Further development of the change-point model – Differentiating thermal power characteristics for a residential district in a cold climate

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ABSTRACT

The building and service sector accounts for nearly 40% of total energy use in Sweden. The existing, historic building stock accounts for large part of this energy use and comprises an important part of the national pursuit to increase energy efficiency. One main problem for decreasing energy use in the existing building stock is the lack of data describing thermal performance characteristics. This paper presents a novel development of the change-point model for predicting the thermal performance of buildings using selected time periods based on time-dependent variations in climate and user behavior. The predicted thermal power characteristics include total specific heat losses (Q_{total}), energy use for hot water circulation (HWC) and hot tap water (HTW), and balance temperature. A residential district with 73 historic buildings in Linköping, Sweden, has been used as the study object.

The developed model is shown to be effective and robust for describing building thermal performance. The average R^2 was 0.70 for predictions of specific heat losses. The sensitivity analyses conclude that the selected time steps and months correspond to the highest R^2 value. The average variation width for prediction of the balance temperature is 0.9 °C for buildings in the interquartile range based on a three-year comparison of hourly heating power supply data. Moreover, from a property owner perspective, the model is shown to be useful for identifying deviating thermal power characteristics and can easily be used to get an overview of a district.

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1. Introduction

Residential buildings are one of the main contributors to resource exploitation. On a global level, it is estimated that buildings utilize 35% of the final energy use and contribute approximately one-third of CO_2 emissions [1]. Energy efficiency in residential buildings is a key factor in the work to achieve sustainable development in the building sector. In fact, the existing building stock is identified as the sector with the highest energy savings potential within the European Union (EU) [2]. Despite the likely future increase in space cooling as a result of global warming [3], it is of interest to study the heating energy savings potential in residential buildings situated in Northern European countries due to their cold climate. This is especially the case when considering that comfort cooling is uncommon today in buildings used for residential purposes. In Sweden, about one-third of the buildings were built in 1945 or before (hereafter referred to as "historic buildings"). Due to the generally poorer thermal properties of the build-

ing envelope in older buildings compared to newer ones [4], this segment of the building stock is also most likely to account for a higher energy savings potential.

There is a need to identify buildings with poor thermal performance in order to fulfill the energy efficiency potential in the building sector. To identify these buildings, it is necessary to map the building stock and obtain an overview of the thermal performance of the buildings. Furthermore, mapping a building stock and identifying buildings with poor thermal performance is a multifaceted challenge. Large numbers of buildings cannot be analyzed on a building-by-building basis due to large quantities of data. Instead, this requires an approach based on automatic data processing. In addition, there is a need to process the heating power supply data to differentiate various thermal power characteristics of a building. Currently, average values of key performance indicators (KPIs), e.g. kWh/m², are gathered in databases such as the National Energy Audit Program for Buildings (GRIPEN) [5]. However, this information is not updated continuously, and describing a building's thermal performance in terms of specific energy use creates interpretation difficulties since the KPIs are highly dependent on the user behavior in a building, such as the set indoor tem-

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Nomenclature

E	Energy (Wh)		T_{out}	Outdoor temperature (°C)
P	Hourly heating power supply (W)			
P_{IHG}	Internal heat gains (W)		*List of abbreviations*	
P_{solar}	Solar gains (W)		BXX	Building number XX
$Q_{\text{infiltration}}$	Infiltration losses (W/°C)		DH	District heating
Q_{total}	Total specific heat losses (W/°C)		DTPC	Differentiating Thermal Power Characteristics
$Q_{\text{transmission}}$	Transmission losses (W/°C)		HTW	Hot tap water
$Q_{\text{ventilation}}$	Ventilation losses (W/°C)		HWC	Hot water circulation
T_{b}	Balance temperature (°C)		KPI	Key performance indicator
T_{in}	Indoor temperature (°C)			

perature. By using actual heating power supply data in combination with outdoor temperature, a building's change-point model can be determined. In literature, change-point models are also often referred to as energy signatures. The change-point model describes the building's energy performance from a number of points (often referred to as parameters), e.g. specific heat losses (W/°C) and balance temperature (°C). Other points that are usually quantified in a change-point model include energy use for hot water circulation (HWC), and hot tap water (HTW), i.e., the baseload. Hence, by using change-point modelling it is possible to generate several KPIs for evaluation of the energy performance in buildings. These KPIs are more descriptive in terms of building energy performance compared to specific energy use which allows for a better understanding of a building and can be used for purposes such as building classification.

A common approach for determining a building's change-point model involves linear regression. In this case, the change-point model is often visualized in a power versus outdoor temperature graph. The work performed by Hammarsten [6] in 1987 is one of the earliest papers published in the field of change-point models. Hammarsten [6] explained how a change-point model for building energy performance can be modeled, and investigates the impact of different time resolutions on the results. Other issues adressed included how a model can be supplemented with parameters for solar and wind. The overall conclusion of the study was that a change-point model is a suitable approach for calculating a building's energy performance. One issue with current change-point models is the need for data related to user behavior in order to accurately predict the thermal power characteristics of a building. This data collection is rather time-consuming, especially when investigating a larger number of buildings, such as an entire district.

An uninvestigated area in the field of change-point models is the exploration of the possibilities for differentiating building thermal power characteristics when using only heating power supply data with no detailed data about building operation or building envelope characteristics. To illuminate this unexplored field of research, the proposed research aims to develop a change-point model, titled *DTPC* (Differentiating Thermal Power Characteristics), for predicting building thermal power characteristics in terms of specific heat losses, Q_{total}, P (HWC), P (HTW), and balance temperature, T_{b}, using hourly district heating (DH) data and local climate data in the form of outdoor temperature. The model is implemented in the Matlab software and is mainly designed to investigate a building district because the main input consists of easily accessible heating power supplies with hourly resolution, and no measured detailed data about user behavior in the building is used. *DTPC* allows buildings with poor thermal performance to be identified in building districts, and can hence be used by various actors such as local, regional and national energy agencies with the aim of increasing energy efficiency measures in the building sector. Furthermore, *DTPC* can be a helpful tool for property owners in the quest to identify a malfunctioning technical system since unexpected heating power supply data can easily be identified. Hence, property owners can analyze the technical performance of a building in detail based on an initial screening of the heating power supply data.

The novelty of the present work is to model, predict and differentiate the thermal performance of buildings within a district by using statistical analysis based on selected time periods during the year. To assess the impact of various model assumptions in the numerical procedure a sensitivity analysis is performed with regard to predictions of energy use for HWC, specific heat losses and balance temperature. Seventy-three historic buildings built between 1908 and 1945 in the residential district of Vasastaden in Linköping, Sweden, are selected as the study object.

2. Theoretical background

2.1. Building thermal power characteristics

This section describes the building thermal power characteristics that are important to this research, as well as various types of change-point models and related research.

2.1.1. Hot water circulation

The energy use for HWC constitutes part of the baseload in a building and ensures an instantaneous flow of domestic hot water at tap points. In practical terms, this means that hot water is always available. The hot water flow is achieved using a circulation pump. Further information about the function of HWC systems can be seen in [7].

A major problem with energy use for HWC systems is the heat losses that occur in the pipes. These losses vary depending on the design of the pipes. There are estimated values for HWC energy use, but these figures vary significantly. For residential buildings, annual figures between 4 kWh/m² and 25 kWh/m² are stated by BELOK [8], a cooperative project between the Swedish Energy Agency and Sweden's largest residential property owners. Another study performed by the Swedish Energy Agency and residential owners that included 12 residential buildings showed similar figures ranging from 2.3 kWh/m² to 28 kWh/m² [9].

2.1.2. Hot tap water

The heat demand for HTW is directly linked to the residents' behavior. It is important to be aware of the fact that user behavior varies between individuals, apartments, and multi-family buildings. This requires individual calculations of the HTW energy use for each building. The patterns for HTW energy use are generally characterized by two peaks, one during the morning and one during the evening [10]. A development program by the Swedish con-

struction and real estate industry (Sveby) estimates energy use for HTW at 25 kWh/m² for multi-family buildings [11]. Multi-family buildings located in Stockholm, Sweden, with a total of 1,500 apartments were used as the main data source for setting the average energy use for HTW. The buildings had separated hot water measurement but no individual charging. The corresponding figure for single-family houses is 20 kWh/m².

2.1.3. Specific heat losses

The specific heat loss, Q_{total}, describes the building's energy performance when using actual heating data, i.e., information about the technical performance of the building is obtained. Q_{total} consists of transmission losses through walls, roof, floor and windows, cold bridges, and infiltration and ventilation losses. Consequently, the energy use of a building (excluding HWC and HTW) can be formulated according to Eq. (1).

$$E = Q_{total} \cdot \psi = (Q_{transmission} + Q_{ventilation} + Q_{infiltration}) \cdot \psi \qquad (1)$$

where E is the energy use (Wh), Q_{total} the total loss term (W/°C), ψ the degree hours (°C·h), $Q_{transmission}$ the transmission losses (W/°C), $Q_{ventilation}$ the ventilation losses (W/°C) and $Q_{infiltration}$ the infiltration losses (W/°C). This results in Q_{total} describing the sum of the loss term for transmission, ventilation and infiltration.

2.1.4. Balance temperature

The balance temperature describes the fictive temperature that the heating system needs to heat up to. In other words, this corresponds to when the internal heat gains and solar gains are equal to the heat losses and no additional heating is needed for the building. The balance temperature, T_b, of a building can be calculated according to Eq. (2).

$$T_b = T_{in} - \frac{P_{IHG} + P_{solar}}{Q_{total}} \qquad (2)$$

where T_{in} is the preset indoor temperature, P_{IGH} is the internal heat gains from people and electrical appliances, and P_{solar} is the solar gains.

2.2. Change-point models

2.2.1. General description

Linear regression, a part of statistical analysis, is often used to determine the points in a change-point model. Commonly used methods are based on a least-square approach. The number of points depends on the energy balance model of the building.

