildings,' co-edited with the Royal Federation of Architects' Associations in Belgium (FAB) and the National Confederation of the Building Industry (NCB) [56]. Despite the emergence of the oil crisis in the 1970s, there was no systematic improvement in building energy efficiency. However, the occupied areas were remarkably reduced. The single floor bungalow archetypes with I or L plans dominated the single-family households' construction scene.

Finally, the two representative buildings were also selected strategically. Plans and geometric forms of the two houses were described and analyzed. Based on the typology analysis and classification, two theoretical reference models were created. The energy performance data compiled in the database (Section 2.3) allowed us to select two typical archetypes to represent the 1945–1969 and 1970–1990 vintages.

2.5. Energy characteristics of reference houses

Two levels of energy characterization are carried out for the selected houses based on the recommendations of Krarti [60]. An analysis of energy use intensity (electricity and natural gas) and a walkthrough survey are conducted between 2016 and 2019 for 1500 households. Key informant interviews are conducted in Dutch and French one-to-one with main stakeholders living in the selected hectares with first-hand knowledge of the location. The key informal interviews assured introducing the project, building trust, and maintaining confidentiality. The walkthrough surveys allowed us to inspect the energy efficiency characteristics and energy use for 2016–2019 based on monthly bills. The walkthrough audits allowed us to understand the performance of the building and to identify the usage patterns. Monthly energy use was retrieved via private databases. Private companies such as Engie, Lampiris, and Luminus gave access to the consumption data

based on the occupant's consent. The *Commission de Régulation de l'Electricité et du Gaz* (CREG) database was also used as part of the study. The CREG is the federal organism for the regulation of the electricity and natural gas markets in Belgium. This allows consumers to compare their current energy contract with the current market offer. It collects data on the production and consumption of electricity and gas in Belgium and reports on price trends. As a result of this step, 250 households were excluded from the 1500 households sample due to data discrepancies or none constituent consent. As a consequence, 1328 audits were conducted via field visits and self-administered online and paper-based surveys.

The second type of energy characterization was highly detailed and involved several techniques to reduce the uncertainty of energy efficiency characterization parameters and occupancy patterns. The smartphone-based survey was developed to identify the occupancy density and profiles in the different households' thermal zones on a daily, weekly, monthly and seasonal level. With some modifications made to meet the current occupancy profiling exercise's objectives, the survey was replicated at the building level for representative samples of archetypes A and B. The sampling design consisted of a random sample—a free, open-source application allowed collecting the responses and compiling them on the server via the cloud. Once repetition of the answers patterns was found, the request of occupancy information input was stopped.

As a consequence, 160 household occupants participated in the occupancy surveys between 2016 and 2019. The collected data was compiled with the central project database and analyzed to describe the representative households' energy performance to serve later the building modeling stage. The occupancy surveys provided insights to justify the choice of the two representative archetypes.

The annual occupancy schedule has been set based on an average yearly schedule representing 2016–2019. The occupancy surveys and data loggers' data were used to determine households' heated thermal zones, size, composition, age, and occupants' presence. The survey involved information about water consumption and Domestic Hot Water (DHW) use. The number of vacation days was determined per household. The daily occupancy schedule has been established in line with ISO 18,523 recommendations [61]. A special section in the energy audit involved characterizing the artificial lighting, HVAC systems, and energy sources. The audit questionnaire included questions describing the mechanical ventilation systems and components. Mobile heating units and heating were checked. Visual inspection for all chimneys took place to trace and understand the heating strategy and energy sources.

2.6. Development of the benchmark models

Two representative simulation models were made based on the previously described selection process and building characterization. The building energy models were created using EnergyPlus (Version 8.2.0) [62].). All simulations were performed for the location of Uccle, in the Brussels-capital region, in Belgium. The country falls almost entirely within Köppen-Geiger classification of temperate oceanic climate (Cfb) with no dry season and warm summer [63]. Overall, Belgium's climate is mild-cold and humid, with a significant amount of rainfall during the year. Residential buildings are typically heating-dominated with an average of 2941 Heating Degree Days (HDD) and 90 Cooling Degree Days (2014–2019, base temperature 15 °C HDD and 24 °C CDD) [64]. Brussels meteorological weather data for

2016–2019 were requested from the Belgian Royal Meteorological Institute [65].

2.6.1. Calibration

The building energy models' validity has been further checked against the public statistics and verified through a model calibration and utility bill comparison. According to ASHRAE Guideline 14 [58], calibration was done to evaluate the goodness-of-fit of the energy models. The ASHRAE Guideline 14 uses two indices to assess the goodness-of-fit of the building energy model [66]. The Mean bias error, MBE, and the Coefficient of variation of the Root mean square error, CV (RMSE). MBE is a non-dimensional measure of the overall bias error between the measured and simulated data in a known time resolution, and it is usually expressed as a percentage:

$$MBE = \frac{\sum_{i=1}^{Np}(m_i - s_i)}{\sum_{i=1}^{Np}(m_i)} \ [\%] \tag{1}$$

where m_i (i = 1, 2, ..., Np) are the measured data, s_i (i = 1, 2, ..., Np) are the simulated data at time interval i and Np is the total number of the data values.

CV(RMSE) represents how well the simulation model describes the variability in the measured data. It is defined as:

$$CV(RMSE) = \frac{1}{m}\sqrt{\frac{\sum_{i=1}^{Np}(m_i - s_i)^2}{Np}} \ [\%] \tag{2}$$

where, besides the quantities already introduced in Eq. (1), m is the average of the measured data values. The evaluation of a building energy simulation model's accuracy is made according to the model's conformity with the recommended criteria for MBE and CV (RMSE).

According to the ASHRAE Guideline 14, the simulation model is considered calibrated if it has MBE that is not larger than 5%. CV (RMSE) is not larger than 15% when the monthly data are used for the calibration.

To get reliable building energy models and increase the accuracy of estimating the building's performance, the models of detached single-family houses underwent two subsequent calibrations. The building model was first calibrated based on the building's measured monthly gas consumption. An uncertainty analysis was then performed to identify the most influential independent input variables, including the weather, building envelope, and occupancy [67].

2.6.2. Weather normalization

Weather normalization was applied to isolate weather changes on the archetypes energy performance for the period 2016–2019 [68]. The degree-days method was used to represent the total positive or negative difference [69]. The degree day is the difference between a base temperature and an average temperature of the place taken as a reference. This notion considers that the heat losses are proportional to the difference between the indoor T° and the outdoor T° of modeled building. This degree-days method, therefore, allow to establish the normalized consumption. The relationship between these two consumptions can be selected based on the equation below:

$$\text{Normalized consumption} = \frac{\text{monitored energy use} \times \text{normal degree days onsite}}{\text{observed degree days onsite}} \tag{3}$$

2.6.3. Building envelope performance monitoring

The envelope airtightness and conductivity values were identified as influential modeling input parameters with high

uncertainty. Despite the airtightness values found in several studies [70], including the earliest work of Bossaer et al. (1998) [71], we could not find a reliable value of envelope infiltration at 50 Pa [m^3/h.m^2] for the detached houses built between 1945 and 1990. Therefore, an airtightness test took place using the pressure measuring device DG-700 and software TECTITE Express 5.1 and BlowerDoor® measurement according to EN 13829 [72] and STS P 71-3 [73].

