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Evaluation of district heating patterns for Hungarian residential buildings: Case study of Budapest

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ABSTRACT

The present study focuses on analysing the heat consumption of multifamily buildings. The study evaluates measured district heating consumption data in Budapest, Hungary. The examined 218 buildings were grouped into 11 building types based on their architectural characteristics and analysed separately. The study aims to answer the question: how the buildings' characteristics influence the energy demand of the buildings. In the buildings only the total energy consumption is measured, thus the domestic hot water energy demand was examined in the summer months, when there is no heating in the building. The domestic hot water heat loss was 37–54% of total heat consumption in the summer period. The specific total district heating consumption data [kWh/m^3/day] has higher deviation in colder months. The length of heating period is 183 days in Hungary, however the average length of heating period was longer in the examined buildings and it was even longer in case of the uninsulated buildings. From the measured consumption data the energy signature curves were developed for each building type for both the insulated and uninsulated buildings separately and the results were compared and analysed in detail. The energy signature diagrams showed a significant gap between the insulated and uninsulated buildings' total district heating consumption data in the heating period. Lines were fitted to the data and the slope of the lines fitted to uninsulated buildings' data indicate higher decline for every building type. A separation method was also suggested to divide the data of heating and non-heating period if its term is unknown. The difference between the average slope values of the fitted lines were analysed compared to buildings' characteristics. It aimed to examine if the consumption reduction is influenced by the buildings' physical parameters. In conclusion, the buildings' characteristics did not always influence the final results (e.g. domestic hot water heat loss). But uninsulated buildings tend to have longer heating periods and buildings with smaller cooling surface area per heated volume had a predominantly lower energy consumption reduction rate.

1. Introduction

Assessing the energy consumption of buildings is crucial, as buildings are responsible for about one third of the World's total energy demand [1,2]. Many efforts have been made to reduce global energy demand and to reduce emissions from energy production. Developing building-focused strategies requires a sound understanding of energy consumption in buildings and the factors that influence it.

District heating systems could reduce emissions from the buildings they supply. Thanks to centralised energy production, a variety of energy production solutions could be used. Different heat sources can be integrated into the system including cogeneration plants and renewables. The system is convenient for consumers to use as it is managed by district heating companies [3].

It has always been known that district heating technology is beneficial and could be one of the most energy efficient solutions to supply energy consumers in the future [3]. Therefore, it is not surprising that many articles have been devoted to the study of physical and operational parameters of district heating systems and the analysis of energy consumption data. M. Åberg et al. have analysed the impact of reduced heat demand on the district heating system in Linköping [4]. Improvements in district heating systems have led to reduced energy demand in buildings, which influences the behaviour of district heating systems. There is a huge effort to improve the physical parameters of district heating buildings in order to reduce their energy consumption. A.

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Arriazu-Ramos et al. have studied the effects of these renovations [5]. Another example is given in a review study by E. Guelpa et al. that summarizes the potential of demand-side management techniques in district heating systems [6]. Demand-side management is a widely used technique and its application in district heating systems can improve their performance. The impact of different operating and physical parameters on the district heating system has been studied by M. Pirouti et al. [7]. The aim of the research was to minimize energy costs and consumption.

Accurate knowledge of the energy consumption of district heating buildings is essential for the efficient operation of district heating systems [8]. There are many articles dealing with the analysis of energy consumption data. Further research is still needed as there are research gaps and the energy use in buildings is constantly changing. P. Gianniou et al. studied Danish single-family households with district heating [9]. Their results show that there are early morning and evening peaks in the daily heat consumption profiles. Weekday and weekend consumption profiles are similar in shape; only the morning peak occurs later in the weekends. A discrepancy was also found when looking at previous articles. Z. Ma et al. found that the type of district-heated building has a strong influence on energy consumption profiles [10], while E. Calikus et al. showed that energy consumption profiles do not depend on the type of building usage [11].

The energy consumption of the buildings is hard to predict, and it depends on various parameters [12,13]. The energy consumption of a dwelling obviously depends on the location of the dwelling within the building, and is also strongly influenced by the surrounding spaces [14]. Individual meters can also influence the energy consumption of a building. These meters could be used to measure the energy consumption of the occupants separately; therefore, consumers are motivated to reduce their energy consumption, as they pay their costs based on the metered data. As a result, the energy load of the building could be reduced by using the metered data for cost allocation [15]. Occupant behaviour also has a significant influence on energy consumption, but it is very difficult to model or predict. There are many articles that have investigated the impact of occupant behaviour on energy consumption [16–19] and identifying the influencing factors of their behaviour [20].

The energy consumption profile of residential buildings is still in the focus of researchers. With smart meters, huge amount of data can be collected and analysed in different ways: for example, by identifying consumption profiles and influencing factors to get more information about buildings [21]. These results help to predict energy consumption, optimise energy production and improve comfort parameters. Data-driven approaches are widely used to analyse heating load profiles [11,22]. Among these, clustering methods are very popular [9,23,24].

Energy signature analysis examines the relationship between energy consumption and external temperature [25,26]. Their use can be beneficial for both professionals and occupants, as they can easily provide important information about the building, pointing out potential operational issues [26]. The energy signature diagrams have a weather-dependent and a non-weather-dependent part, which can be separated based on the external temperature [27]. Different solutions are used to fit linear trends to the energy consumption-temperature data and to find the intersection temperature value. The method described by M. Eriksson et al. considered intersection temperatures between 10 and 20 °C and selected the best result based on R^2 values [28]. A.J. Summerfield et al. plotted the heating performance data as a function of external temperature and used linear regression analysis to determine the fit when the external temperature is between 0 and 15 °C [29]. Using the energy signature method, different kinds of energy sources could be analysed independently: for example gas and electricity consumption [30]. An interesting solution to analyse the energy signature data is cluster analysis [25]. This method can be used to identify the most typical building characteristics. The comparison of energy signature diagrams can also help to monitor the efficiency of renovation [31].

For renovation projects the key indicator is the energy savings. However, when a building is renovated, the expected energy savings for the building differ from the actual figures. To quantify this effect, the performance gap need to be calculated. The performance gap is the "difference between measured and calculated energy consumption" [32]. Its value is influenced by several parameters. For example, S. Bakaloglou et al. and D. Charlier et al. have identified how different parameters (personal characteristics, building characteristics, climatic characteristics, etc.) affect the performance gap [33,34]. Different strategies can be used to reduce the performance gap. S. Cozza et al. have classified them into two groups according to their objective: improving the building performance or improving the calculation method [32]. To calculate the energy performance gap, calculated and measured data are needed. These data can be collected from different databases, such as surveys [33,34], using various tools [35], measurements [35,36], or calculations [36].

There have been several articles examining energy consumption data for residential and non-residential buildings. Many studies have also analysed the energy demand and energy use of district-heated buildings. These results are relevant in many areas: i.e., finding optimal parameters for the operation of the district heating system or synchronising the production and consumption using demand-side management strategies. However, to the authors' knowledge, no study has examined the energy consumption of many buildings grouped into building types. By studying and comparing the results, the impact of the characteristics and features of different building types on energy consumption could be investigated. Therefore, in this study more than 200 district heated buildings were grouped into building types and their energy consumption was analysed separately. The aim of the research is to quantify the building characteristics influence to the energy consumption.

In case of big data analysis and data mining technologies, the analysation methods should be automatized to shorten the processing period and to require less human resources. The heating and domestic hot water energy consumption of district heated buildings is often measured together. To get more accurate results, the heating and domestic hot water consumption should be separated. In this paper a simple method is suggested to separate the energy consumption automatically.