Change-point models describe the actual power demand of a building as a function of outdoor temperature. The time resolution varies in most cases from hourly to monthly data. ASHRAE has listed guidelines for developing change-point models based on various building energy systems [12]. Comfort cooling is modeled with two points (slope and break point on the y-axis). A three-point model is used for describing heating (slope, break point and the baseload which consists of the energy use for HWC and HTW and is not related to the building technical performance). The three-point model can also have a fourth point, i.e., the slope after the balance temperature, if there is a heat recovery system. A building with heating and comfort cooling is modeled with five points: two slopes, two break points and a baseload. For residential buildings in a Northern European climate located within a DH area, three-point models are the most common with DH compensating for all energy use needed for space heating, HWC and HTW. An illustration of a three-point model is visualized in Fig. 1 with the energy use for HWC and HTW described by the baseload.

It is crucial to be aware of the difficulties involved in using change-point models to describe a building's energy performance, such as the need for accurate heating data and knowledge about
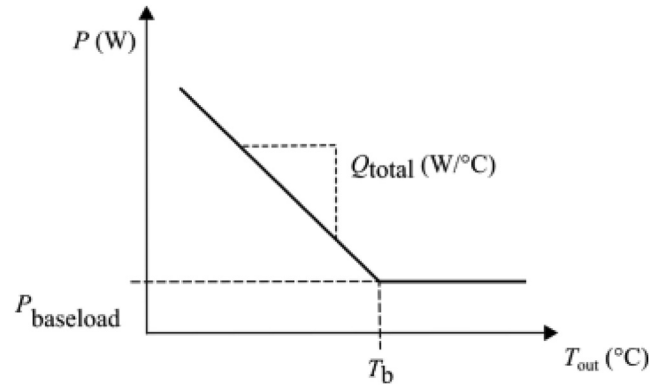

Fig. 1. Visualization of a three-point change-point model.

user behavior. With a malfunctioning heating system, the heating data will not give a justified description of the building energy performance. Potential issues related to user behavior include airing that results in higher heat output from the heating system and variations in set indoor temperatures. In addition, it is important to emphasize the impact from internal heat gains, such as the use of electrical appliances, which directly affects the building balance temperature. Due to differences in user behavior between various buildings, this creates difficulties in developing change-point models where there is no data about the internal heat gains. This is especially the case when considering the time-dependent characteristics of user behavior.

2.2.2. Related research

Data on actual building energy use was originally used by heating suppliers for billing purposes. More recently, a change has occurred whereby this data is used for tasks such as estimating building energy performance and assessing possible impact from energy renovation measures. Claridge et al. [13] addressed the potential of data from actual energy use as early as 1992. Possibilities in the form of investigating a building's energy systems for proper function, evaluating energy renovation measures and possible changes in the system's regulation to reduce energy use were included in the study. Change-point models have been used in numerous other scientific investigations to determine building energy performance in various contexts, e.g. [14–22]. The areas of application include investigating building energy performance before and after renovation.

Hitchin [16] reviewed the energy performance standard for buildings, ISO 13790:2008, as well as an alternative method based on a change-point model for calculations of monthly utilization factors. The ISO standard is commonly used for implementing the Energy Performance of Buildings Directive in Europe. In many cases, when the variation in day-to-day heat gains is low the two methods predict similar heating requirements. However, Hitchin [16] concludes that the change-point model is generally more robust than the standard ISO calculation. This is because the standard ISO calculation underestimates heating and cooling demand when the day-to-day variation in heat gains is high. In addition, it provides more information about the building, such as balance temperature, and is therefore preferred. Kim and Haberl [15] used a three point change-point model to calibrate an initial simulation model against measured energy use and weather data. Two single-family houses in Texas, USA, were selected as a case study. It was found that the model simulated the current performance of the building more realistically after calibration, as well as accurately predicting future energy-efficient measures. Vesterberg et al. [14] investigated the robustness of a linear regression method to calcu-

late a building's specific heat losses and heat losses to the ground. Two multi-family buildings located in Sweden were selected as case study. The model was based on DH data and electricity use over the course of two years. It was concluded that the method was robust, with specific heat losses varying by less than 2% when using data from two different years. Linear regression was also used by Farmer et al. [17] to determine the specific heat losses of three dwellings located in the UK. Sjögren et al. [18] investigated the energy performance of 100 multi-family buildings in Sweden in terms of specific heat losses. A change-point model approach was used, similar to the aforementioned investigation by Farmer et al. [17]. To calculate the specific heat losses accurately, Sjögren et al. [18] emphasize the need for data relating to household electricity use and indoor temperature. In addition, the authors question the energy use per square meter figure as a measure of building energy performance, as this is largely affected by user behavior in the building. The significance of user behavior has also been mentioned by [17,19,20]. Sjögren et al. [20] have investigated the effects on specific heat losses depending on the time period and the energy gained from solar gains and internal heat gains. This study included nine multi-family buildings constructed between 1998 and 2003, located in Stockholm, Sweden. Three years of monthly heating data were used together with annual cold water use, as well as electricity use for some buildings. The specific heat losses were found to be fairly constant when calculated during periods with small amounts of solar gains. Using change-point modeling, Park et al. [19] quantified the energy performance of 128 apartment complexes representative for the building stock in Seoul, South Korea. Input data for the investigation included building properties and monthly utility bills for natural gas, electricity and DH over the course of three years, 2009–2011. It was stated that it is possible to determine the optimal energy renovation measures by using parameters of change-point models. Meng and Mourshed [21] found that the balance temperature varies significantly depending on building thermal characteristics, operation and user behavior. It is therefore not realistic to assume a fixed balance temperature. The results were found using a three-point change-point model when studying 119 non-residential buildings located in Cardiff, Wales. Arregi and Garay [22] used change-point models to investigate the energy performance in three tertiary buildings located in the UK, Spain and Sweden. The study was performed using simulation procedure and monitoring data both before and after energy renovation. The results show that the optimum time resolution is dependent on how the building is used, e.g. longer intervals are needed in cases with discontinuous use to balance disruptions due to usage patterns.

Prior research in this field has not revealed the possibilities of differentiating thermal power characteristics in a residential district based on the use of heating power supply data alone with no description of user behavior or building envelope characteristics. In light of this research gap in the field of change-point models, the authors have developed a change-point model using hourly heating supply data and outdoor temperature data for time-effective prediction of thermal power characteristics.

3. Methodology description

The model presented in this paper includes five steps. Step *I* consists of collecting hourly heating power supply data for the buildings in the district and corresponding outdoor temperatures for a continuous time period of a minimum of one year, as well as building data in the form of heated area and construction year. Step *II* consists of selecting time periods based on seasonal and daily patterns in terms of climate and user behavior, to allow for differentiation between various building thermal power character-

istics. In Step *III*, assumptions are made connected to the model in terms of building operation and user behavior, while Step *IV* consists of the numerical procedures during the selected time periods for differentiating thermal power characteristics. In Step *V*, the results are interpreted and analyzed. A sensitivity analysis is then performed with regard to the model assumptions and selection of time periods in order to investigate and possibly improve the robustness of the model. A schematic of *DTPC* is given in Fig. 2.

3.1. Data collection

The first part of the proposed methodology is the collection of hourly heating power supply, which is three years of continuous DH data in the current research, for the studied buildings. In addition, local climate data in the form of outdoor temperatures for the corresponding time period needs to be collected. Furthermore, using some type of declaration register, data about the buildings in terms of heated area is collected. Hence, it is possible to predict performance characteristics per heated square meter and thus compare the thermal performance of various buildings. In addition, construction year data can also be collected to allow for a comparison of buildings constructed in different time periods. In this research, the Swedish energy declaration register GRIPEN [5] is used to gather data about the heated area and the construction year.

3.2. Selecting specific time periods

A building is operated and used differently depending on the season and the time of day. For instance, due to colder outdoor temperatures during the winter compared to autumn and spring, more space heating is required. HTW use for household appliances is also more common during time periods when people are generally at home and not at work. This directly affects the amount of energy use for HTW in the building. In short, these two examples clarify that the heating power supply is time-dependent because of seasonal and daily patterns in terms of climate and user behavior. Therefore, by investigating specific time periods and using numerical procedures, various building thermal power characteristics, e.g. energy use for HWC and specific heat losses, can be identified. The selection of time periods for calculating the various building thermal power characteristics is presented in Fig. 3.