Moreover, a 21 days U-value monitoring took place on different envelope surfaces using gSKIN® KIT-2615C (U-Value Kit) according to ISO 9869-1:2014 [74]. The kits were installed to measure a representative brick cavity wall [75], the roof, and the attic (loft) floor. Most of the investigated attic slabs were insulated, and literature [16] did not provide accurate and representative values. Therefore, the conductivity and heat capacity of the attic slab required special attention.

2.6.4. Occupancy behavior verification

With the house owners' consent, three data loggers, namely TESTO IAQ 160, were placed in the two selected houses. The data loggers uploaded five readings (temperature, humidity, CO2, and pressure) every 15-minutes to the cloud. The field measurements took place in the summers of 2018 and 2019 to refine residents' specific behavioral characteristics. With the help of the survey responses and the monitoring data, occupancy schedules were verified. Lighting, plug loads, and domestic hot water schedules were developed based on the energy and indoor environment monitoring data. The profiles were accordingly scaled to match the needs of the building energy modeling software based on the work of Koupaei et al. 2019 [76]. After defining both daily and yearly periods of heating (and cooling), and natural ventilation using meteorological weather, the heating, cooling, and natural ventilation schedules were created.

3. Results

The results of the database are presented in this section. The two selected reference buildings are described in detail regarding their energy characteristics, energy models, and the validation results.

3.1. Database of Belgian post-WWII single-family houses

The buildings are grouped according to their archetype and organized by hectare. Fig. 4a shows the Distribution of extracted buildings per municipality in Belgium. Fig. 4b indicates that most detached residential buildings are concentrated in the northern and middle parts of Belgium. Accordingly, our selected grids contain 1500 buildings located within the north and middle of Belgium (Fig. 2) to ensure well representation of extracted buildings.

However, a comprehensive database of 1328 households was created, bringing together all the post-WWII single-family houses database's geometric and energy efficiency characteristics. The architecture of the one thousand houses was analyzed. Two archetypes of houses were identified from the data collected: archetype A corresponding to dwellings built between 1945 and 1969 and archetype B corresponding to homes constructed between 1970 and 1990. Both archetypes had to be distinguished due to the disparity in architecture, house configuration, occupancy density, and energy performance. Fig. 5 represents the one thousand reference dwellings visited during the field surveys for typology A and B.

As shown in Fig. 5, the architectural style and the vintage and other characteristics such as the occupant density and construction materials differ between these two periods. Archetype A (1945–1969) included 716 audited households. The measured energy use (electricity and natural gas) for archetype A in 2018 is presented in Fig. 6. The measured energy use (electricity and natural gas) for archetype A in 2018 is presented in Fig. 6. Archetype B (1970–1990) included 612 audited households, and its measured energy use breakdown is presented in Fig. 6.

3.2. Selected reference buildings

Two reference buildings were identified as a representative, as shown in Fig. 7 and described in Table 2. Archetype A represents the 1950s and 1960s free-standing housing. First, archetype A represents a standardized rectangular plan with a cavity wall cladding with brick. The typical house comprises two floors with unoccupied attics and is covered with a sharply gabled roof. Most of the households had an underground garage and a cave. The archetype came within reach of broad sections of the Belgian population from the 1950s onwards [77] and was named the 'Belgian Villa,' or the
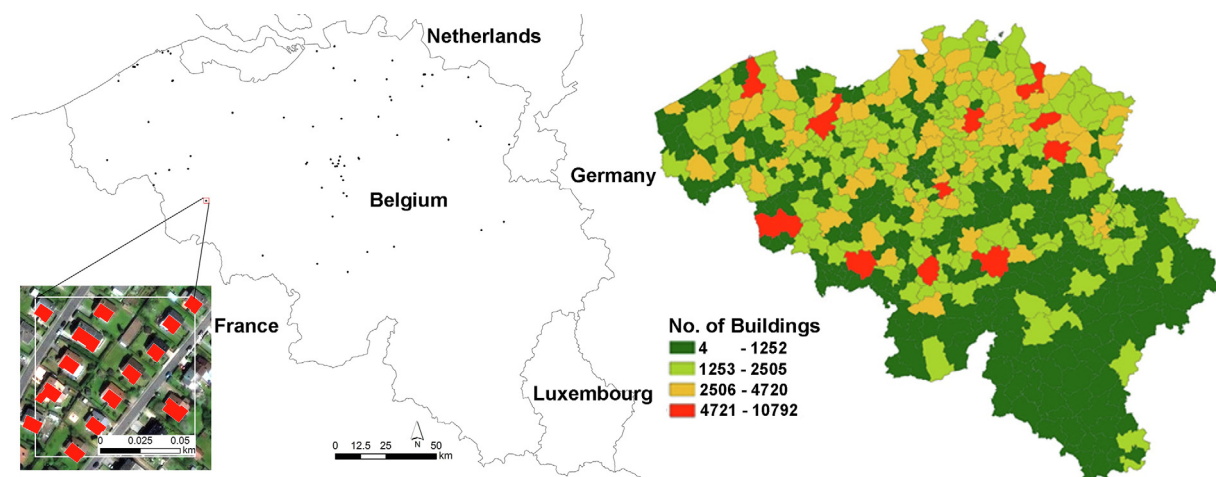

Fig. 4. a, number of detached residential buildings per municipality between 1945 and 1990. Fig. 4b, Distribution of the 1328 representative buildings in 82 ha throughout Belgium,

Fig. 5. a. Dwellings representative of archetype A, Fig. 5b. Dwellings representative of archetype B.

'Fermette' or 'De Taeye-houses' [78]. The average surface area is often between 250 m² and 300 m². The houses historically comprised at least two chimneys and were heated with fuel oil. From the audited sample (716 homes) we found that more the 70% of households went through an energy retrofit and replaced the fuel oil with natural gas boilers.

Second, archetype B is characterized as a single-floor house, unoccupied attic, and a separate garage unit next to the house. Archetype B represents standardized rectangular or L-shaped plans with a cavity wall, which is cladded with brick. Fig. 7 shows the selected reference building. The archetype gained importance in Belgian living culture in suburbia. It represented the rural and rustic style of pseudo farm housing [79]. Facades comprised of retroelements and washed old brick (cavity walls) [78]. The house plan was more open, avoiding a reception space with an open kitchen. The average surface area is often between 180 m² and 240 m². The archetype was named the 'Bungalow' with prefabricated concrete attic floors and ground slabs [78]. The attic side walls had a typical timber cladding, and the houses seemed to be more standardized and fabricated in an industrial way.