The benefits of refurbishment investments of buildings depend of various parameters. The payback time of these projects is influenced by the physical parameters of the buildings. Therefore the selection of buildings could have a significant impact. To examine the buildings' features to these refurbishments, the energy consumption of insulated and uninsulated residential buildings were analysed separately in this paper. The refurbishment of the buildings usually do not reach the desired effect and the difference between the planned and actual state (performance gap) play a very important role as well. The performance gap of the building types also should be analysed separately to help the decision making process.

The research methodology is described in the Methodology section, which describes the data collection and evaluation process; it contains information on the data collected and includes the equations used. The main findings of the study are presented in the Results section. The Conclusions section summarises the whole research process and the main results of the study.

2. Methodology

FŐTÁV Zrt. is one of the district heating companies in Hungary, supplying district-heated buildings in Budapest. The company supplies the energy needs of buildings for heating and domestic hot water. Data on buildings with only district heating for domestic hot water have been analysed in previous studies [37,38]. The proportion of district-heated buildings in Hungary (2011) is significant: 15.5% of buildings are supplied by district heating. This proportion is 28.1% in the capital, Budapest [39].

For the case study, residential buildings – located in Budapest – were selected, the heat consumption data was provided by FŐTÁV Zrt. The data collection took place in spring 2021. FŐTÁV Zrt. started to implement their monitoring system in 2012. Three main criteria were defined for the selection of buildings supplied by district heating whose energy consumption data are monitored:

- buildings must be connected to the monitoring system
- only their heating consumption or their consumption of heating and hot water for domestic use must be provided by district heating.
- at least one full year of data is available.

After the filtrering process 2383 buildings remained from the database, from which 2144 had both heating and DHW supplied (H-DHW type) by district heating and the remaining 239 buildings had only heating demand (H-type) supplied.

These buildings were grouped based on the heated spaces they have. The aim of the research is to investigate the energy consumption of residential buildings. Therefore, buildings with a heated volume greater than zero and no other type of heated volume (e.g. garages, public spaces, staircases) were selected, thus all examined buildings had unheated staircases. After this selection, 63 H-type buildings and 881 H-DHW-type buildings remained.

The following data were provided for the evaluation:

- the substation identification number;
- heat consumption [GJ];
- address of the building;
- number of flats;
- heated volume [m^3];
- daily heat consumption [GJ];
- daily hot water consumption [m^3];
- DHW setpoint temperature [°C];
- external temperature [°C];
- setpoint temperatures (external temperature – heating water temperature pairs) [°C];
- starting and end date of the heating season.

The selected 944 buildings were surveyed using geoinformatics software (Google Maps) and the following data were collected:

- image data of the buildings;
- condition of windows (new/ old/ mixed);
- external insulation (insulated/uninsulated);
- roof shape (flat roof/pitched roof);
- type of pitched roof space (occupied/ unoccupied);
- the number of pitched roof levels occupied;
- structural material (prefabricated panel/not prefabricated panel);
- the number of occupied levels;
- number of unoccupied levels;
- the total number of levels;
- type of unoccupied spaces (garage, open space, basement, storage room, etc.);
- the building type (building typology created by the authors).

A building typology database was also created based on the exterior surfaces of the buildings. For the structural material examination only the prefabricated panel and not prefabricated panel building categories were considered. The prefabricated panel buildings are easily recognisable by their structure (e.g. similar façade shape, the visible coupling gap between the panels is in the uninsulated case) and they are also common in the post-communist countries in Central and Easter Europe. For the not prefabricated panel types a more in depth examination of the structural material would be required, which was out of scope of the current paper. Building section types were identified based on the shape of the section; the number, size, shape and location of walls, windows and doors and their distribution. Buildings categorised into the same building types contain the same building sections, but the number of sections and levels; the ground and the top floor of them could differ.

For example, Type 1 building section is introduced in Fig. 1. These sections have rectangular shape. They have four uniform non-enclosed balconies and four uniform wide windows (balcony-window-balcony-window-window-balcony-window-bal cony) in every occupied floor on the front surface. They have two uniform enclosed balconies and six uniform narrow windows (window-window-balcony-window-window-balcony-window-wi ndow) in every occupied floor on the back side of the building. They have no balconies or windows on the shorter surfaces. They have 11 occupied floors and a basement in the ground.

In total, 46 H-type buildings and 689 H-DHW-type buildings were surveyed with geographic information software. Due to the small number of H-type buildings, their analysis was discarded. The H-DHW buildings were classified into building types as mentioned above. Based on the building stock examined, 65 building types were identified. Of these, only those in which more than 10 buildings were classified were further analysed. Those buildings that did not have at least 90% of the 2020 data were deleted from the database.

In summary, energy consumption data for 218 district-heated buildings were analysed for 2020. These buildings were classified into 11 different building types. The process of selecting the buildings is shown in Fig. 2. The main parameters of the categories are presented in Table 1.

The location of the buildings surveyed is shown in Fig. 3**.**, where each building type is indicated by a different colour. The figure clearly shows that the different building types are not specific to different areas but are mixed.

The daily average external temperature and daily heat consumption data for buildings categorised in Type 1 are shown in Fig. 4. Different colours indicates the different buildings. The red dotted line represents the external temperature values. During the summer (there is no heating season in Hungary), relatively constant energy consumption data indicate the heat demand for DHW.

The daily heat consumption was measured in GJ. This was converted to kWh and divided by the heated space volume to get kWh/m^3/day unit to obtain a commonly used specific value.

There are measurement errors in the database, thus the calculated heat consumption data was filtered to remove the outlying data. Heat consumption data below 0 kWh/m^3 or above 1 kWh/m^3 (five times average consumption) were deleted from the database, by this filtering process only 0.21% of the data was deleted.

The water consumption of the domestic hot water system was examined only in the summer period (June-August). In order to create specific consumption values the heated building volume was used, as shown in **Equation (1)**.

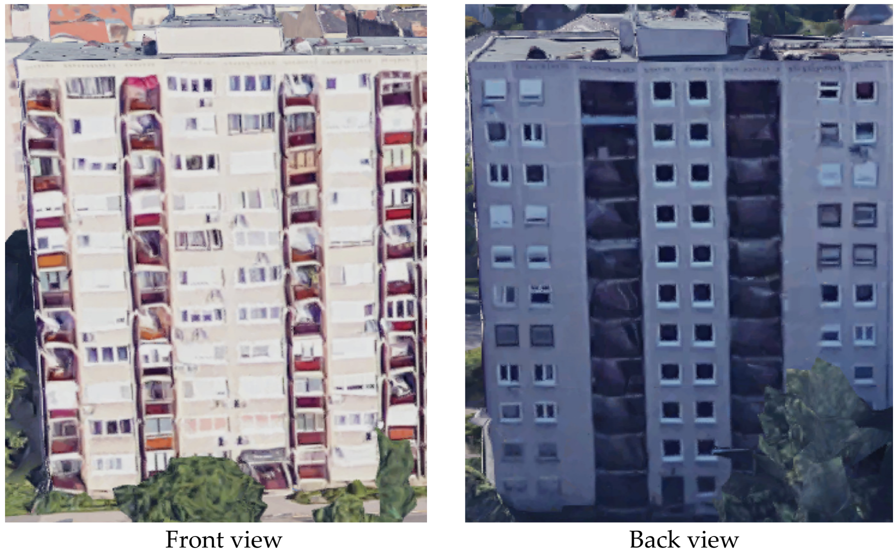


Fig. 1. Type 1 building front and back view.