The four lowest hourly averages for heating power supply in July are used to quantify the energy use for HWC. Generally, in residential building districts located in Sweden, one can ignore the power to compensate for heat losses that occur during summer months since the outdoor temperature is often above the balance temperature of the building. This is especially true for July, as this is the month with the highest average outdoor temperature. In addition, July was the warmest month in two of the three years for which hourly outdoor temperatures have been collected for Linköping. July is also the most common vacation month in Sweden, according to the governmental statistics agency SCB [23]. However, some heating will still occur for the heating power supply for HTW, P(HTW). To differentiate the heating power supply for HWC, P(HWC), from other heating supply in July, the average heating power supply is calculated for each hour during the day. Hence, hours when heating is required for P(HTW), e.g. using domestic hot water, can generally be identified. If only the hourly average with the lowest value is selected, there is a risk that this will not be representative of P(HWC). The reason why the four hours with the lowest averages are selected is explained by a detailed analysis of the data based on hourly heating supply averages, showing a clear baseload during this time period. It should be noted that these findings are in the same range as the results from a study performed by Widén et al. [24] based on two different data sets, the first consisting of 29 people in ten households and the second
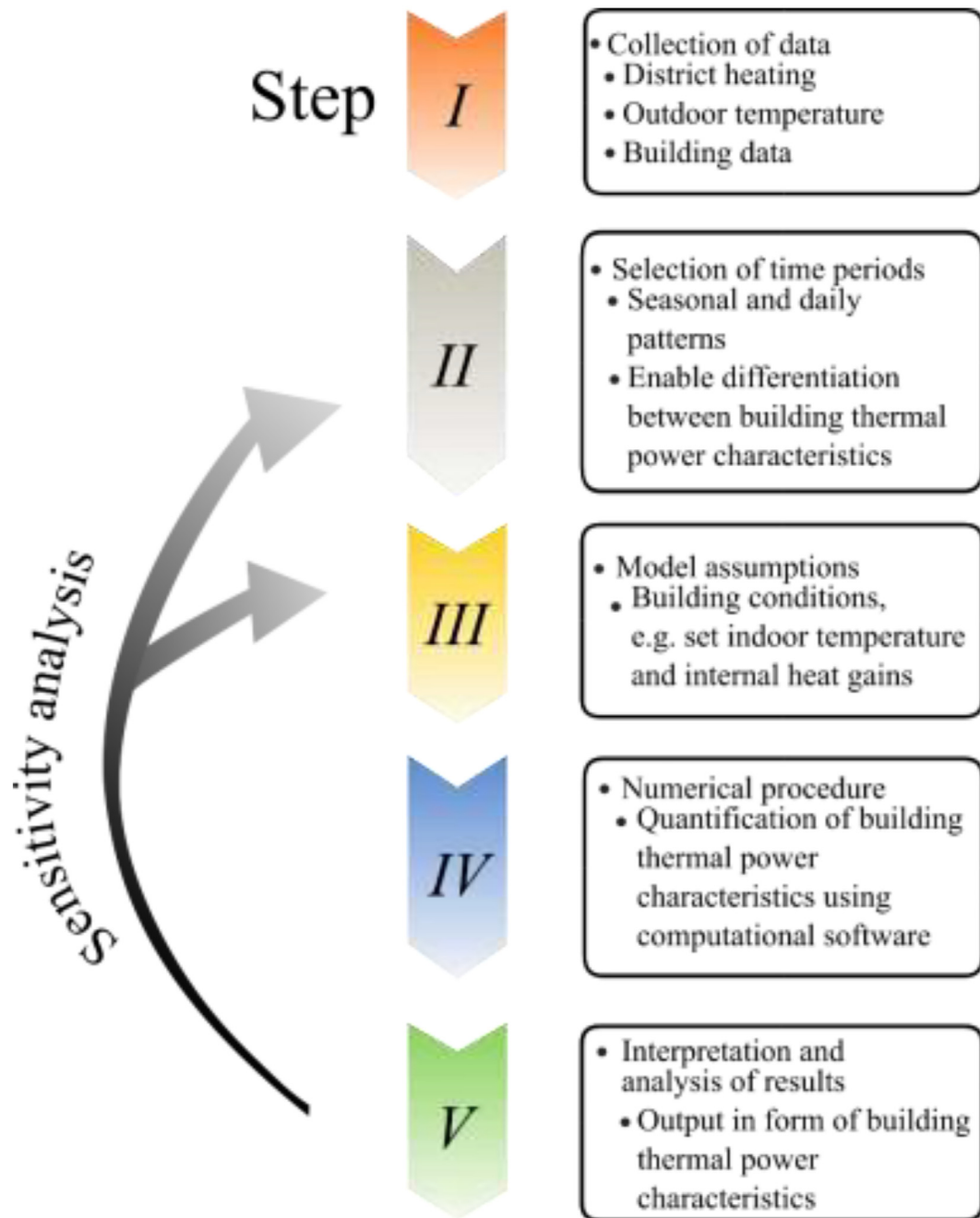
Fig. 2. Schematic of DTPC.

consisting of two multi-family buildings with 40 people in 24 households. The study concluded that no HTW use occurred for approximately four to five hours per day.

January and February between 00:00 and 05:00 (24-hour clock) are used to quantify Q_{total}. Calculating the specific heat loss using only the heating power supply where the energy use for HWC and HTW are also included is a complex task. However, by selecting time periods where the energy use for HTW is not common and the heating supply to the building consists almost solely of space heating and energy use for HWC, it is possible to calculate the specific heat losses. Hence, the use of hourly energy supply data between 00:00 and 05:00 for January and February is proposed. This time period is characterized by no solar gains on the building envelope, a small degree of human occupancy affecting the building energy use, which can be through airing, and the coldest overall outdoor temperature during the year which results in a high temperature difference between indoors and outdoors. It is important to be aware that internal heat gains and solar gains decrease the building heating demand. However, it is not within the frame of this research to predict building energy use with consideration to heat gains, but to predict Q_{total} based on the building technical performance. In addition, the heat transfer through the building envelope is also affected by the amount of solar radiation on the building envelope. Therefore, in order to accurately predict Q_{total} it is important to use heating data based on time periods characterized by a small impact from internal heat gains and solar radiation. Moreover, the red bars in the top left corner of Fig. 3 show hourly energy use for the HTW profiles for apartment buildings based on the standard EN 12831–3 [25]. Hence, the use of HTW is generally very uncommon during the time steps used for quantifying Q_{total}.
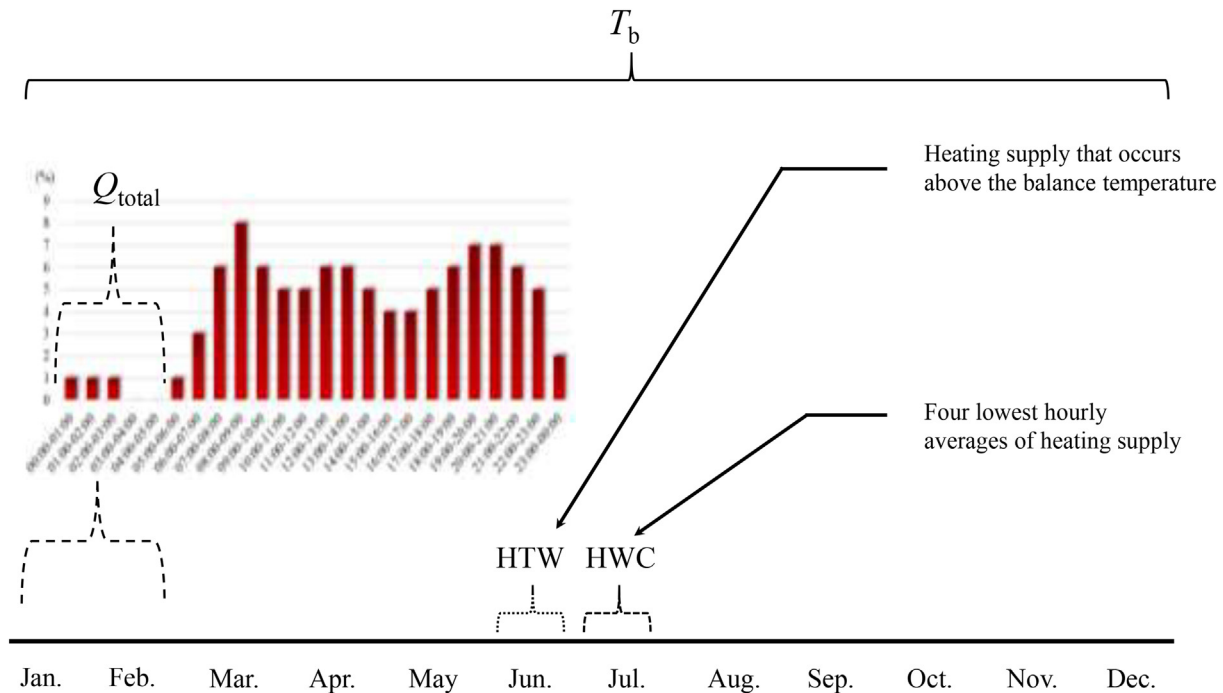
Fig. 3. Selected time periods for quantifying the various building thermal power characteristics.

Heating power supply that occurs above the balance temperature in June is used to quantify HTW use. When predicting the P(HTW), it is important to analyze time periods when P(HTW) can be differentiated from P(HWC) and space heating. Therefore, it is necessary to select time periods with fairly high outdoor temperatures and when residents are present in the building to a high degree, in order to accurately characterize user behavior concerning the use of P(HTW). It is crucial to note the need for a time period with a sufficient number of hours when outdoor temperatures are above the balance temperature in order to ensure representative P(HTW) characteristics for the building. If there are only a few time steps with an outdoor temperature above the balance temperature, there is a high risk of not achieving a characteristic P(HTW) load. June, July and August are the months that fulfill the above-mentioned conditions to a much greater extent compared to the rest of the year, with average temperatures for Linköping of 15.9 °C, 17.0 °C and 16.2 °C respectively. It can also be noted that on average there are 168, 211 and 269 time steps during June in 2014, 2015 and 2016 with a measured outdoor temperature above 18 °C, 17 °C and 16 °C respectively. This shows that the prediction of the P(HTW) use is not based on a few data points since there are a significant number of time steps with outdoor temperature above common balance temperatures in buildings. Moreover, according to SCB, absence from work due to vacation is three to seven times more common in July and August than in June (considering figures between 2015 and 2018 [23]). In addition, June accounts for between 6% and 8% of total annual vacation absence from work. Hence, the data set for predicting P(HTW) consists of time periods when residents are generally present in their dwellings and with sufficient time steps of outdoor temperatures above the balance temperature. Another important factor is the need for local and updated P(HTW) data for accurate load profiles [26], which is the case in the suggested research. Following the reasoning above, the selection of time steps with outdoor temperatures above the building balance temperature during June, using recent heating supply data, is reinforced.

Calculations of the balance temperature are based on heating supply data from a whole year. Hours when the outdoor temperatures are higher than the balance temperature are excluded from the calculations, i.e., during time periods when the heating system should not be operating and there is no demand for space heating. An example of what hours are above the balance temperature without demand for space heating is visualized by a duration diagram in Fig. 4.