The building energy models are multizonal thermal spaces that are categorized as (1) living area (living, dining, and kitchen), (2) sleeping area (bedrooms), and (3) short-presence area (bathrooms and corridors. Fig. 8 illustrates the two modeled archetypes in 3D view. Fig. A1, in Appendix I, shows the plans and facades of both archetypes. Further details regarding the

thermal zoning schemes can be found in a detailed modeling report [21].

3.3. Energy characterization of the two reference buildings

The energy characteristics of the two reference simulation models are described in this section.

3.3.1. Energy use intensity

As shown in Fig. 7, the EPC rating of archetype A is F, and the rating of archetype B is E. The carbon emissions calculations are based on the assumptions proposed by Georges et al. [80]. The characterization of the energy use of the 1328 households indicated that the average energy use intensity of archetype A is 148.7 kWh/m²/year for heating (including DHW) and 17.7 kWh/m²/year for electricity. Fig. 7 indicates that archetype B's average energy use intensity is 139.8 kWh/m²/year for heating (including DHW) and 14.9 kWh/m²/year for electricity (see Table 3).

3.3.2. Occupancy density and schedules

Archetype A was dominated by senior couples or single female seniors (>70 years old). Almost all of the investigated occupants were first house owners. In the past, they had, on average, three children who all left the house. A significant amount of survey respondents indicated a usufrucary ownership, which means they do not have full ownership of the property right. Most interviewed occupants granted the usufruct to their children or grandchildren to reduce the inheritance tax burden. Archetype B was dominated

Fig. 5 (continued)

by senior couples (>60 years old) where at least one occupant was pensioned. Overall the occupancy density in both archetypes was low, and several spaces were not used.

Based on the schedule available in the standard ISO 18523 part 2, we defined the occupancy period. However, ISO 18523 was developed for an average age category of 45-year old occupants. Therefore, our surveys and monitoring observations were used to create novel schedules. Fig. 9 presents the occupancy schedules for the three space categories as (1) living area (living, dining, and kitchen), (2) sleeping area (bedrooms), and (3) short-presence area (bathrooms and corridors. Since occupants were mainly seniors, we considered the same schedules for a weekday and the weekend. Tables 4 and 5 summarize the holidays and occupation periods use for both archetypes.

3.3.3. Lighting intensity and schedules

The data collected from the survey allowed us to define the most commonly used types and numbers of lamps. The dominant types of lamps used were mainly compact fluorescent lamps (64%) followed by LED lamps (28%). Halogen lamps were found primarily in the dining and living areas. Artificial lighting was not used during the daytime of the day or in the absence of occupants. As seen from the survey, the average lighting power intensity for living areas was 12 W/m^2. For the bedroom, for example, the average lighting power density is 8 W/m^2, with an average variance of 6.1 W/m^2. Fig. 9 presents the lighting schedules applied to the three main space categories. Lighting schedules were modified during the winter period to extend the operation in the living areas

2 h after 08:00 and 1 h before 17:00. Several attempts to validate the lighting schedules were achieved by comparing the outcomes with the reports published by Flemish Energy Agency [81] and IP Belgium [82].

3.3.4. Plug load intensity and schedules

The penetration rates and saturation rates of house appliances were determined based on survey findings. Table 6 lists the most found house appliances in Belgian post-WWII single-family houses. The 20 listed appliances had a saturation rate higher than 65% in the surveyed sample. The national average of household appliances is 77appliance per household [83]. The unit capacity of the plugged appliances (standby and continuous) was estimated based on the running hours and power values. The average plug load power intensity is estimated at 9 W/m^2. Surprisingly, around 15% of households had an air conditioning unit (split), 17% had a dehumidification device, and 25% had mobile electric heating devices. Finally, the monthly and annual electricity use was used to validate the modeling assumptions.

3.3.5. Cooking and domestic hot water

Most visited households were connected to the district gas grid. Households located in Walloon and Flemish Brabant, Hainaut, Brussels, and Antwerp provinces were mostly using lean gas imported from the Netherlands. The households are in a transition phase since 2018 and until 2029 to replace it with rich gas. Lean gas will be replaced by rich gas imported from Norway, the United Kingdom, Qatar, and Russia. Most households had gas-fired boilers
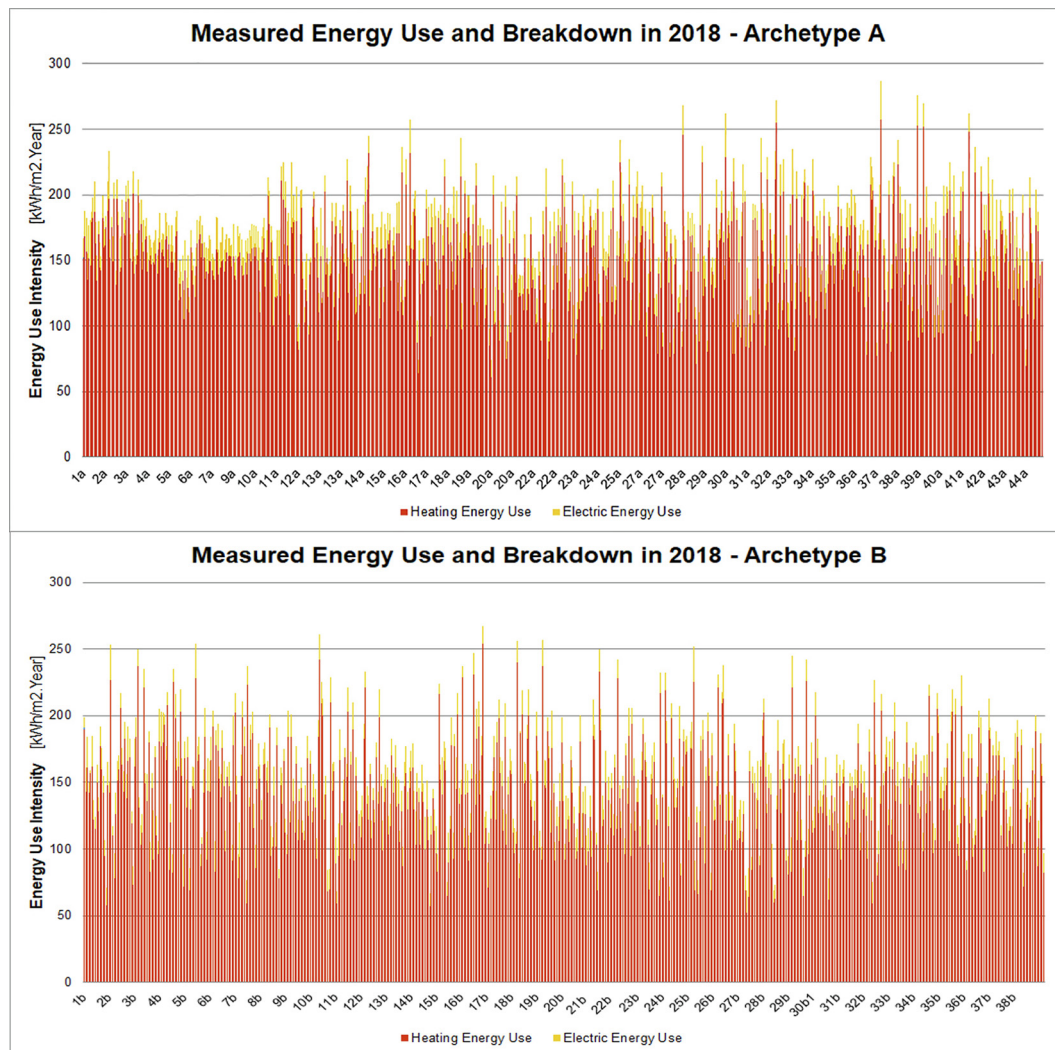
Fig. 6. a. Measured energy use intensity for archetype A, Fig.6b. measured energy use intensity of archetype B.