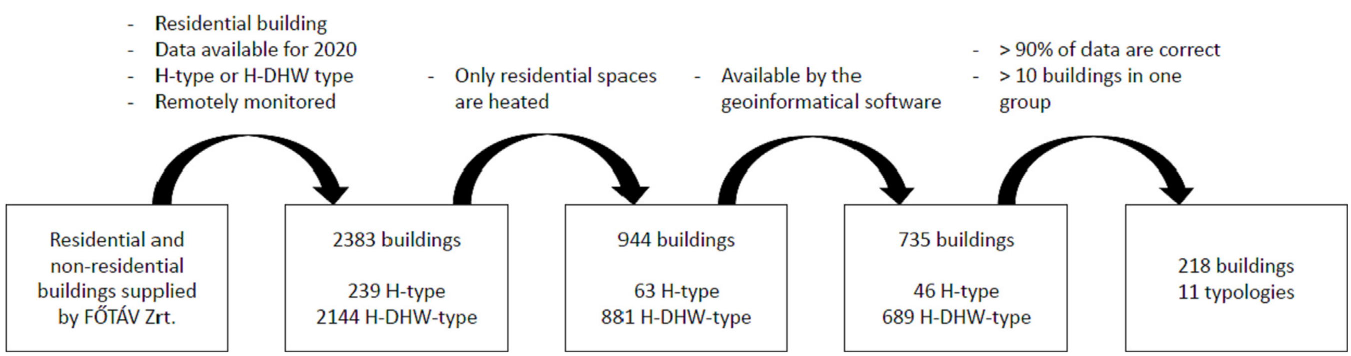


Fig. 2. Building selection process.

$$v\left[\frac{m^3}{m^3}\right] = \frac{V[m^3]}{V_{space}[m^3]} \quad (1)$$

- v: specific domestic hot water consumption $\left[\frac{m^3}{m^3}\right]$
- V: domestic hot water consumption $[m^3]$
- V_{space}: heated building volume $[m^3]$

Erroneous data were also found in this database: water consumption data were deleted from the database if it was less than 0 m^3/m^3 or greater than 0.001 m^3/m^3 (two times average consumption) by this filtering process only 1.42% of the data was deleted.

The net DHW demand was calculated on the basis of water consumption according to **Equation (2)**.

$$q_{dhw,net}\left[\frac{kWh}{m^3}\right] = \frac{c\left[\frac{kJ}{kg\cdot K}\right]\cdot\rho\left[\frac{kg}{m^3}\right]\cdot v\left[\frac{m^3}{m^3}\right]\cdot(\Theta_{dhw}-\Theta_{cw})[^\circ C]}{3600\left[\frac{kJ}{kWh}\right]} \quad (2)$$

- $q_{dhw,net}$: net DHW demand $\left[\frac{kWh}{m^3}\right]$
- c: specific heat capacity $\left[\frac{kJ}{kg\cdot K}\right]$
- ρ: density $\left[\frac{kg}{m^3}\right]$
- v: domestic hot water consumption $\left[\frac{m^3}{m^3}\right]$
- Θ_{dhw}: hot water temperature $[^\circ C]$
- Θ_{cw}: cold water temperature $[^\circ C]$

In this study, as in previous studies, a heat capacity value of 4.178 kJ/(kg K) for water, a density value of 988.1 kg/m^3 and a cold water temperature value of 15 °C were used [37,38].

The heat losses of the DHW system were calculated according to **Equation (3)**.

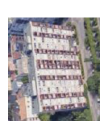
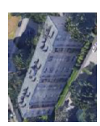
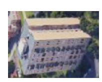
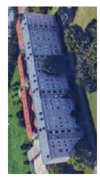
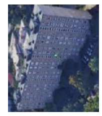
$$q_{dhw,loss}\left[\frac{kWh}{m^3}\right] = q\left[\frac{kWh}{m^3}\right] - q_{dhw,net}\left[\frac{kWh}{m^3}\right] \quad (3)$$

- $q_{dhw,loss}$: domestic hot water heat loss $\left[\frac{kWh}{m^3}\right]$
- q: heat consumption $\left[\frac{kWh}{m^3}\right]$
- $q_{dhw,net}$: net DHW demand $\left[\frac{kWh}{m^3}\right]$

The ratio is calculated according to **Equation (4)**.

$$q_{dhw,loss,p}[\%] = \frac{q_{dhw,loss}\left[\frac{kWh}{m^3}\right]}{q\left[\frac{kWh}{m^3}\right]} \quad (4)$$

Table 1
Parameters of the examined building typologies.

Type	Type 1	Type 2	Type 3	Type 4	Type 5	Type 6	Type 7	Type 8	Type 9	Type 10	Type 11
Number of buildings	35	28	23	21	21	20	19	14	14	12	11
Number of total flats	3186	3652	1242	696	855	2016	718	1297	1186	1894	2140
Total heated volume [m^3]	472,730	452,711	146,013	90,042	116,165	262,260	97,032	173,333	182,193	265,560	303,171
Percentage of buildings with new windows	0%	11%	13%	14%	5%	15%	5%	0%	21%	0%	27%
Percentage of buildings with old windows	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Percentage of buildings with mixed windows	100%	89%	87%	86%	95%	85%	95%	100%	79%	100%	73%
Percentage of buildings with insulation	49%	21%	43%	52%	24%	20%	11%	36%	29%	0%	27%
Percentage of buildings without insulation	51%	79%	52%	48%	71%	75%	89%	64%	64%	100%	73%
Percentage of buildings with partly insulation*	0%	0%	4%	0%	5%	5%	0%	0%	7%	0%	0%
Percentage of buildings with flat roof	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
Percentage of buildings with pitched roof	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Average number of occupied levels	11	11	5	5	5	8	10	11	5	11	11
Average number of all levels	12	12	5	5	5	9	10	12	6	12	12
Picture											

* not all 4 facades were insulated.

- $q_{dhw,loss,p}$: domestic hot water heat loss percentage $[\%]$
- $q_{dhw,loss}$: domestic hot water heat loss $\left[\frac{kWh}{m^3}\right]$
- q: heat consumption $\left[\frac{kWh}{m^3}\right]$

3. Results

3.1. Domestic hot water heat loss

During the summer, only district heating of domestic hot water is used in the buildings, as no space heating is needed. This will allow a more accurate analysis of the energy demand for domestic hot water and will allow an assessment of whether the heat loss from domestic hot water is influenced by the characteristics of the buildings. The buildings' envelope influence the internal air temperature. Uninsulated buildings' unheated rooms have more similar internal temperature values to external air temperature. The DHW heat loss is higher if the difference between DHW and internal air temperature is higher. The number of occupied levels influence the length of the DHW pipeline, therefore its surface as well. Higher surface area causes higher DHW heat loss. The examined buildings were all built between 1960 and 1990 and the level of insulation on the DHW pipes are similar. In case of a business as usual refurbishment the insulation of the DHW pipes in the shafts due to the extensive labour costs, thus all buildings have similar insulation properties for the DHW pipes. Table 2 summarises the average values of DHW system heat loss in summer, the percentage of uninsulated buildings and the average occupancy levels. It can be observed that building insulation and the number of floors do not affect the DHW heat loss values during the summer period.

3.2. Total district heating consumption variation

Boxplot diagrams were created for each building type to examine the variation in energy consumption data. Fig. 5 presents a boxplot of the heat consumption data for building Type 1. The same pattern was observed for all building types: the variation is larger in the heating season. In the graph, the endpoints represent the minimum and maximum values, the median value is in the middle of the coloured boxes and the endpoints of these boxes represent the first and third quartiles, which means that 50% of the data are in the coloured boxes.