3.3. Model assumptions

Since no data in the form of e.g. internal heat gains and set indoor temperature is used in the proposed change-point model, a number of assumptions are made. These are:

- Constant indoor temperature. The average indoor temperature is assumed to be constant in the building and is set at 21 °C, which is in the same range as the recommendations from the Public Health Agency of Sweden [27].
- Internal heat gains. During the calculation of the specific heat losses Q_{total}, internal heat gains from electrical appliances and occupants is taken into consideration. Heat gains of 3.4 W/m^2 from electrical appliances is taken into account of which 70% is accounted for as useful energy (giving a figure of 2.4 W/m^2) [11]. Heat gains from occupants is estimated at 80 W/person [11], and the number of occupants in each residential building is predicted using data from SCB (Statistics Sweden – a government agency that produces official national statistics) [28]. The average living area per person in a multi-family residential building in Linköping is 40 m^2 [28], which results in heat gains of 2 W/m^2 from occupants.
- No comfort cooling. It is assumed that no comfort cooling exists and is supplied to the buildings because it is uncommon in multi-family residential buildings located in a Northern European climate, especially in historic buildings.
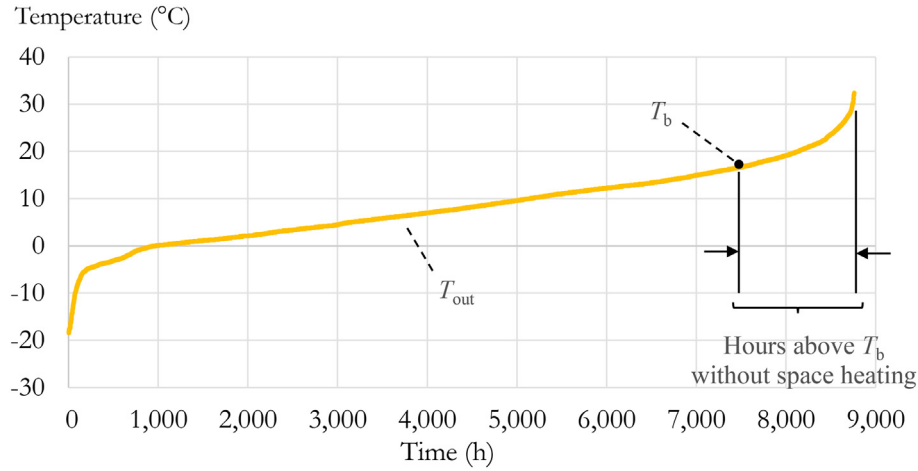
Fig. 4. Visualization of what hours are above the balance temperature without demand for space heating.

3.4. Numerical procedure

This section describes the numerical procedure in the proposed change-point model. The numerical procedure is implemented using the software MATLAB R2018b. The model takes about one minute of CPU time on a quadcore desktop with a 3.7 GHz processor for the 73 historic buildings included in the study object.

The numerical procedure for calculating the various thermal power characteristics starts by predicting the energy use for HWC, see Eqs. (3) and (4).

$$\overline{P(HWC)}_i = \frac{P(HWC)_{i,1} + ... + P(HWC)_{i,\,31}}{31} \tag{3}$$

$$P(HWC) = \frac{\overline{P(HWC)}_{i,min} + ... + \overline{P(HWC)}_{i,min+3}}{4} \tag{4}$$

- In Eq. (3), $\overline{P(HWC)}_i$ (kW) represents the individual average power for each hour of the day (i.e., i = 00:00, 01:00,...,22:00, 23:00). The numerical procedure is performed considering all the days in July, and the average for each hour is hence calculated by dividing the sum by 31.
- In Eq. (4), $P(HWC)$ (kW) is the hot water circulation and $\overline{P(HWC)}_{i,min}$ (kW) is the lowest hourly average heating supply to the building, $\overline{P(HWC)}_{i,min+3}$ (kW) is the fourth lowest hourly average. According to Eq. (3)–(4), HWC is set to the average of the four hours with the lowest averages in terms of heating power supply.

Next, the specific heat losses, Q_{total}, are calculated – see Eq. (5)–(6).

$$Q_{total,sum} = \sum_{j=1}^{k} \frac{(P_{\cdot j} - P(HWC))}{(T_{in} - T_{out,j})} \tag{5}$$

$$Q_{total} = \frac{Q_{total,sum}}{k} \tag{6}$$

In Eq. (5), $P_{\cdot j}$ is the hourly heating supply to the building at hour j. $P(HWC)$ is the hot water circulation based on the calculations in Eq. (4). T_{in} corresponds to the set indoor temperature and $T_{out,j}$ is the outdoor temperature at hour j. The mathematical operation is performed for each hour during January–February between 00:00–05:00 as shown in Fig. 4 with a set indoor temperature of 21 °C. Q_{total} is set as the average based on the calculations during the selected time period according to Eq. (6), with $Q_{total,\,sum}$ as the sum of all hourly Q_{total} calculated in Eq. (5) and divided by the number of time steps, k, in the selected time period.

By calculating Q_{total} and $P(HWC)$, it is possible to predict the balance temperature T_b, see Eq. (7) and (8). Moreover, this enables prediction of the $P(HTW)$ use by setting the average energy use that occurs during outdoor temperatures above the balance temperature as the $P(HTW)$. Hence, the energy use for $P(HTW)$ is a fixed figure for all time steps during the year. As described in section 3.2, June is the selected time period for predicting the $P(HTW)$ use.

$$T_{b,\,sum} = \sum_{l=1}^{8760} \frac{(P_{\cdot l} - P(HWC) - P(HTW))}{(Q_{total})} + T_{out,l} \tag{7}$$

$$T_b = \frac{T_{b,sum}}{8760} \tag{8}$$

As can be seen in Eq. (7), $P(HWC)$ is deducted from the heating supply data during calculations of the balance temperature in the numerical procedure. $T_{b,\,sum}$ is the sum of all hourly balance temperatures calculated during a year. The numerical procedure is performed through an iterative calculation process where the balance temperature is set to a fixed temperature in the first iteration. Thereafter, using the calculated $P(HTW)$, the new T_b is calculated as the average of all hourly balance temperatures, see Eq. (8). For each iteration, the new estimated balance temperature is set to the previously estimated T_b + 10% of the absolute difference between the calculated T_b and the previously estimated T_b. The calculation is performed until the tolerance level, i.e., the difference between the last two calculated balance temperatures, is achieved. This is less than 0.1 °C in the current research. It should be noted that during time steps when $T_{out} > T_b$, i.e., when the outdoor temperature is higher than the balance temperature, and when there is no heating supply for space heating, are excluded from the calculations of the new balance temperature. Furthermore, quantifying the balance temperature allows for a final screening of the studied buildings in terms of thermal performance, as well as identifying deviating trends in the DH data, since both the specific heat losses and HWC are used as input in the numerical procedure. This is facilitated by the use of several years of continuous DH data and outdoor temperature data. Consequently, it is possible to carry out a time-effective plausibility check of the quantified thermal power characteristics.

3.5. Sensitivity analysis

A sensitivity analysis approach is applied in this research in order to investigate and quantify the impact of variations in selected time periods (Step *II* in *DTPC*) and model assumptions (Step *III* in *DTPC*) on the predicted thermal power characteristics. This allows the parameters whose variation has the largest impact on the result to be calculated . In this research, the model output will be investigated depending on variation in a) the number of hourly averages for representing energy use for HWC; b) months and hours of a day for predicting specific heat losses; and c) assumptions concerning set indoor temperature and internal heat gains for predicting specific heat losses and balance temperature.

4. Description of the study object

Vasastaden is a central district located in Linköping, Sweden, with the geographic co-ordinates latitude 58.42 and longitude 15.61. Vasastaden consists mostly of multi-family buildings built before 1960, of which a significant proportion was built in 1945 or before.

Heating power supply to the buildings is generally distributed via the local DH network. The district is characterized by rental properties with approximately 6,000 residents. In the present research, 73 historic buildings are selected as the study object with a total heated area of 126,955 m^2. The buildings were constructed between 1908 and 1945. Hourly energy use data for each building has been collected between 2014 and 2016 at the local energy company Tekniska Verken AB. Outdoor temperature data for the corresponding time period has been obtained from the Swedish Meteorological and Hydrological Institute (SMHI) via a weather station located at Malmslätt, approximately 8 km west of Vasastaden. The mean annual outdoor temperature was 8.4 °C, 8.3 °C and 7.8 °C for 2014, 2015 and 2016, respectively. A duration diagram of the temperatures for 2014, 2015 and 2016 is illustrated in Fig. 5. The general trend is that 2016 has the coldest outdoor temperatures. Furthermore, heated areas for the buildings are obtained from GRIPEN [5]. Data on the total heated area, distributed by construction year for the 73 buildings, is given in Fig. 6. There is a large variation in heated area between the various construction years included in the study object. A large proportion of the total area in the district can be attributed to buildings con-

structed in 1929, 1942 and 1944 corresponding to 58,494 m^2, or 46% of the total area. It is important to note that many buildings constructed prior to 1929 were assigned a construction year of 1929, hence the large heated area for this specific year.

Based on data from GRIPEN [5] for the studied district, the average energy use is 120 kWh/m^2 for the buildings constructed between 1908 and 1925, 137 kWh/m^2 for the buildings constructed between 1926 and 1935, and 107 kWh/m^2 for the buildings constructed between 1936 and 1945. The purpose of the age differentiation is to allow for a basic comparison of buildings constructed in different time periods, as well as for pedagogical reasons during later interpretation of the results. Photos of representative buildings for the time periods can be seen in Fig. 7. The building to the left is constructed between 1908 and 1925, the building in the middle between 1926 and 1935 and the building to the right between 1936 and 1945.