that were replaced after 1990 and thus are compatible with rich gas. The analysis of gas utility bills allowed defining the baseline of energy use for DHW and cooking (see Section 3.3). The water use per person was surveyed, representing an average of 30 m³ per household (2 senior occupants), which stands for 41 L/person/-day. The DHW hot water (of 60 °C) was calculated to reach 25 L/person/day. The cooking activities were assumed to reach 40–60 min per day.

3.3.6. HVAC systems and comfort setpoints

More than 80% of households were heated by natural gas. A small number of households had a fuel oil boiler or a pellet or wood logs heating system. More than 90% of households had a hydronic heating system with a hot water loop and radiators. The household owner indicated replacing the heating system at least once before the year 2000. Radiators were fitted with thermostatic valves to control hot water flow in response to the local sensed setpoint temperature. Radiators in children's rooms and non-occupied spaces were left closed. The thermostat average setpoint temperature was 23 °C in living areas, including the kitchen. Radiators were completely open. The thermostat in the bathroom and short-presence areas were set to 16 °C where radiators were left closed. Occupied bedrooms were set to 18 °C, where radiators

were left half-open. The real measured setback temperature in both households was 13 °C when occupants were absent during holidays. Therefore, the thermal comfort setpoint criteria complied with ISO 17772-1,2 requirements (Category I) [84] for senior adults with low metabolic rate and impaired control of body temperature [63 and 64]. Almost none of the investigated households had a mechanical ventilation system. 78% of survey respondents indicated opening windows for natural ventilation during winter and summer. Several attempts to validate the heating energy use and schedules were achieved by comparing the outcomes with the reports published by the Flemish [86] and Walloon [87] and federal government [88].

3.4. Numerical model calibration

Several iteration rounds tool place based on several input validation measures. The MBE and CV(RMSE) values of monthly energy use were calculated and are presented in Table 7. The obtained values are in acceptable ranges

Table 8 indicates the energy use intensity normalization after weather normalization. Brussels' HDD days were extracted from the Eurostat website for the years 2016–2019 [64]. Both archetypes' energy use was compared with the observed energy use
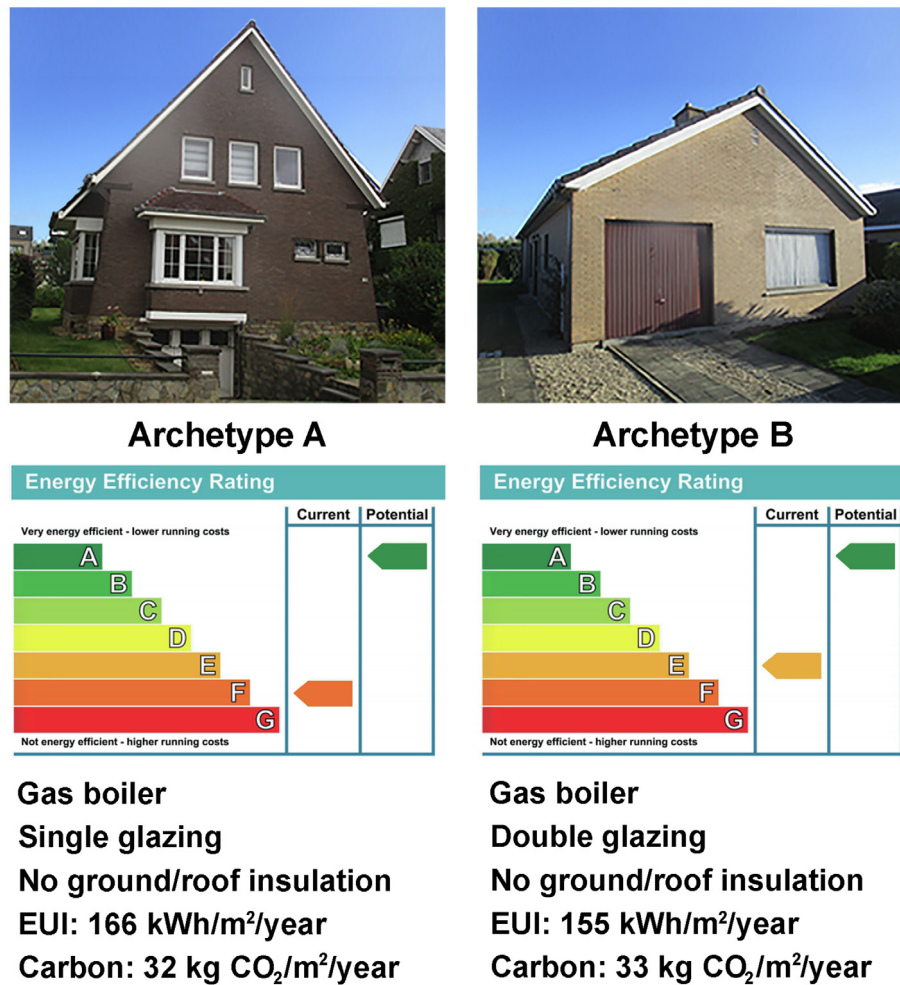
Fig. 7. Measured energy use intensity and carbon emissions between 2016 and 2019 for archetype A in Wezembeek-Oppem, Flanders, and archetype B in Frasnes-lez-Anvaing, Wallonia.

Table 2
General description of archetypes A and B.

Building description	Archetype A	Archetype B
Number of floors	2	1
Total area (m²)	259	148
Occupants	2	2
Total volume (m³)	774	636
External wall area	254	198
Roof area	192	187
Floor area	259	148
Windows area	24.7	20.4
Windows U-value	2.90	2.76
Windows G-value	0.74	0.60
Wall surface absorptance	0,80	0.70
Walls U-value (W/m²K)	1.72	1.70
Roof U-value (W/m²K)	1,25	1.40
Ground U-value (W/m²K)	0.46	0.46
Attic Floor U-value (W/m²K)	1,1	1.1

intensity extracted from the energy bills. The difference between the heating degree values lies between −4° and +3.5° HDD—the weather normalization allowed to neutralize the effect of weather and validate the results presented in Table 3.