As observed earlier, the variation in heat consumption data was higher in the colder months. To compare the results for different building types, the coldest month, January was chosen. Fig. 6 shows a boxplot of the average daily heat consumption for different building types for January. The percentages represent the percentage of uninsulated buildings in each type. The graph shows that the variation in heat consumption data does not depend on the physical parameters of the buildings: the buildings with the highest energy consumption variation are not the ones with the highest percentage of uninsulated buildings. The median value also differs from the expected results: their values are not proportional to the proportion of uninsulated buildings. The same results could be observed in every month.

3.3. Length of heating period

It is assumed that the length of the heating period depends on the characteristics of the buildings. Less insulated buildings have higher heat loss and may therefore need heating during warmer periods. The shape of buildings (area/volume ratio) may also affect their heating needs. Thus, the relationship between the length of the heating season and the physical parameters of buildings have also been analysed. Fig. 7 shows the building types in order of heating season length. The figure also shows the percentage of build-

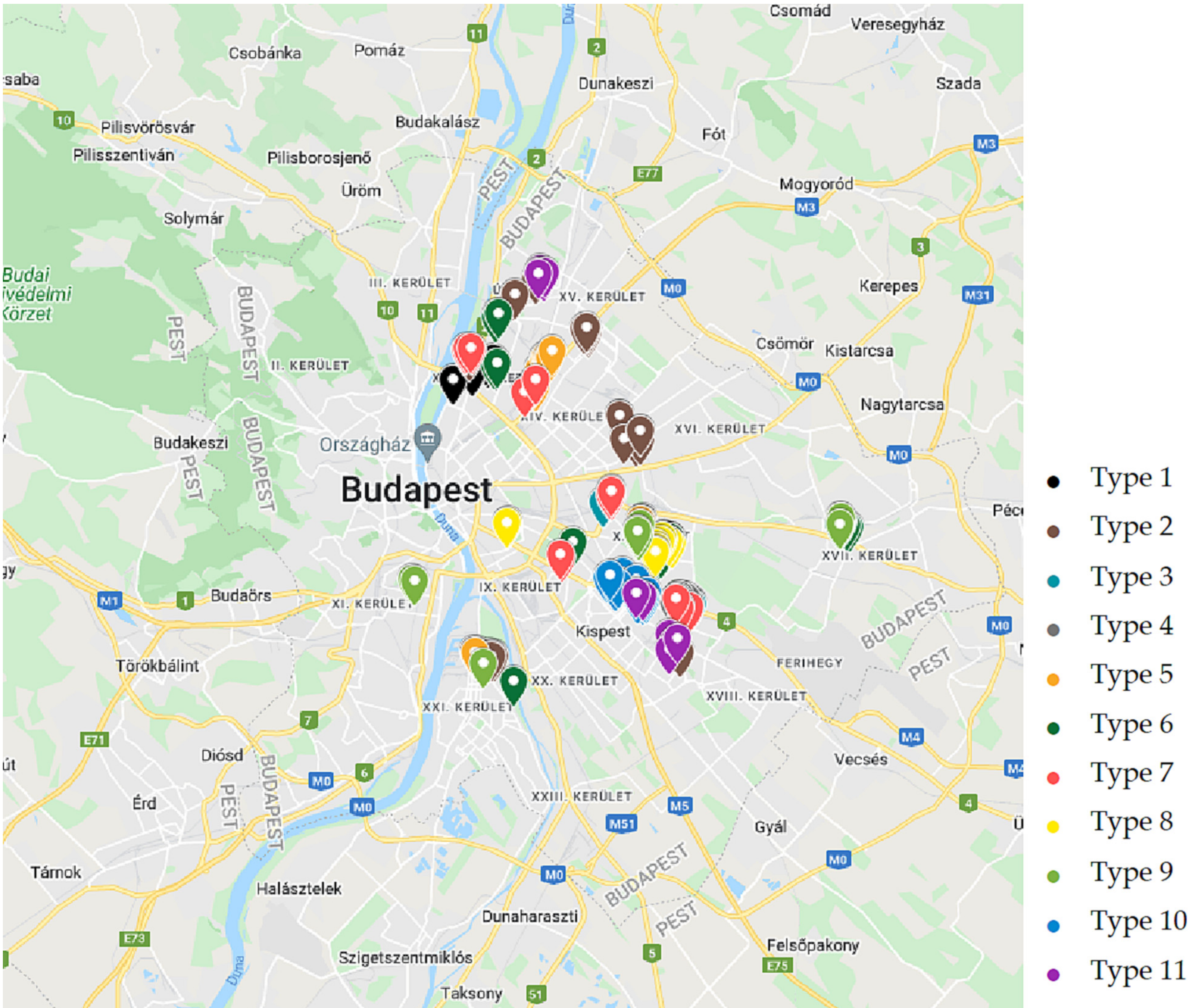


Fig. 3. Location of the examined buildings.

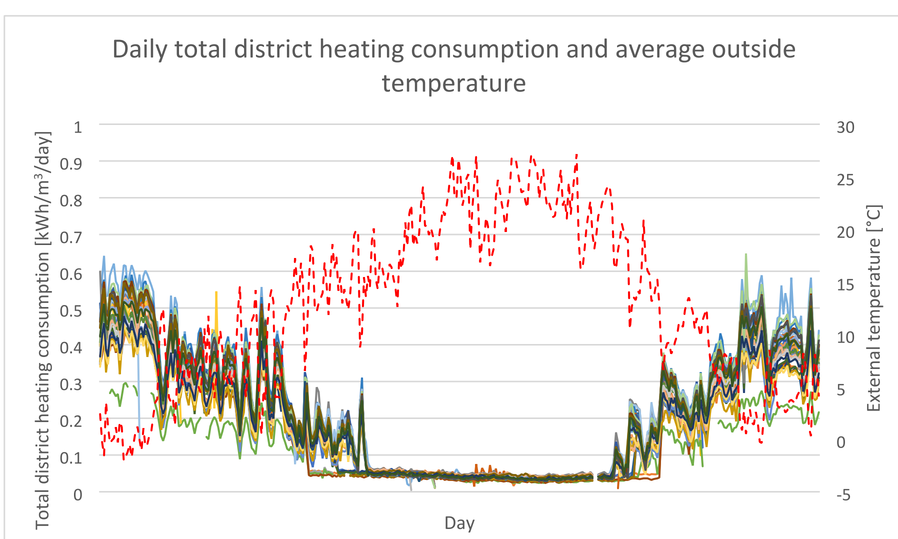


Fig. 4. Daily district heating consumption and average external temperature data (Type 1).

Table 2
Average DHW system heat loss ratio.

	Type 1	Type 2	Type 3	Type 4	Type 5	Type 6	Type 7	Type 8	Type 9	Type 10	Type 11
DHW heat loss	40%	54%	37%	40%	43%	49%	45%	43%	51%	51%	49%
Percentage of uninsulated buildings	51%	79%	52%	48%	71%	75%	89%	64%	64%	100%	73%
Average number of occupied levels	11	11	5	5	5	8	10	11	5	11	11

ings with different level of insulation: uninsulated, partially insulated and insulated along with the number of occupied floors. The percentage of uninsulated buildings does not affect the length of the heating period. The average length of heating period was examined separately (insulated, uninsulated, partly insulated buildings) for every building type as well. The results are presented on Fig. 8. The uninsulated buildings' heating period is longer in most cases but there are also exceptions: Type 1, Type 3, Type 8, where the insulated buildings have longer heating periods. For Type 4 and Type 5 the length of the heating season is nearly identical regardless of the insulation level. Building shape (number of occupied floors) also has no effect on the length of the heating period. The ratio of insulated/partially insulated/uninsulated buildings by length of heating days was also examined: the ratio is almost the same regardless of the length of the heating period. The economic and financial situation may also influence this result, but such analysis exceeds the scope of the current paper. In Hungary, the standard heating period lasts from 15th of October to 15th of April. This period covers 183 days. The average length of the heating period in the case of every building type is more than the standard value since the heating of the buildings' is not only dependent on the date and external temperature, but it can be requested to be turned on or off in the buildings by the occupants as well. This also reduces the expected savings due to a refurbishment, since the building is not optimally operated and the favourable effect of a possibly shorter heating season is not exploited.