5. Results and discussion

5.1. Building thermal power characteristics using DTPC

This section presents the results in the form of quantified building thermal power characteristics using the proposed change-point model, together with an associated discussion. First, the HWC and HTW use are presented, followed by the specific heat losses and balance temperature for the buildings in the studied district. Lastly, a sensitivity analysis is presented in order to show the robustness of the proposed model. The preliminary analysis shows significantly varying performance characteristics when comparing 2014, 2015 and 2016 in terms of balance temperature for three buildings: *B*33, *B*39 and *B*63. The balance temperature is assessed here because it is the final step of the numerical procedure. Through detailed investigation of the hourly heating supply over the course of the three years it was found that the heating supply is significantly lower during the night in *B*33, suggesting e.g. a lowered indoor temperature or a building with high thermal inertia which emits heat during this time period when temperature changes occur. Analysis of the heating supply data for *B*39 and *B*63 shows ambiguous heating supply patterns for both buildings. There are strong fluctuations in measured heating supply to the building, which are difficult to elucidate without detailed knowledge about factors such as user behavior and performance of the
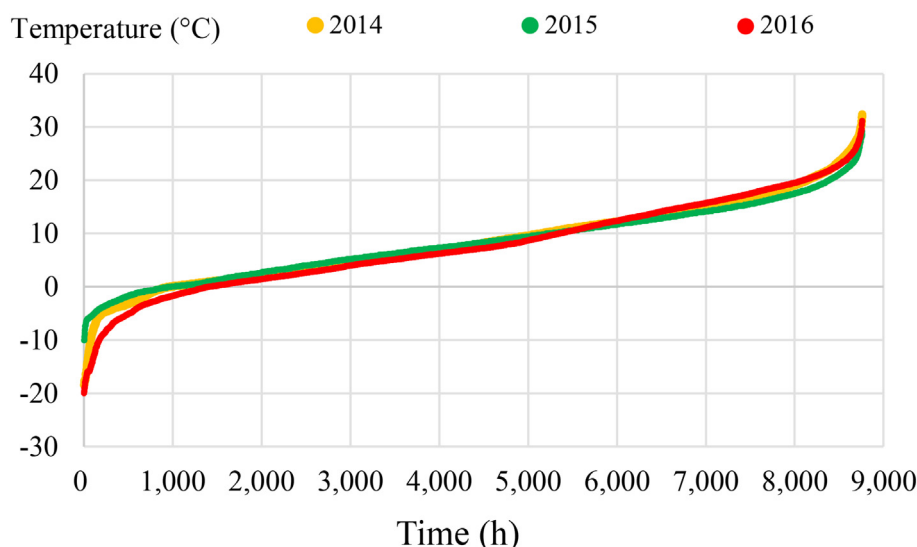

Fig. 5. Duration diagram of the outdoor temperature in Linköping, Sweden, for 2014 (yellow), 2015 (green) and 2016 (red). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
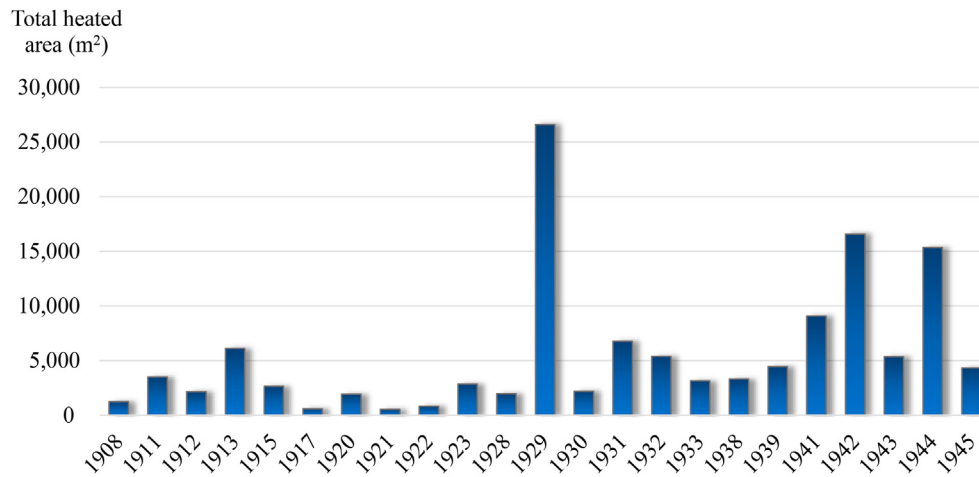
Total heated
area (m²)

Fig. 6. Total heated area by building construction year.

Fig. 7. Photos of representative building constructed between 1908 and 1925 (left), buildings constructed between 1926 and 1935 (middle), and buildings constructed between 1936 and 1945 (right).

building's technical system. However, possible explanations include the use of an accumulator tank and some type of commercial activity in the building. The aforementioned buildings are henceforth excluded from the analysis. This is also the case for deviating trends in quantified thermal power characteristics as a result of e.g. energy renovation, which occur during one of the three years for which heating power supply data has been collected.

5.1.1. Hot water circulation and hot tap water use

HWC corresponds to the baseload in a building together with HTW use. However, the baseload only constitutes part of the heating supply to a building and consequently the heating bill, and it is difficult to separate this from space heating without individual measurements. Therefore, despite the large number of scientific papers within the field of change-point models, a differentiation between these thermal power characteristics has not yet been performed using only heating supply data and local outdoor temperature, to the best of the authors' knowledge. Since both P(HWC) and P(HTW) constitute the building baseload, the accumulated energy

use for P(HWC) and P(HTW) is first presented in this section. Thereafter, a differentiation between P(HWC) and P(HTW) is given.

The energy use for HWC and HTW is presented in Fig. 8, calculated as the average of figures for 2014, 2015 and 2016. Buildings constructed between 1908 and 1925 are presented at the top, buildings constructed between 1926 and 1935 in the center, and buildings constructed between 1936 and 1945 at the bottom. As shown by the dotted line, the average energy use for HWC and HTW is 19 kWh/m², 31 kWh/m² and 26 kWh/m² for buildings constructed between 1908 and 1925, between 1926 and 1935, and between 1936 and 1945 respectively. The average energy use for HWC and HTW is 27 kWh/m² for the entire district. When comparing the energy use required for HWC and HTW during 2014, 2015 and 2016, it can be seen that the variation width, i.e., the largest difference in terms of predicted energy use when comparing the three years, is relatively small. Thirty-nine of 70 buildings (56%) have a variation width equal to or less than 5 kWh/m² (39%).

The energy use for HWC is presented in Fig. 9, calculated as the average figure for 2014, 2015 and 2016. As shown by the dotted line, the average annual energy use for HWC is 11 kWh/m², 17 kWh/m² and 14 kWh/m² for buildings constructed between

Fig. 8. Calculated energy use for HWC and HTW. Buildings constructed between 1908 and 1925 are presented at the top, buildings constructed between 1926 and 1935 in the center and buildings constructed between 1936 and 1945 at the bottom. The average when including all buildings in each time period is visualized with a dotted line.

1908 and 1925, between 1926 and 1935, and between 1936 and 1945 respectively. The average energy use for HWC is 15 kWh/m^2 for the district. In comparison with Belok [8] and a study by the Swedish Energy Agency and residential owners [9], which calculated the HWC at between 2.3 kWh/m^2 and 28 kWh/m^2, it can be noted that the energy use for HWC is in the same range as earlier Swedish studies. Moreover, the authors wish to point out that the

measured hourly DH data (in kWh) is rounded to the nearest integer. Hence, considering the use of accumulative data in the numerical procedure, the impact from rounded kWh data is low. In addition, the average variation width is 2 kWh/m^2 (12%) when comparing figures for 2014, 2015 and 2016 after excluding diverging heating supply trends in the data during July. This indicates that the calculated energy use for HWC is relatively constant over-
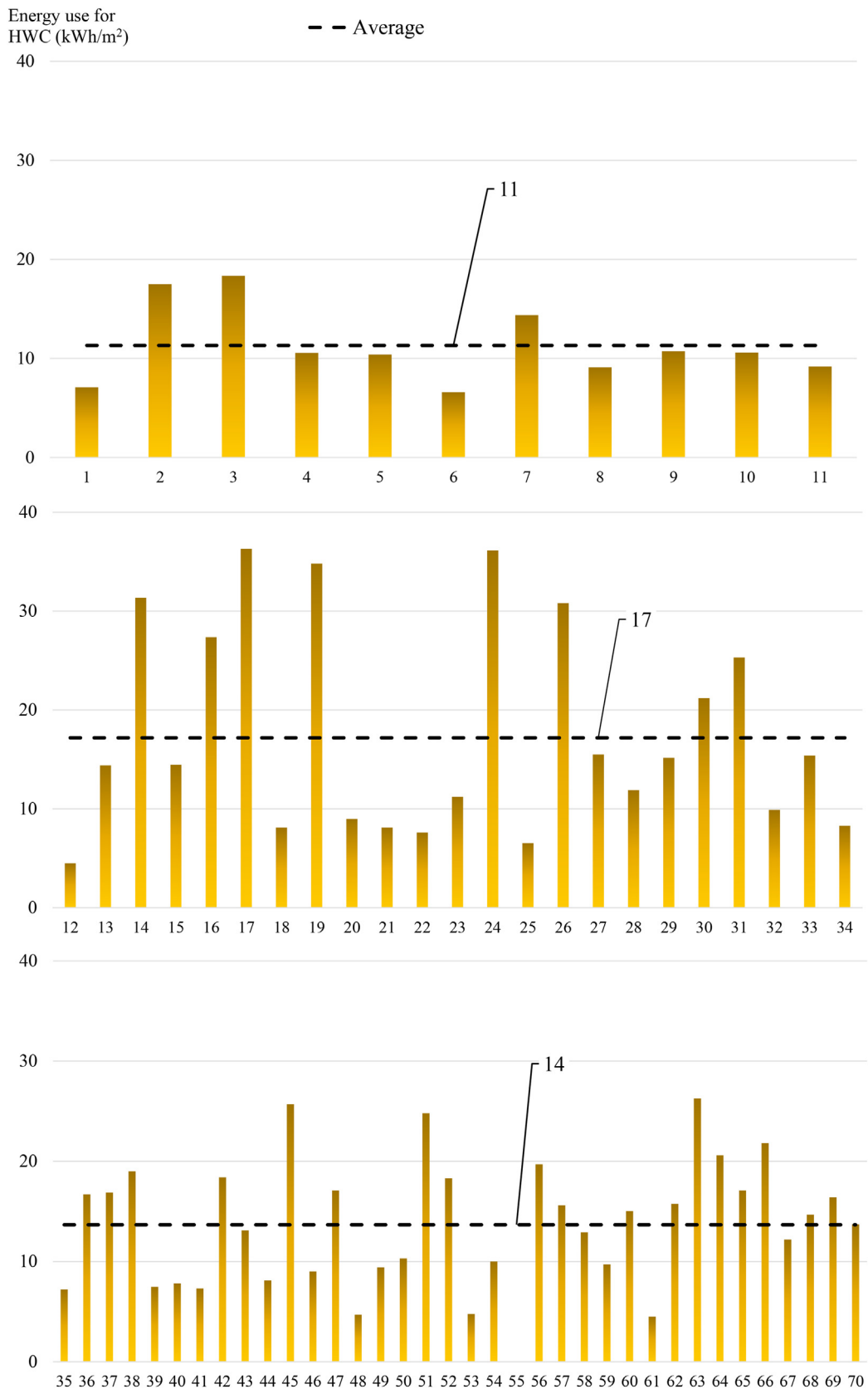
Fig. 9. Calculated energy use for HWC. Buildings constructed between 1908 and 1925 are presented at the top, buildings constructed between 1926 and 1935 in the center and buildings constructed between 1936 and 1945 at the bottom. The average when including all buildings in each time period is visualized with a dotted line.