Moreover, the envelope input parameters were refined through U-value monitoring and airtightness measurements. The final U-values of the building envelope and internal floors are presented in Table 9. Also, the blower door test results are indicated in Table 9. The leaky nature of the households was confirmed due to the difficulty to reach 50 Pascal when depressurizing the tested buildings. Several plastic masks were taped over electricity outlets, chimney dampers, opening frames until we could calculate the total air change per hour from air leakage with an accuracy of 90%.Our findings are close to the assumptions reported by the Flemish [50] and Walloon [67] studies. More important than the absolute energy use per household, it was essential to provide reliable envelope performance values based on in-situ monitoring. The reported values reduced the uncertainty of the building energy model remarkably.

In a final attempt to validate the multizonal energy model, household occupancy profiles were refined. The repetition of the surveys allowed us to reach a high agreement on the most probable profiles. Despite the size of the large dwellings, the occupancy characterization confirmed that the elderly occupied both households. However, the most important observation revealed from the occupancy behavior verification stage (Section 2.6.4) was finding that occupants use mobile electric and gas heaters. There was a difficulty to match the simulated electricity use values with the measured ones during calibration for December, January, and
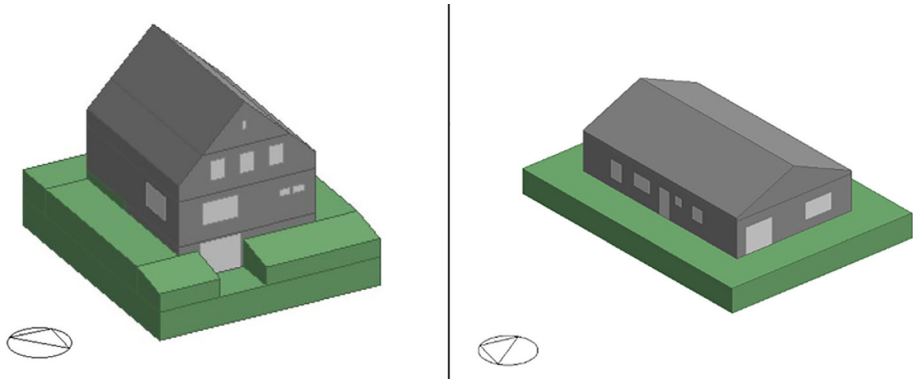
Fig. 8. Typology A and B in 3D view.

Table 3
Heating demand, electricity demand, and energy use intensity.

Buildings Type	Average heating energy demand [kWh/m²/year]	Variance	Average electricity demand [kWh/m²/year]	Variance	Average energy use intensity [kWh/m²/year]	Variance
Archetype A	148.7	33.5	17.7	7.6	166.4	
Archetype B	139.8	38.4	14.9	5	154.7	

Fig. 9. Occupation schedule.
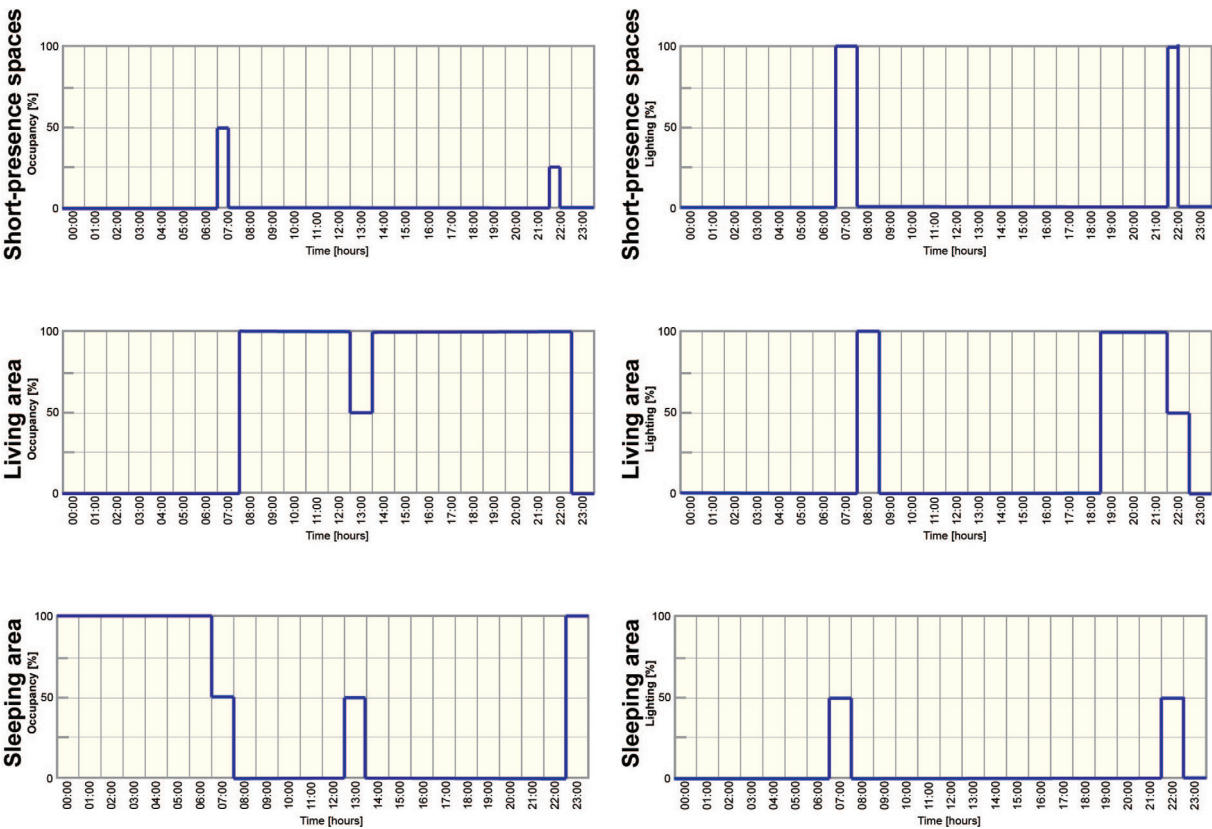
February. The backtracking of survey respondents, logbooks, and post-hoc interviews revealed that more than 25% of occupants used electric heating, electric heating mobile convectors, and fan-assisted heaters. The main reason was to improve the personalized thermal comfort and comfort perception. The use of electric heating devices justified the calibration problem and allowed to

Table 4

Occupation status of apartment members in a typical apartment for five family members.

2018/2019	Member	Archetype A		Archetype B	
		Senior 1	Senior 2	Senior 1	Adult 2
–	Status	Pensioned	Pensioned	Full-time	Pensioned
Days at home	06:00–09:00	Often	Often	Often	Often
Weekday	09:00–12:00	Often	Often	Seldom	Often
	12:00–15:00	Regularly	Regularly	Seldom	Regularly
	15:00–18:00	Often	Often	Seldom	Often
	18:00–23:00	Often	Often	Often	Often
	23:00–06:00	Often	Often	Often	Often
Days at home weekend*		Often	Often	Regularly	Regularly

*The same schedules for a weekday and the weekend were used with slight differences.