In case of district-heated buildings, it is possible to turn the heating on before the heating period starts; or to turn the heating back on after the heating period ends if the occupants require it due to weather conditions outside. In the year examined, heating was switched back on in only 23 out of 218 buildings. Of these 23 buildings, 20 are uninsulated (14% of all uninsulated buildings surveyed) and only 3 are insulated (4% of all insulated buildings surveyed), however in average the switch off – on time period was only 3.6 days.

3.4. Energy signature diagrams

The energy consumption of buildings can be easily described using energy signature diagrams. Fig. 9 presents the energy signature diagram for an example building from Type 1 and it shows that the heating and non-heating period data can clearly be divided into two different groups. During the non-heating period, the external temperature has only a minor impact on energy consumption (mainly during the transition period). However, the external temperature has a significant impact on energy consumption during the heating period. Based on the measured data, two lines can be fitted into the two separable data groups.

Average values were also created to compare the results for different building types with different insulations. The average daily district heating consumption was calculated as the sum of the daily consumption of all buildings and the heated volume of all buildings according to **Equation (5)**. An example of the fitted lines is shown in Fig. 10**.** The figure shows a diagram of the energy performance of Type 1 insulated and non-insulated buildings. All building types show similar characteristics: the slope of the fitted line for uninsulated buildings indicates a greater decline than the slope of the fitted line for insulated buildings during the heating period. The only exception was Type 10, since in this building type all buildings were uninsulated. This result indicates the expected outcome: if the external temperature decreases during the heating period, more energy is needed to heat the uninsulated buildings to the required inside temperature.

$$\bar{q}\left[\frac{kWh}{m^3}\right] = \frac{\sum Q[GJ]}{\sum V_{space}[m^3]\cdot 0,0036\,\frac{GJ}{kWh}} \quad (5)$$

- $\bar{q}$: average heat consumption $\left[\frac{kWh}{m^3}\right]$
- Q: heat consumption $[GJ]$
- V_{space}: heated volume $[m^3]$

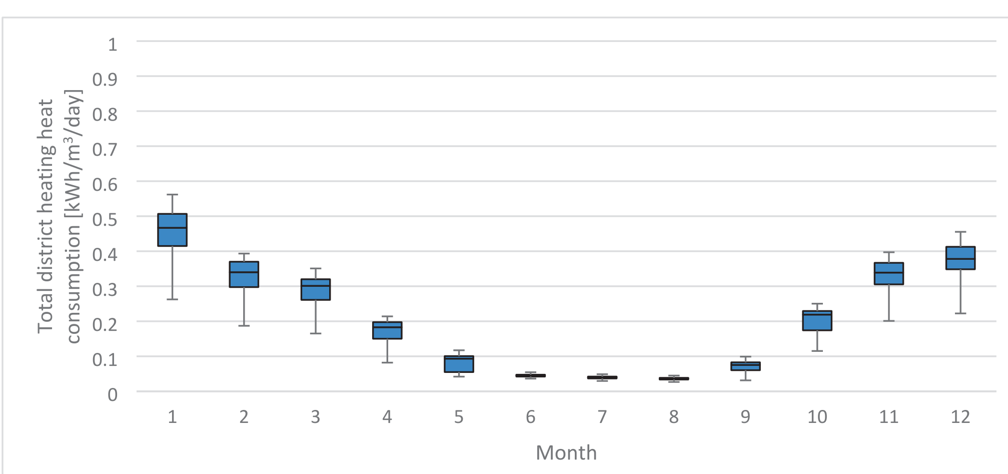


Fig. 5. Boxplot diagram of district heating heat consumption (Type 1).

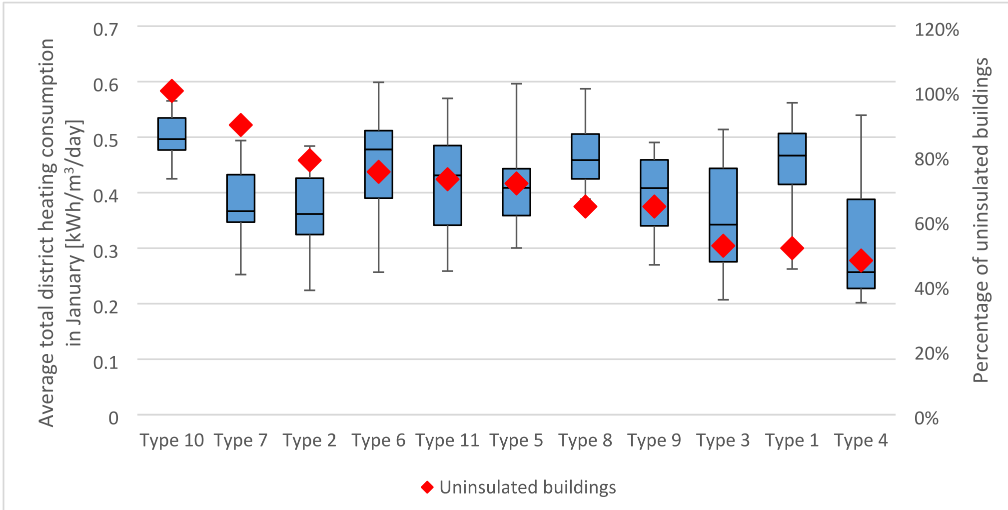


Fig. 6. Boxplot diagram of average daily district heating heat consumption in January.

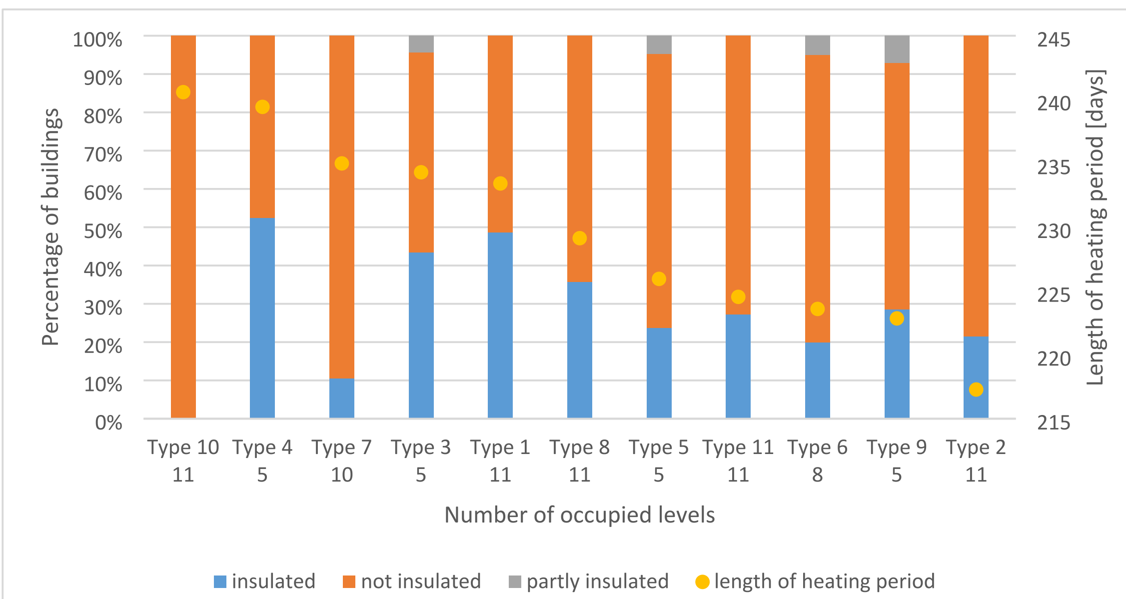


Fig. 7. Comparison of the length of the heating period and the features of the building types.