all for each building, regardless of which of which year the DH data is based on.

Calculated energy use for HTW for the buildings is presented in Fig. 10. The average annual energy use for HTW is 8 kWh/m², 14 kWh/m² and 12 kWh/m² for buildings constructed between 1908 and 1925, between 1926 and 1935, and between 1936 and 1945 respectively. The variation between the years is higher compared to the previously calculated HWC. The reason for this can be directly attributed to the energy use for HTW directly reflecting the user behavior. However, as mentioned above, 56% of the studied buildings have a variation width equal to or less than 5 kWh/m² when the energy use for both HWC and HTW is included, indicating good overall reliability, especially when considering the use of only heating power supply data and outdoor temperature in *DTPC*.

5.1.2. Specific heat losses

The specific heat losses for the buildings are shown in Fig. 11 and are calculated as the average figure from 2014, 2015 and 2016. The figures are presented in W/(m² ◻ °C) to enable a comparison of the thermal performance between the various buildings. In cases where deviating heating supply trends are found during a year compared to the other two years, these years are not considered when calculating the average. This occurs in nine out of 73 buildings (12%). A deeper analysis of the data between 00:00 and 05:00 in January and February shows that deviating heating power supply data can be attributed to a number of reasons, such as significantly lower heating power supply during the night compared to the day time. This is observed in *B*48 and *B*63 during 2016, indicating lower night-time temperature. Moreover,t large differences in the calculations of specific heat losses between the years can also be seen, which is the case in *B*14, with a fourfold increase in losses during 2015 and 2016 compared to 2014. This may be the result of connecting the heating power supply connection point to additional buildings. Another interesting trend that can be noted from detailed analysis of the data is that there is no registered heating power supply to the building, which indicates a malfunctioning heating system or supply sensor. This is observed in the first quarter of 2014 in *B*50 and *B*57.

As presented in Fig. 11, the specific heat losses in the district vary between 0.59 W/(m² ◻ °C) and 2.25 W/(m² ◻ °C) due to varying building thermal performance. The average is 1.06 W/(m² ◻ °C). The average variation width is equal to or less than 5% (corresponding to ~ 0.05 W/(m² ◻ °C)) when comparing calculations from 2014, 2015 and 2016. To investigate the variability of the data points included in the calculations, a total of 354 time steps during a non-leap year considering the selected time period, the average standard deviation (σ) is calculated for each building indicated by the error bars in Fig. 11. The results show a low volatility with an average standard deviation less than 0.11 W/(m² ◻ °C). This means that by selecting specific time steps during January and February, there are low differences overall in the predicted specific heat losses after processing measured heating supply data and outdoor temperature. Furthermore, it is of interest to assess how good the fit is in terms of supplied heat to the building at a certain outdoor temperature. It is important to mention the control of the heating system, which may be somewhat delayed compared to sudden changes in outdoor temperature, and hence affects the coefficient of determination, i.e., the predicted R^2 value. Other influencing factors include energy use for HTW and airing, for example. Examples of linear regression based on hourly heat supply dependent on outdoor temperature for four buildings – *B*1, *B*26, *B*56 and *B*69 – together with a 95% confidence bound on the regression line are shown in Fig. 12. The heated area is 1,241 m² for *B*1, 1,137 m² for *B*26, 891 m² for *B*56 and 1,069 m² for *B*69. The coefficient of determination is 0.66, 0.72, 0.66 and 0.65 for *B*1, *B*26, *B*56 and *B*69 respectively. The average R^2 is calcu-

lated at 0.70 for the building district, which shows that the supplied heat to the building is largely explained only by varying outdoor temperatures. It is also important to note that the heat supply is affected by the thermal inertia of the buildings. Buildings with a higher thermal inertia can store more heat in the building structure and consequently emit the stored heat when temperature changes occur. This will, in turn, result in lower specific heat losses. Moreover, the buildings' position and exposure to wind, which affects the buildings' infiltration losses, also influence the heat supply. By using equivalent temperature, it is possible to account for the impact from variation in wind velocity. Furthermore, the weather station measuring the outdoor temperature is located 8 km west of the buildings, which means that the outdoor temperature between the two sites may vary slightly.

An interesting trend that can be noted when analyzing the entire district is a correlation between building construction year and specific heat losses; the older the building, the higher specific heat losses per m² of heated area. However, the authors suggest that this correlation should be further analyzed with heating power supply data for a larger number of buildings. This is because the correlation can be attributed to factors other than varying construction approaches during the time periods, such as energy renovation performed in parts of the district. Other factors include the distribution between opaque and transparent building envelope, and the exposure to wind, which influences infiltration losses as mentioned above. In addition, there are differences in the number of buildings within each age group, as well as variations in specific heat losses within the same age group.