Table 5

Holidays schedules for the year 2021.

Name	Start date	End date	Number of days
Easter Holidays	30/03/2021	05/04/2018	7
Summer Holidays	01/08/2018	15/08/2018	15
All Saints'Day Holidays	28/10/2018	05/11/2018	7
Christmas Holidays	24/12/2018	01/01/2018	7

increase the curves fit shown in Figs. 10 and 11. The monitoring of indoor quality parameters in both households confirmed several behavioral estimations concerning the heating setpoints and occupancy presence and patterns.

4. Discussion

Benchmarking allows characterizing existing buildings to enable reliable simulations and realistic future renovation scenarios. In this section, we discuss the study findings and position them regarding the state-of-the-art.

4.1. Summary of the main findings

Two reference models representing 633.702 post-WWII single-family houses in Belgium were created and validated. As shown in Table 9, archetype A has an average energy use intensity of 166 kWh/m²/year and represents detached single-family houses built between 1945 and 1969. Archetype B has an average energy use intensity of 155 kWh/m²/year and represents detached single-family houses built between 1970 and 1990. Both archetypes represent buildings built before or during the oil crisis in the 1970s, thus before any building energy efficiency requirement.

The results of the benchmarking of the two reference models are summarized in Table 9. The buildings hardly comply with any building energy efficiency criteria. The heat gains are low due to the small size of windows (see WWR values) and external roller shutters in most households. However, the heat losses are remarkably high, as indicated by the high U-value of the envelope and poor airtightness. The air change rate at 50 Pa pressure was 14.5 and 13.8 ACH, both benchmark models, respectively. Each building is equipped with one or two chimneys that act as passive stack ventilation. The openings in the envelope cause the leakage flow to be high. Also, the internal gains are low due to the low occupancy density. Older people choose to remain in their large homes, which host in the past 2–3 children on average. The most important and tangible outcomes of both building performance characteristics are described below:

- One thousand three hundred twenty-eight representative single-family households have been selected nationally (out of 633,702) with an automated algorithm using GIS database (Belgian cadaster).
- Two multizonal energy benchmark models were created in EnergyPlus based on the representative building stock performance and were calibrated based on the ASHRAE BESTEST requirements
- A dataset containing the physical and thermal characteristics of more than 1300 buildings has been created
- The average annual electricity use intensity for archetypes A and B is 17,7 kWh/m²/year and 14,9 kWh/m²/year.
- The average heating use intensity for archetypes A and B is 148.7 kWh/m²/year and 139.8 kWh/m²/year.
- The EPC rating for archetypes A and B is F and E, respectively, higher than expected (G rating).

Table 6

Appliances found in typical Belgian post-WWII single-family houses.

Appliance	Watt-hour	Daily Operating Hours	Appliance	Watt-hour	Daily Operating Hours
Furnace fan	50	1.5	HD Television	50	5
Coffee machine	600	0.2	Deep Fryer	1500	0.05
Microwave	1500	0.2	Washing machine	680	0.8
Mobile charger	5	24	Refrigerator (2 doors)	95	24
Phone charger	3	3	Kettle	1500	0.2
Built in Oven	300	0.1	PC/ Laptop/Tablets	150/60/40	2
Electric Iron	1100	0.1	Freezer	15	24
Vacuum cleaner	330	0.05	Radio	15	0.1
Clothes Dryer	561	0.8	Dishwasher	720	1
DVD/CD Player	40	0.05	Electric Stove	650	0.9

Table 7

MBE and CV(RMSE) of the monthly energy heating and electricity consumption.

Statistical indices	MBE (%)	CV(RMSE) (%)
Typology A Monthly calibration (Natural gas)	1,6	0,02
Typology A Monthly calibration (Electricity)	2,75	9,5
Typology B Monthly calibration (Natural gas)	0,1	0,38
Typology B Monthly calibration (Electricity)	3,1	10,8

- The building envelope air permeability was very poor, with an average of 13.8 and 14.5 vol/h at 50 Pa, for both archetypes, respectively. Several chimneys, cracks around openings, and added extensions, such as verandas, are the leading cause of this problem.
- Most windows are double glazed due to window retrofits that took place before the year 2000. However, the overall windows performance is low, with a high conductivity value ranging around 2.8 W/m^{2}K.
- Similarly, the envelope conductivity, around 1.7 W/m^{2}K for walls and 1.3 W/m^{2}K for roofs, is high. Surprisingly, more than 40% of households has poorly insulated bitumen felt shingles roofs.
- The households are dominated by elderly occupants (>65 years old) and have a low occupancy density with average households area of 250–300 m^2 and 180–240 m^2 for archetypes A and B.

4.2. Strengths and limitations of the study

The renovation of the post-WWII residential building stock offers many opportunities to neutralize the building sector's carbon emissions across Europe [4]. Therefore, building benchmarking is the basis for energy performance assessment approaches to reduce energy use and align with minimum performance requirements [89]. Using calibrated building simulation provides insights into the performance issues applicable across Europe. Moreover, the detailed characterization of the building performance allows closing the performance gap.

In this study, an essential vintage of single-family households was characterized by actual monthly energy use data for natural gas and electricity with four years of monitoring (2016 and 2019). The study identified a type of owners and age group that are not often studied in the literature [22]. Also, we are not aware of a West European study that characterized such a sample size of post-WWII single-family houses using GIS and fieldwork data collection techniques. Most of the existing studies found in the literature are based on statistical methods to create theoretical benchmark models [17]. The study results present a representative and accurate characterization of energy efficiency and occupant behavior. Using building performance simulation enables a systematic identification and classification of the performance gap's root causes for any future renovation scenario.

A novel approach was used to identify and verify performance issues using evidence-based calibration to increase the newly created models' confidence and accuracy. With the help of a mixed methodological approach, previously used [90], the study was able to survey house owners, collect energy bills, perform walkthrough audits and more importantly, perform in-situ blower door test and conductivity monitoring. The presence of smart meters in many households due to photovoltaic installation helped verify the monthly energy profiles. A systematic and structured data collection approach with a team of 15 participants allowed triangulating the data sources. The triangulation approach allowed revealing insights on the occupancy behavior and building energy efficiency.

Table 8

Normalised energy use intensity for archetypes A and B between 2016 and 2019.