To examine the dependence of district heating consumption data on external temperature, R^2 values were calculated for two periods. The average R^2 values of the fitted lines for the different building types are summarised in Table 3**.** This shows that the heat consumption in the colder period is clearly influenced by the external temperature. In contrast, there is little relationship between heat consumption in the warmer period and the external temperature.

The line fitted to the heating period data also indicates the energy consumption of the building and thus its physical parameters. The steeper the slope, the more energy is needed to maintain the required comfort parameters in the building when the external temperature decreases. Therefore, the determination of the heat loss coefficient can be very useful and can represent the building in a simple single number.

3.5. Separation of heating ad non-heating period data

If the start and end dates of the heating period are not known, the two sets of data should be separated by an approximation. Different solutions have been tested for this purpose:

- The heat consumption data were sorted in descending order, the largest difference between the next two data was found and the average of the corresponding external temperatures was calculated. The data were then separated based to this temperature.
- The lines were fitted to the heat consumption in the summer (June, July, August) and winter (December, January, February) periods.
- K-means clustering method was used to group the data into two clusters.

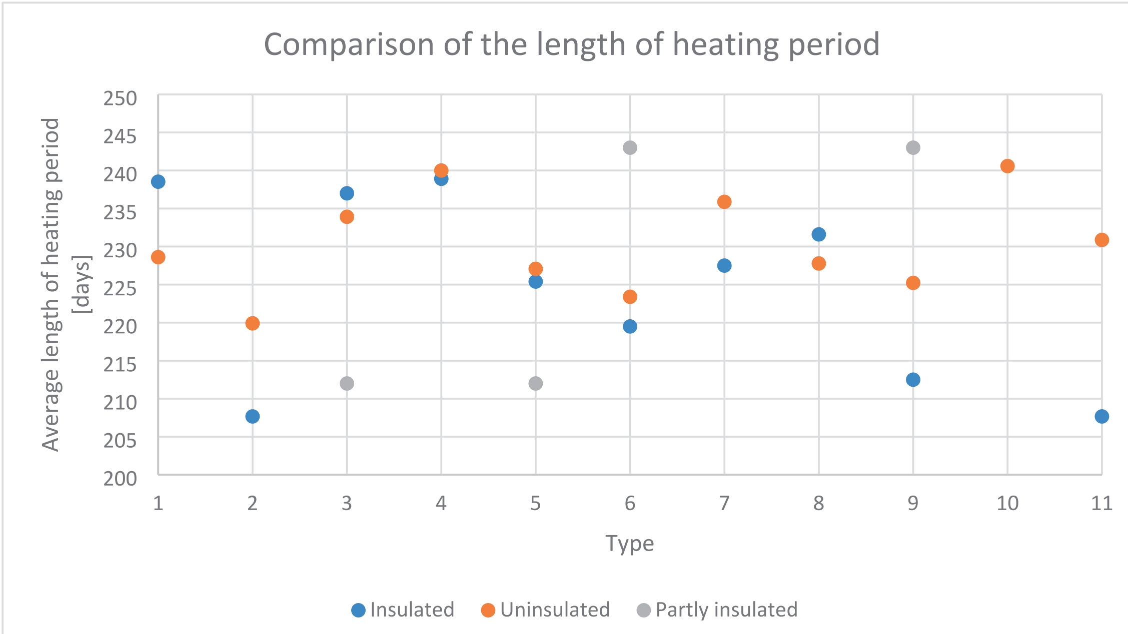


Fig. 8. Comparison of the length of the heating period.

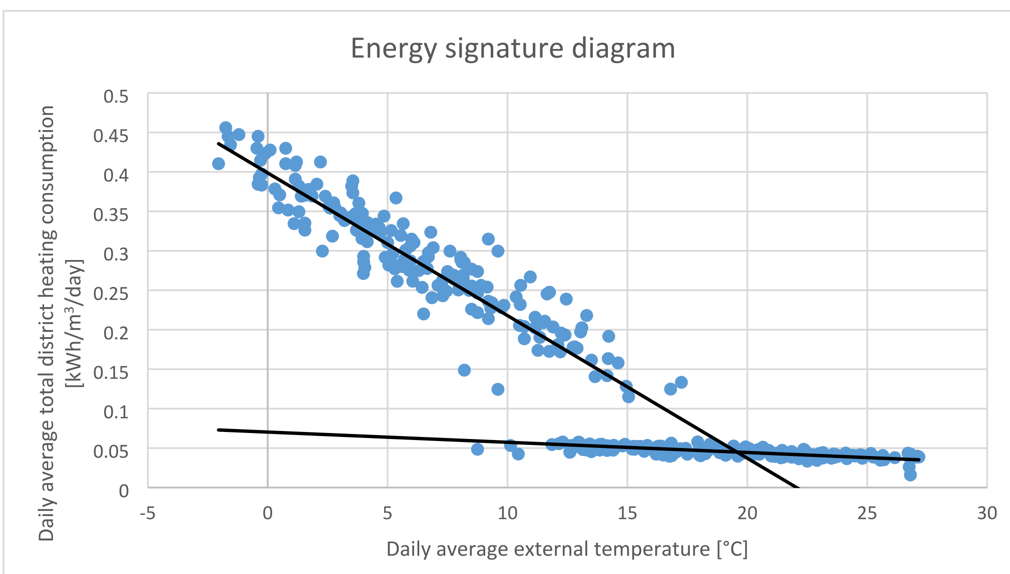


Fig. 9. Energy signature diagram of an example building from Type 1.

- The first group was created by the heat consumption of the summer days and those data whose values are less than the average of the summer heat consumption plus its deviation. The rest of the data created the second group.
- The first group contains the summer heat consumption data and those whose values are less than double of the average summer heat consumption. The second group includes the rest of the values.

The best solution was selected based on a comparison with data provided by the district heating supplier, the fitted line R^2 values and visual inspection. Based on these considerations, the last solution proved to lead to the most accurate results; therefore, it was used in further examinations.

Fig. 11 shows an example for the same building as Fig. 9. The heating period and non-heating period data series are shown in two different colours, and the equations of the two fitted lines are also presented on the diagram.

The goodness of this separation method was tested. The separation of the reference data was performed according to the data provided by the district heating supplier; the separation of the tested data was performed according to the method previously determined. Goodness was measured by the percentage of data in the corresponding group. The result of the test is shown in Fig. 12.