5.1.3. Balance temperature

The building balance temperature is calculated simultaneously with the energy use for HTW based on an iterative calculation process, as described in section 3.4. The balance temperature for the studied buildings is shown in Fig. 13, presented as the average figures for 2014, 2015 and 2016. The error bars for each building show the maximum and minimum balance temperatures. A set indoor temperature of 21 °C is used in the numerical procedure, in accordance with the recommendations from the Public Health Agency of Sweden [27]. It should be noted that it is not uncommon from a residential property owner's perspective to have a somewhat higher indoor temperature to satisfy tenants. (The impact from varying indoor temperatures on the balance temperature is investigated in section 5.2.) The average balance temperature is 16.6 °C for the district when using the set model assumptions presented in section 3.3. As shown by the dotted line representing the average balance temperature for the three different time periods, the balance temperature is slightly lower in newer buildings compared to older ones indicating somewhat better thermal performance. This tendency is to a great extent linked to lower heat losses since the assumed internal heat gains are directly proportional to the heated area as mentioned in section 3.3. However, the balance temperature is also dependent on the building's thermal mass, which means that buildings with a higher thermal mass have a lower balance temperature. Furthermore, by comparing the calculated balance temperature for the three different years, it can be seen that there is a low variance. The average variation width is 0.9 °C for the buildings in the interquartile range. Sixty-one of 73 buildings, or 84% of the buildings in the district, have a variation width equal to or less than 2.0 °C. Hence, by using several years of heating power supply data, it is shown that the robustness of the *DTPC* model is fairly satisfactory. As previously mentioned in the proposed study, the predictions of the balance temperature are directly linked to previous calculations since this is the last step of the numerical procedure. Therefore, unreasonable balance temperatures may indicate deviating performance measures of specific heat losses, energy use for HWC or HTW. which in turn may be
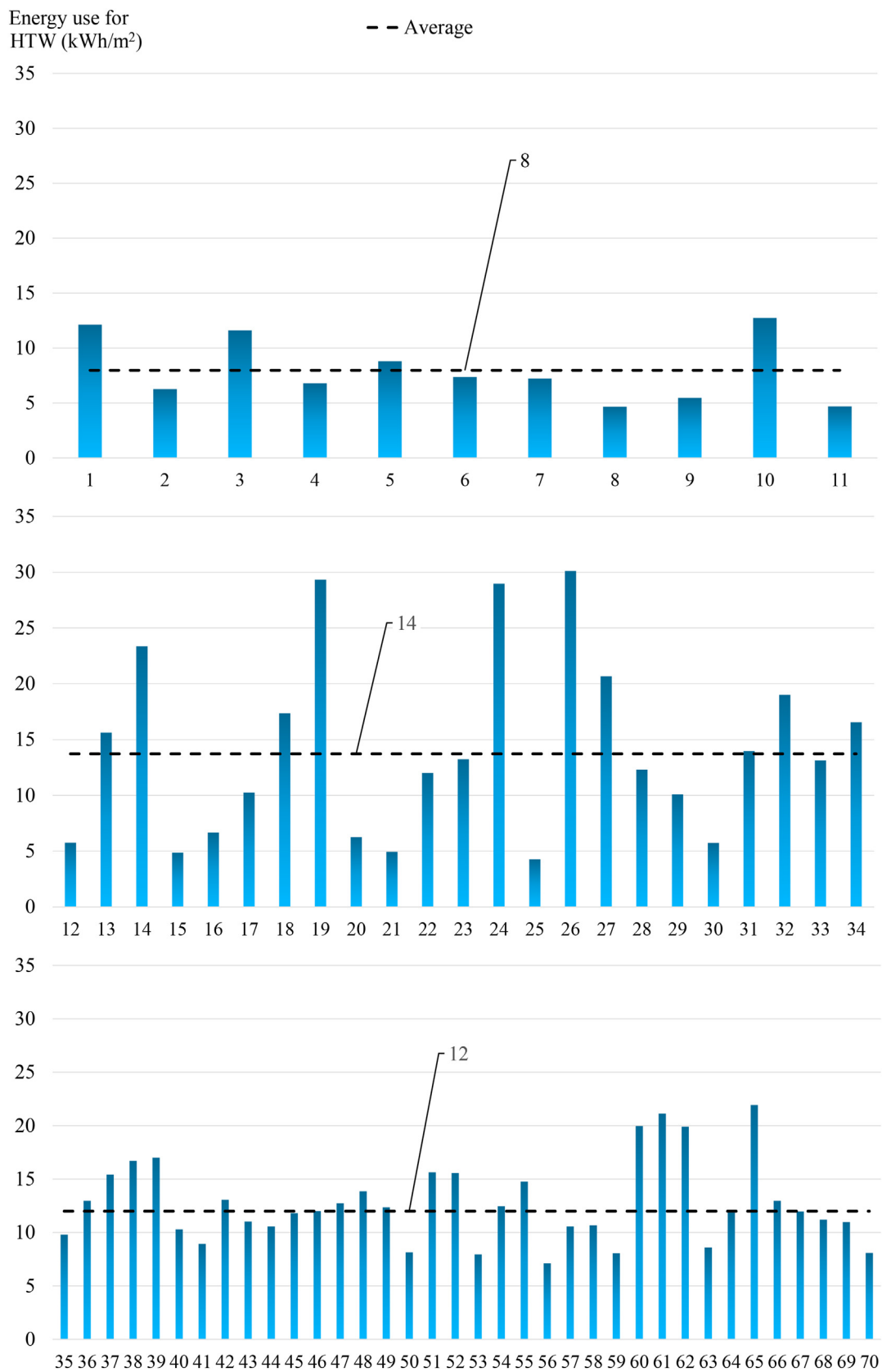
Fig. 10. Calculated energy use for HTW. Buildings constructed between 1908 and 1925 are presented at the top, buildings constructed between 1926 and 1935 in the center and buildings constructed between 1936 and 1945 at the bottom. The average when including all buildings in each time period is visualized with a dotted line.
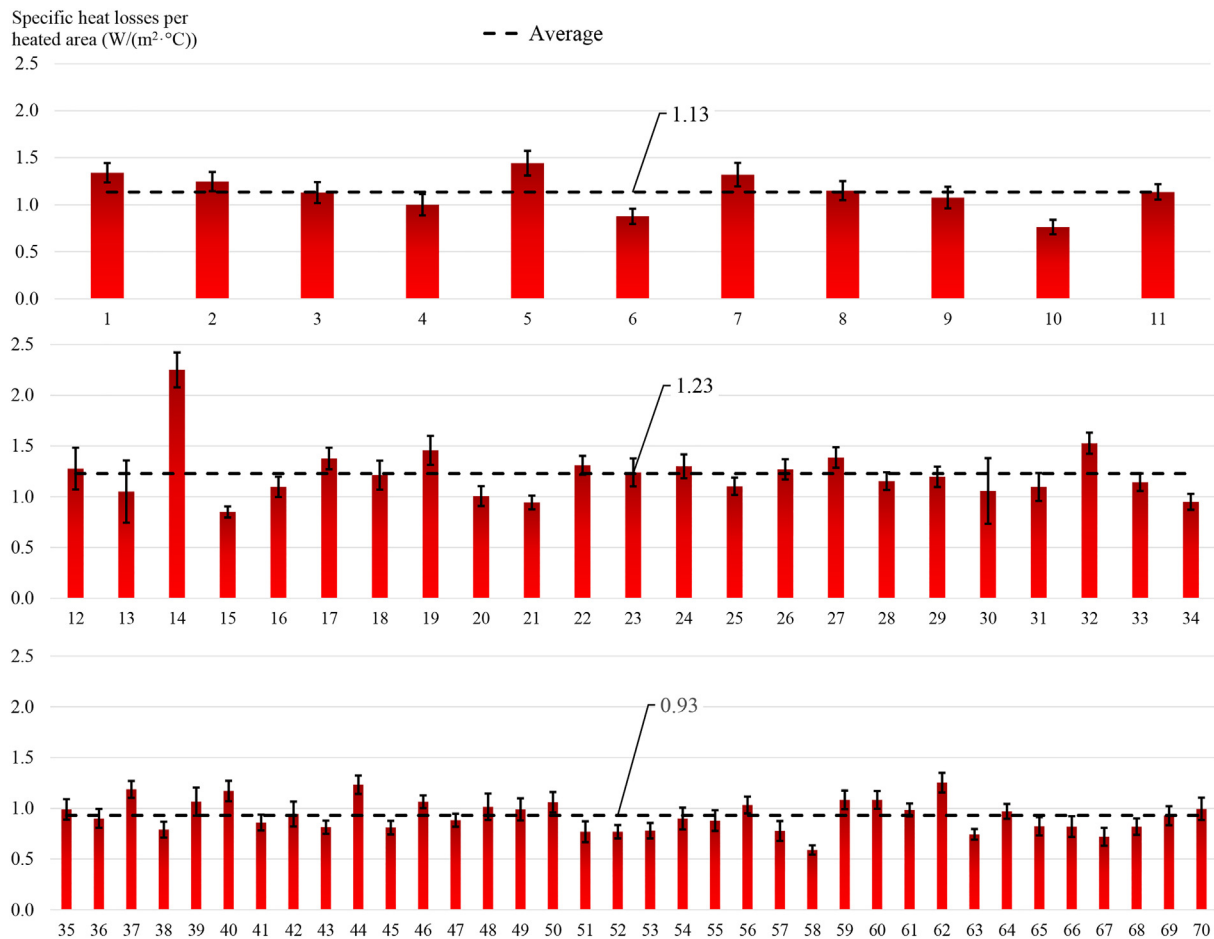
Fig. 11. Specific heat losses per heated area based on calculations for 2014, 2015 and 2016. Buildings constructed between 1908 and 1925 are presented at the top, buildings constructed between 1926 and 1935 in the center, and buildings constructed between 1936 and 1945 at the bottom. The average when including all buildings in each time period is visualized with a dotted line, and each error bar represents the standard deviation.

connected to e.g. a malfunctioning heating system or uncommon user behavior. An example of deviating trends in the data identified by analyzing quantified balance temperatures includes balance temperatures higher than 21 °C in *B*53 and *B*70 when using heating power supply data during 2014. Analysis of previously quantified thermal power characteristics shows that this is the result of unreasonable energy use for HWC in the two buildings: 155 kWh/m^2 and 180 kWh/m^2 in *B*55 and *B*73 respectively.

5.2. Sensitivity analysis

The sensitivity analysis in this research will be performed based on the set assumptions made in the change-point model. Since the energy use for HWC is first predicted in the numerical procedure and is then used as an input for other numerical procedures, it is important to demonstrate that the predicted energy use for HWC can be performed with a high degree of reliability using the proposed methodology. As mentioned in 3.2, the energy use for HWC is calculated as the four lowest hourly averages of heating power supply to the building during July. Two examples (*B*1 and *B*69) of the average hourly energy use ranked from the hour with the lowest average to the hour with the highest average can be seen in Fig. 14, using DH data for July 2016. The 24 hourly averages are divided into six four-hour steps for differentiation purposes in terms of varying hourly heating power supply. An in-depth analysis of the average hourly energy use during July, and for 2015 and 2016, for the other buildings in the district shows that the overall

trends are very similar to those presented in Fig. 14, i.e., a stable baseload that occurs for approximately four to five hours corresponding to the lowest hourly averages. In fact, the percentage differences between the lowest hourly average and the fourth lowest average are 53% and 5% for *B*1 and *B*69 respectively. However, the corresponding comparison for *B*1 and *B*69 between the lowest and sixth lowest hourly average gives a difference of 260% and 22%, which is most likely the result of energy use for HTW. When considering the entire district and the difference between the fourth, fifth and sixth lowest averages compared to the lowest hourly average, the average percentage difference are 19%, 28% and 40% respectively. These findings clearly indicate that the baseload of a building can largely be identified by selecting the four hours with the lowest averages, which is also in accordance with the results from de Santiago et al. [26].