	2016 A	B	2017 A	B	2018 A	B	2019 A	B
Energy use intensity in kWh/m^2/year	174	158	168	169	165	146	156	143
HDD base temperature 15 °C [64]	2556		2448		2383		2379	
The difference compared to the average 2442 HDD (2016–2019)	−4%		+0%		+2.5%		+3.4%	
Normalized energy use intensity (kWh/m^2/year)	**167**	**152**	**168**	**169**	**169**	**150**	**161**	**148**

Table 9

Summary of input parameters for both benchmark models after calibration.

| Model input measures		Typology A	Typology B
Envelope	Window to Wall Ratio (WWR in %)	12%	10%
	Solar Heat Gain Coefficient (SHGC)	0.74	0.60
	Light transmittance (LT)	0.80	0.70
	Solar protection (External)	Roller Shutters	Roller Shutters
	Windows U Value = [W/m^{2}K]	2.90	2.76
	Roof U Value = [W/(m^{2}K)]	1.25	1.4
	Airtightness (at 50 Pa m^3/h-m^2)	290 or 14.5 ACH	276 or 13.8 ACH
Heating system, ventilation, and air conditioning	COP Heating system	0.76	0.80
	Temperature set point [°C] for heating	23	22
	Heating system	Gas-fired boiler	Gas-fired boiler
	Heating fuel	Natural gas	Natural gas
Lighting	Lighting power density [W/m^2]	8–12	8–12
Occupancy	Number of people	2	2
	Occupancy Density [m^2/person]	129,5	74
	Occupancy schedule	See Fig. 9	See Fig. 9
Total	**Average consumption [kWh/m^2/year]**	**166**	**155**
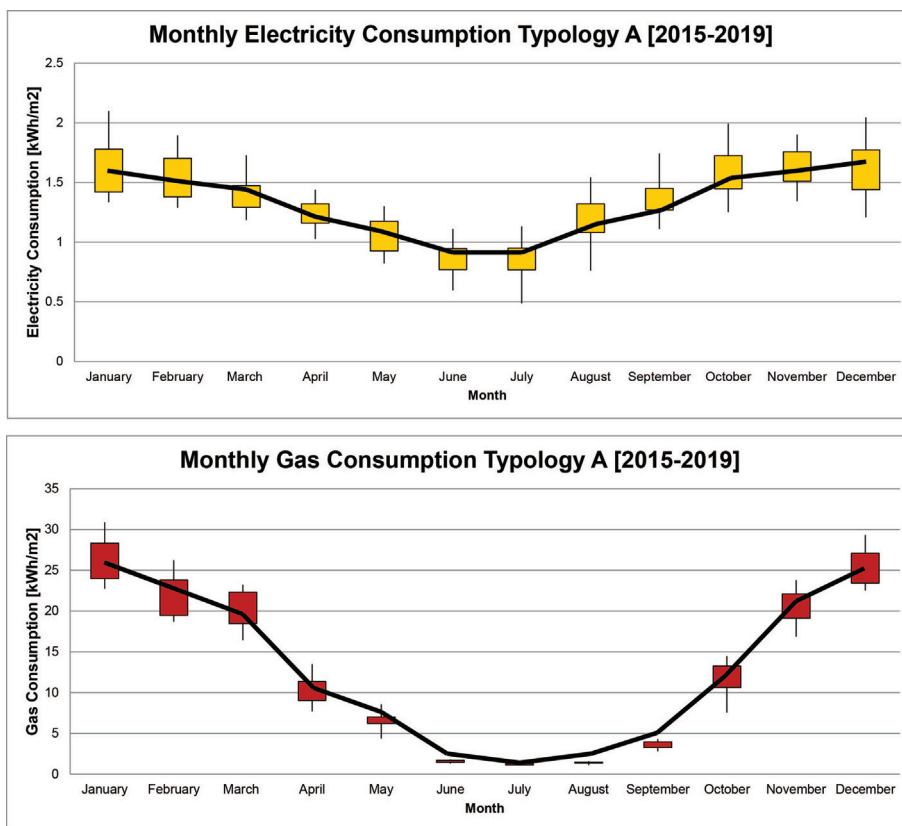
Fig. 10. Surveyed and simulated monthly electricity and gas use of typology A.
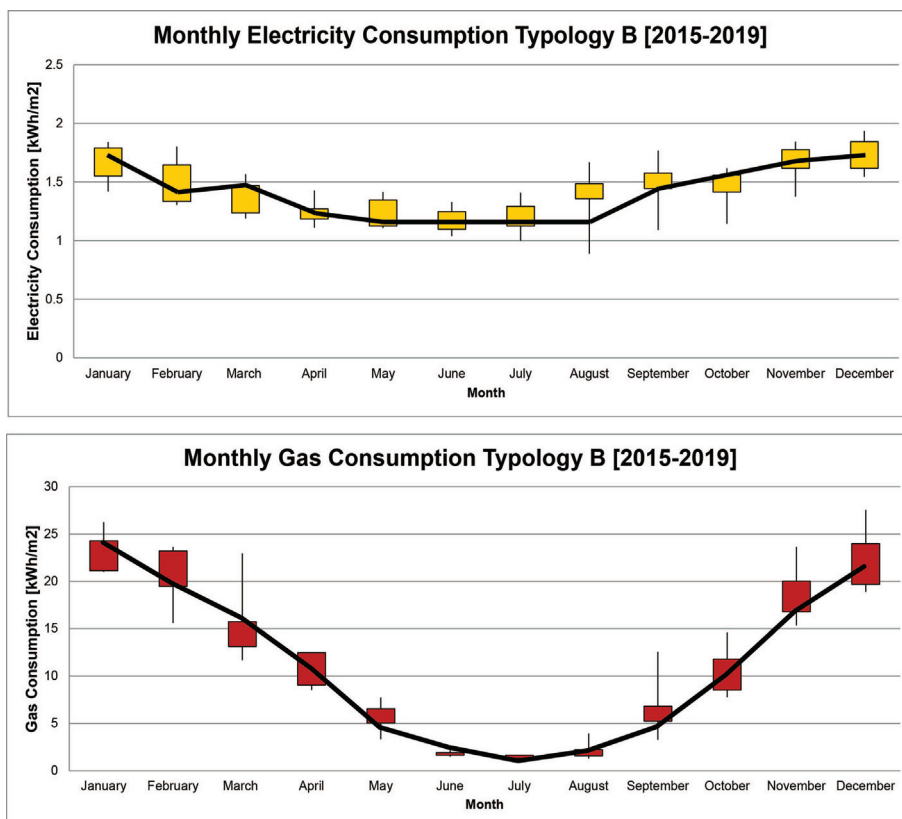

Fig. 11. Surveyed and simulated monthly electricity and gas use of typology B.

Despite the long investigation period that covered 5-years, the results are valuable, and the dataset will be further analyzed and exploited.

This study identified several lessons that can potentially be used to inform and improve current building renovation practices. However, the paper has some limitations, including the thermal comfort characterization. Therefore, a detailed comfort characterization is still underway. The poor envelope performance, air conditioners, mobile electric heaters, and the absence of mechanical ventilation systems were associated with overheating and winter discomfort problems. A thermal comfort assessment paper will deal with the indoor thermal quality issues based on the survey answers and dataset developed in this study.

4.3. Implication for the practice and future research

Belgium and many other industrial countries are facing an aging population. This study found that most households are too large concerning the low occupancy rate of two occupants per household. Unfortunately, the occupants of most of the investigated households ((>65 years of age) did not go through a deep renovation despite their financial capacity. On the other hand, the transfer of ownership of post-WWII households already started and intensified during the next 30 years. If Belgium and Europe wish to achieve the 2050 carbon emission reduction targets, new house owners and nuclear families shall occupy those households and pay for the renovation cost. However, it will be difficult to develop targeted renovation policies and subsidy programs without an accurate characterization. The study findings add to the evidence found in the literature [91] that nuclear families renovate their households at the beginning of their life [92] and not after being pensioned. The survey findings on usufrucuary ownership status confirm that too. Therefore, the moment of buying the post-WWII household will be crucial to implement any deep renovation.