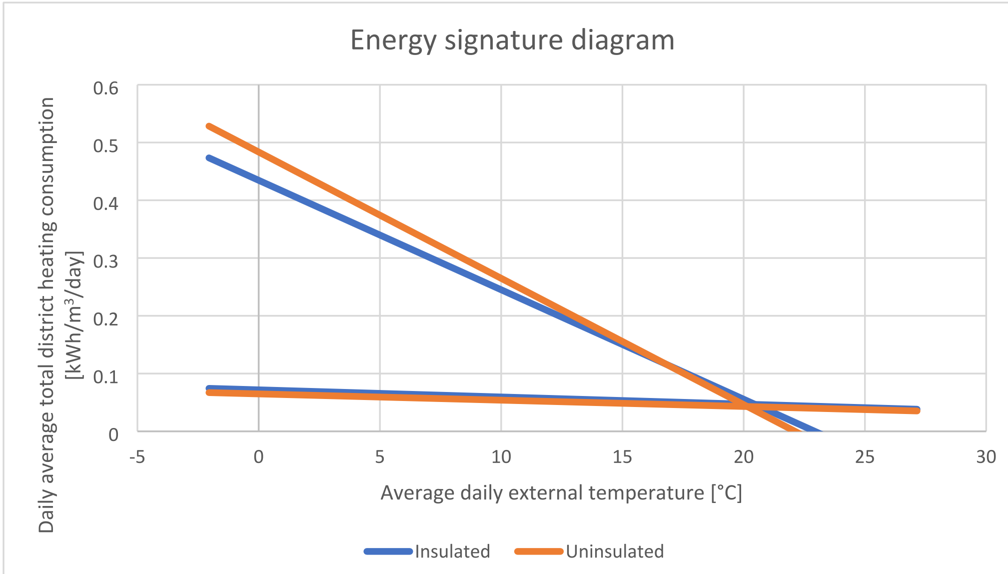


Fig. 10. Energy signature diagram (Type 1 buildings).

Table 3
Average R^2 values of the fitted lines.

R^2	Type 1	Type 2	Type 3	Type 4	Type 5	Type 6	Type 7	Type 8	Type 9	Type 10	Type 11
heating period	0.940	0.917	0.890	0.919	0.909	0.924	0.917	0.930	0.913	0.937	0.919
non-heating period	0.428	0.425	0.320	0.380	0.363	0.396	0.331	0.339	0.378	0.404	0.473

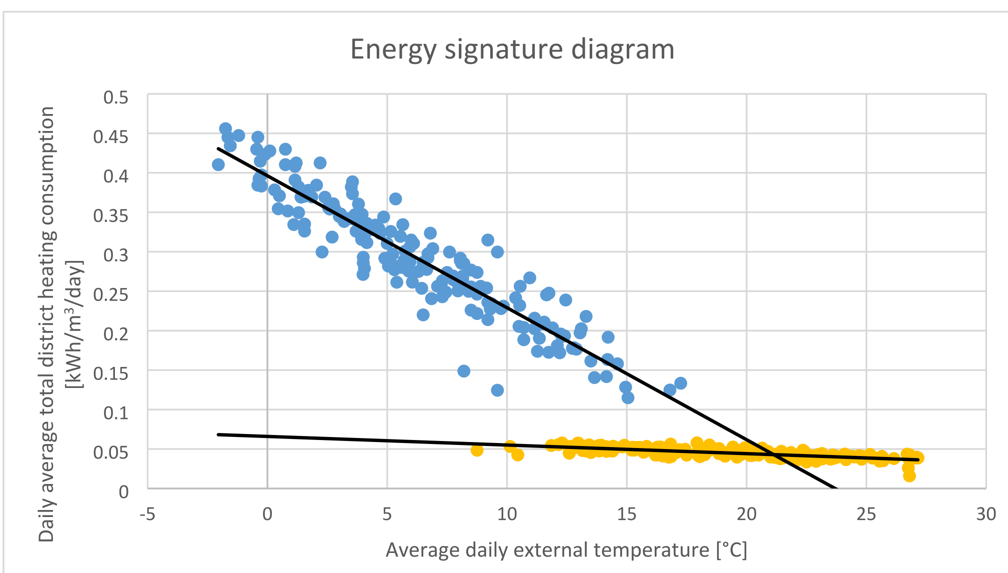


Fig. 11. Energy signature diagram of an example building from Type 1 indicating the heating period and non-heating period data.

On average, 97% of the data were in the correct group, thus the separation method was accepted.

3.6. Slope of fitted lines

The lines fitted to the energy signature diagrams could be described by two parameters, as it is illustrated in **Equation (6).**

$$y\left[\frac{kWh}{m^3}\right] = a\left[\frac{kWh}{m^3K}\right]\cdot x[K] + b\left[\frac{kWh}{m^3}\right] \tag{6}$$

- y: energy consumption [kWh/m^3]
- a: slope of the fitted line [kWh/m^3/K]
- x: external temperature [K]
- b: intersection of the fitted line [kWh/m^3]

As mentioned above, the energy consumption of buildings during the heating season is influenced by the outside temperature, and buildings can be characterised by the slope of the fitted lines. The values of the slope of the fitted lines during the heating period are shown in Fig. 13. The diagram shows the data for each building

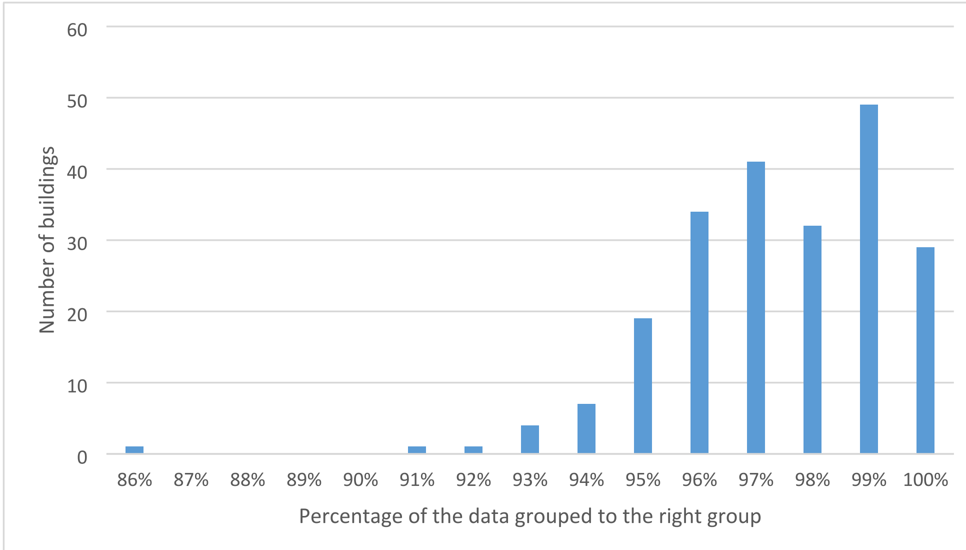


Fig. 12. The goodness of separation: comparison of the data groups separated according to the real data and to the recommended method.