In this context, local governments must prepare fiscal and financial regulation packages to encourage deep renovation endeavors. The decarbonizing of heating in post-WWII residential buildings requires policies, priorities, and timelines to ensure Belgium gets on track to achieve the carbon neutrality targets by 2050. Future research should also explore cost-effective renovation strategies and solutions based on the European Cost Optimality approach [93]. A detailed short-term and long-term road map on the renovation packages should be developed on the national level. Without a road map, it will address the renovation barriers that go beyond issues. Encouraging housing owners to renovate the post-WWII households and motivating them is part of any states' role. The development of an ecosystem of small and middle-size renovation enterprises with skilled labor is a vital element.

Finally, we invite international researchers to develop new occupancy schedules for senior adults beyond the limitations of ISO 18523 [61] and ISO 17772 [85]. The existing standards do not indicate how the elderly behave in the living environment. As a way to support this research endeavor, this study can be considered as starting point for further research on the development of senior adult occupancy profiles for building performance simulation.

5. Conclusions

The energy characterization of 1328 post-WWII single-family houses located in the three regions of Belgium (Brussels, Flanders, and Wallonia) took place based on four-year measurement data (2016–2019). To the authors' knowledge, this is the first energy characterization study of post-WWII single-family houses that have been reported from this part of Europe. The following key findings describe the study outcomes:

- Two accurate energy models representing 633,702 current households to predict energy use intensity and energy efficiency of single-family households built 1945 to 1990.
- The energy use characterization indicated that the average energy use intensity of archetype A is 155 kWh/m^2/year 166 kWh/m^2/year for archetype B.
- The EPC rating of archetype A is F, and the rating of archetype B is E.
- Two representative archetypes were identified and created in EnergyPlus software after several iteration rounds. The models were calibrated according to ASHRAE Guideline 14 using two indices to evaluate the goodness-of-fit of the building energy model.
- Rigorous validation measures consolidated the model input assumptions, namely (1) weather normalization, (2) envelope conductivity and airtightness, and (3) occupancy behavior observations.

The poor envelope performance and large heated house volumes/spaces appeared to be the most influential factor to the high energy use intensity. Despite that, the households were dominated on average by senior couples (>65 years old) the energy use remained relatively high. Consequently, the poor envelop physical and thermal properties resulted in discomfort problems and significant reliance on personalized plugged electric heating. Thus, the increased consumption of gas and electricity urges the need for renovation deep renovation (insulation, double glazing, blinds, mechanical ventilation, etc.). Further research aiming to characterize other post-WWII archetypes better and develop multi-objective renovation scenarios appears necessary to tackle carbon neutrality issues in existing households.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.
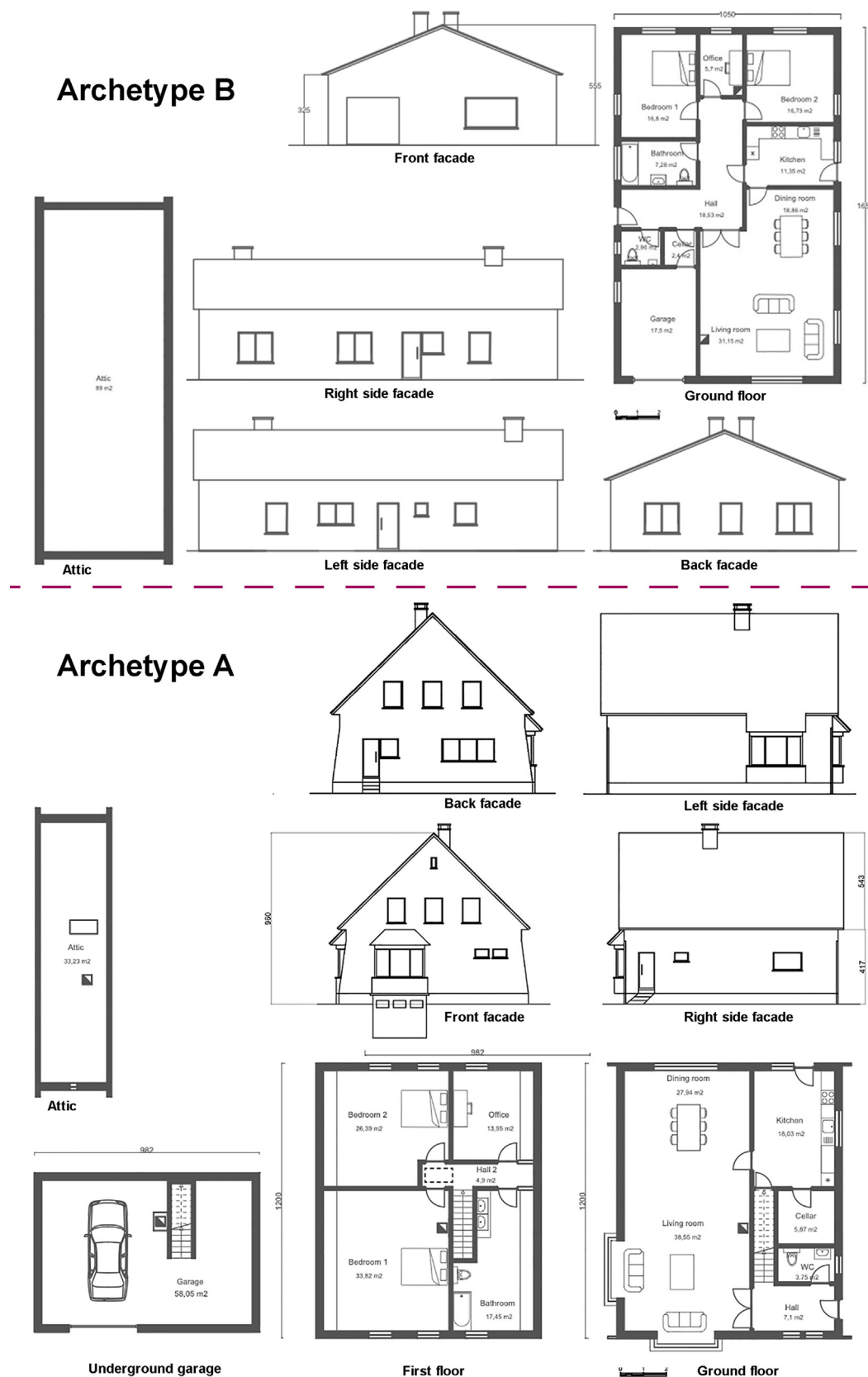
Acknowledgment

Appendix

Fig. A1. floor plans and facades of archetype A and B.

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