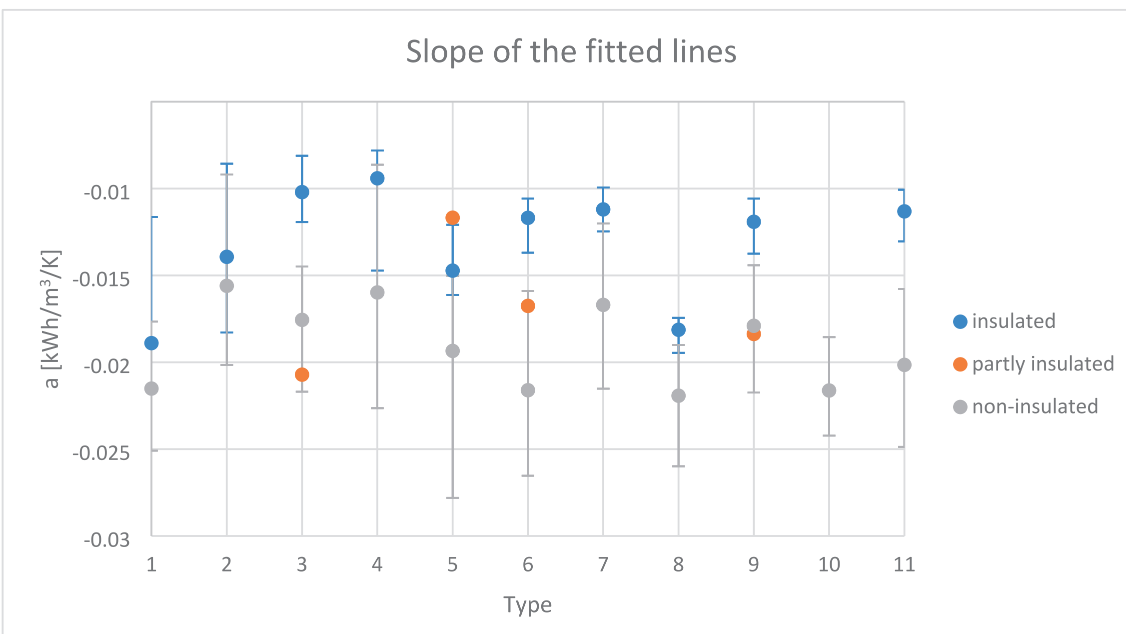


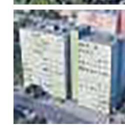
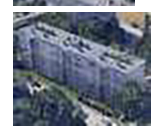
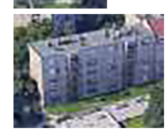
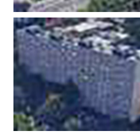
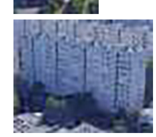
Fig. 13. Slope of the fitted lines (heating period).

type, with the values for buildings with different insulation being linked by different colours. The dots show the average values and the arrowheads the minimum and maximum values. The slopes of the lines fitted to the data for non-insulated buildings always show a higher decline. This result is consistent with the expected results. The difference between the average slope values of insulated and non-insulated buildings indicates the energy savings that could be achieved by the business-as-usual renovation (insulation) of the buildings.

The diagram illustrates an interesting point. For Type 5, the partially insulated building has the lowest slope value. This is due to the time difference between the data collected: the geoinformatical software had data available from 2019, but the evaluated consumption data is from 2020. In this period, the renovation of the building could have been completed: the geoinformatics review showed that the building was fully insulated in 2021.

It can be assumed that the shape of the building (area/volume ratio) can influence the efficiency of renovation. If the building is more compact, it has less cooling surface. Therefore, the insulation applied may not result in as high an energy reduction rate as in a less compact building with a larger surface area ratio. To test this theory, the slope values for insulated and uninsulated buildings were compared for each building type. If the slope values show a greater reduction, then the installed insulation has a greater effect on reducing energy use. The building types were classified according to the difference [%] in average slope values between insulated and uninsulated buildings. The results are presented in Table 4, which includes the slope values, the number of occupied floors

Table 4
Difference between the average slope values of the insulated and uninsulated buildings and the number of occupied levels.

	$a_{uninsulated}$	$a_{insulated}$	$\Delta a/a_{uninsulated}$	Occupied levels	
Type 1	−0,0219	−0,0189	13%	11	
Type 8	−0,0216	−0,0186	14%	11	
Type 2	−0,0155	−0,0134	14%	11	
Type 5	−0,0191	−0,0146	24%	5	
Type 7	−0,0164	−0,0115	30%	10	
Type 4	−0,0154	−0,0100	35%	5	
Type 9	−0,0166	−0,0103	38%	5	
Type 3	−0,0170	−0,0101	41%	5	
Type 11	−0,0202	−0,0120	41%	11	
Type 6	−0,0215	−0,0110	49%	8	
Type 10	−0,0217	–	–	11	

and the picture of all building types. The results showed that building shape has no clear effect on the slope value reduction. Compact, taller buildings (those with a lower floor area/volume ratio) show a smaller energy use reduction and less compact, lower buildings (those with a larger floor area/volume ratio) show a larger energy use reduction, but there are exceptions. For example, buildings of Type 1, Type 8 and Type 2 have very similar shapes to Type 11, but the reduction is much larger for Type 11. Type 7 and Type 6 buildings are also similar in shape, but the reduction is almost double for Type 6 buildings. To draw a meaningful conclusion, several building types need to be examined and compared and for this case, data from more buildings is required.

4. Conclusion

In this study, district heating consumption in Hungarian residential buildings was investigated. The buildings are located in Budapest, the capital of Hungary. District heating is used for space heating and domestic hot water preparation in the examined buildings. A total of 218 buildings, grouped into 11 types, were analysed for their daily heat consumption in 2020. For the building types the ratio of insulated and uninsulated buildings was calculated as well.

When analysing the heat loss of domestic hot water in the summer period, it was found that its value was not influenced by the characteristics of the buildings (insulation, number of floors). The average heat loss is 37–54% in the examined summer period.

Examining the available data, the total district heating consumption data show a larger variation during the heating period. It was also seen that neither the average consumption nor the variation in consumption was proportional to the proportion of uninsulated buildings.

The length of the heating period was also examined. The standard heating period is 183 days in Hungary. The examined buildings had longer heating period. The uninsulated buildings tend to have longer heating period than insulated ones. Before or at the end of the heating season, residents could ask the district heating company to turn the heating on or back on. Only 23 buildings had their heating turned back on during the period under review. Most of these buildings, 20 out of 23 were uninsulated.

Not only the characteristics of the buildings influence district heating consumption. The energy demand of buildings depend on various factors (e.g., financial, economic, personal preferences and occupants' behaviour, etc.). However, it is beyond the scope of this article to investigate these. The aim of our study was to obtain information only from data provided by the district heating supplier and not from questionnaires. The most important parameters of the buildings served, and the consumption data are available for all district heating suppliers and can be efficiently analysed automatically.

Energy signature diagrams of the buildings have been prepared. They make it easy to visualise the energy consumption of buildings, and the slope of the fitted lines describes the behaviour of buildings in a single parameter. In the diagrams, the data for the heating and non-heating periods were separated: the energy consumption of the heating period can by primarily linked to the external temperature.

The start and end dates of the heating period are usually not directly included in the heat consumption data series; therefore, some method must be used to separate the two periods. This study proposed a simple separation method (using twice the average summer consumption value) to group the data. This method worked reliably: 97% of the data were classified into the appropriate group.

When looking at the average energy signature diagrams and average slope values for insulated and uninsulated buildings in different building types during the heating period, it was seen that the uninsulated buildings had higher slope values in all cases. This was in line with the expected results: buildings with poorer building envelopes (higher heat transfer values) require more heating energy to maintain the same indoor temperature. It was also observed that the shape of the building had no clear effect on the difference between the slope values of insulated and uninsulated buildings. Buildings with a smaller cooling surface area per heated volume had a predominantly lower reduction rate, while buildings with a larger cooling surface area per heated volume had a predominantly higher reduction rate. This result is in line with the expectations, but exceptions could be found. To obtain a more accurate result, more building types should be investigated in the future.

In conclusion, it was visible that the length of insulated buildings' heating period tend to be shorter. The average slope of fitted lines for insulated buildings' total district heating consumption in heating period is also smaller. It means that the changing external temperature doesn't influence the heating demand as much as for the uninsulated ones. In case of refurbishments, the expected energy savings are not reached. The reason for this is that the behaviour of the occupants change: they are heating their rooms to higher temperatures, since due to the insulation it is usually cheaper.

In future research, authors plan to analyse further the different building types and calculate the performance gap. The results could be used to investigate whether the efficiency of the investment in a renovation project is influenced by the shape of the buildings and therefore whether the possible choice of buildings depends on this parameter. It could also lead to the conclusion that the savings and payback period of these projects are influenced by the shape of the buildings.

Data availability

The authors do not have permission to share data.

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.

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