The impact of which months are used to calculate specific heat losses (January and February by default in the proposed methodology) is shown in Fig. 15, presented in W/(m^2 · °C) based on the average figures for 2014, 2015 and 2016. The trends are the same for all buildings, and in order to show monthly differences, a limited number of buildings are presented (buildings built between 1908 and 1925). The predicted heat losses are stable to a high degree when using heat supply data and outdoor temperatures during January and February, as well as during December. However, the calculated heat losses are noticeably lower during March (14%) compared to the average when using figures for December, January and February. Deeper investigations show that the trend
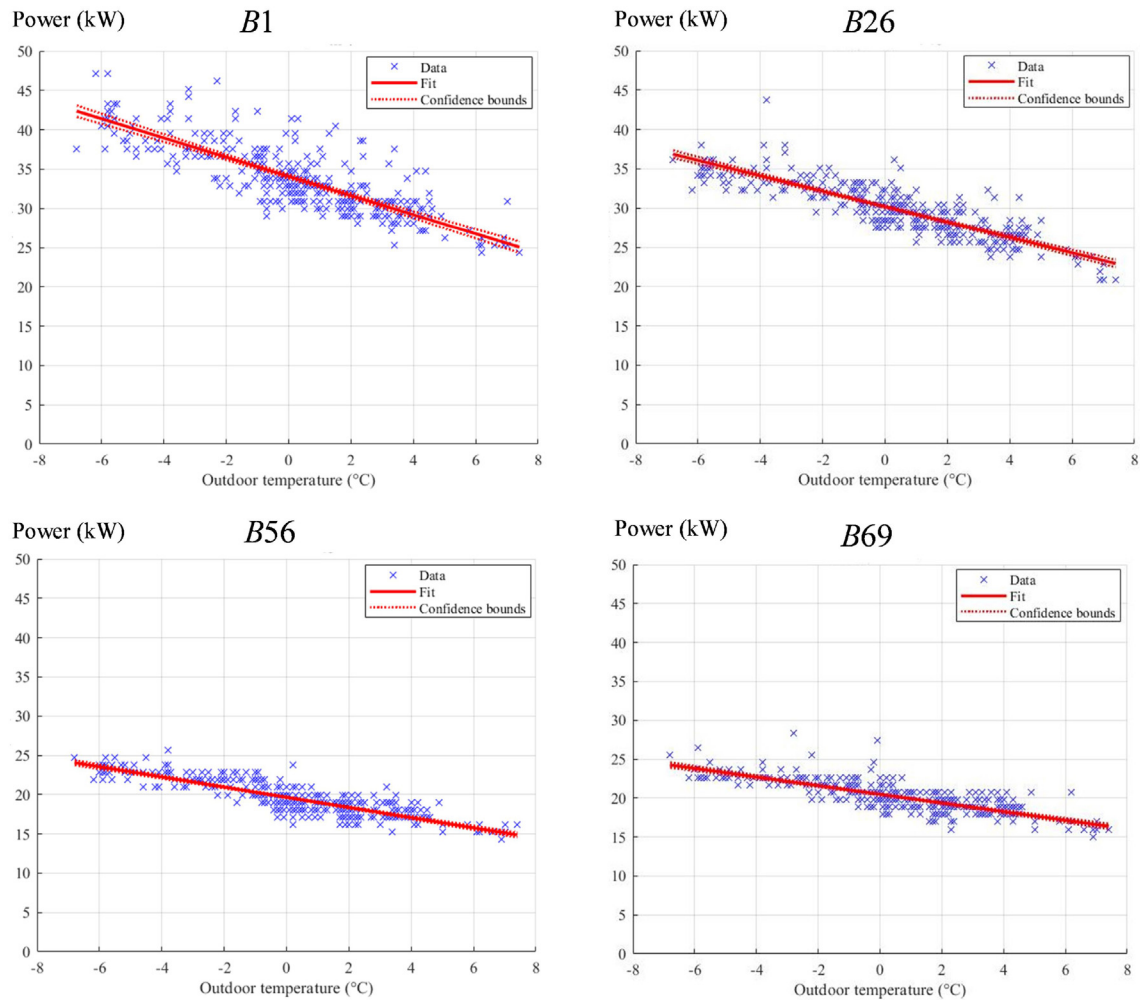
Fig. 12. Four examples of linear regression of the heat supply as a function of outdoor temperature given by the data points, and 95% confidence bound on the regression line.

of lower specific heat losses is enhanced when including April in the analysis. This can be explained by the building thermal inertia and higher solar gains during March and April, compared to December, January and February. Higher solar irradiance results in higher solar gains entering the building and consequently more heat stored in the building structure which can be emitted during the night when the outdoor temperature decreases. Hence, there is a lower need for heating power supply in order to keep the indoor temperature at a fixed level. Moreover, when investigating the coefficient of determination, it is concluded that using January and February results in good predictions of the heating power supply at a certain outdoor temperature. In fact, R^2 is calculated at 0.70 for January–February, 0.70 for December–January and 0.44 for February–March considering the entire district. This shows a rather high R^2 during the selected months, as well as when using December and January in the numerical procedure. Consequently, it is possible to consider other time steps other the ones used in *DTPC* with an acceptable prediction accuracy of the specific heat losses. It is important to be aware of this, especially when investigating districts in other countries with different patterns in terms of outdoor temperature and user behavior.

Another important input for investigating and showing the reliability in terms of the predictions of specific heat losses is the selected time period during the night, i.e., 00:00–05:00. In order to exclude as much energy use for HTW as possible in the numerical procedure for predicting the specific heat losses, it is important

to only consider time periods during the night when the effects of residents' behavior on the prediction are negligible. Hence, differences in measured heating power supply can largely be explained by differences in outdoor temperature. In terms of selected time periods for Q_{total}, the authors have studied the impact on R^2 of using hours before midnight, as well as time periods after 05:00. These time periods are more likely to be characterized by higher amounts of energy use for HTW, which is confirmed by the results presented in Fig. 16. The time intervals included in the numerical procedure are shown on the *x*-axis and the calculated R^2 value on the *y*-axis. The results show a significantly higher R^2 during the time interval used in *DTPC* (00:00–05:00), varying between 0.68 and 0.74, compared to when using time steps before midnight and after 05:00. It is important to note that the specific heat losses are higher when including time steps before 00:00 and after 05:00. Moreover, by including the entire time interval between 00:00 and 05:00, a sufficient number of time steps are used for the predictions of specific heat losses – a total of 354 time steps when considering both January and February during a non-leap year.

The last model input that is investigated is the effect of varying assumptions concerning set indoor temperature and internal heat gains on the predictions of Q_{total} and the balance temperature. This is visualized in Fig. 17, with the average specific heat losses (presented in W/(m^2 · °C)) to the left and the average balance temperature to the right when using a set indoor temperature between 19 °C and 23 °C with a step resolution of one degree. The conse-
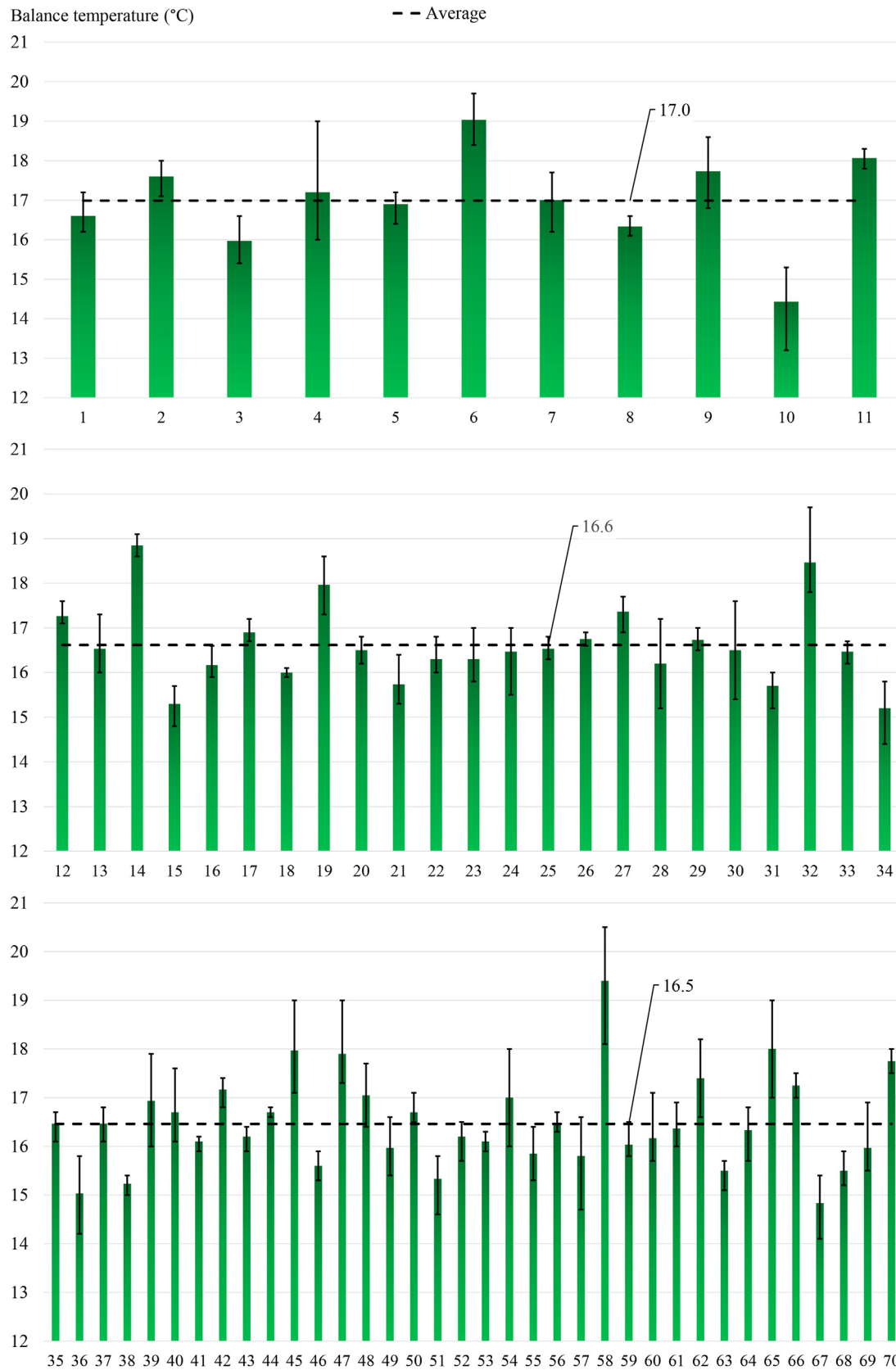
Fig. 13. Calculated balance temperatures. Buildings constructed between 1908 and 1925 are presented at the top, buildings constructed between 1926 and 1935 in the center, and buildings constructed between 1936 and 1945 at the bottom. The average when including all buildings in each time period is visualized with a dotted line, and each error bar represents the maximum and minimum balance temperatures calculated for each building.
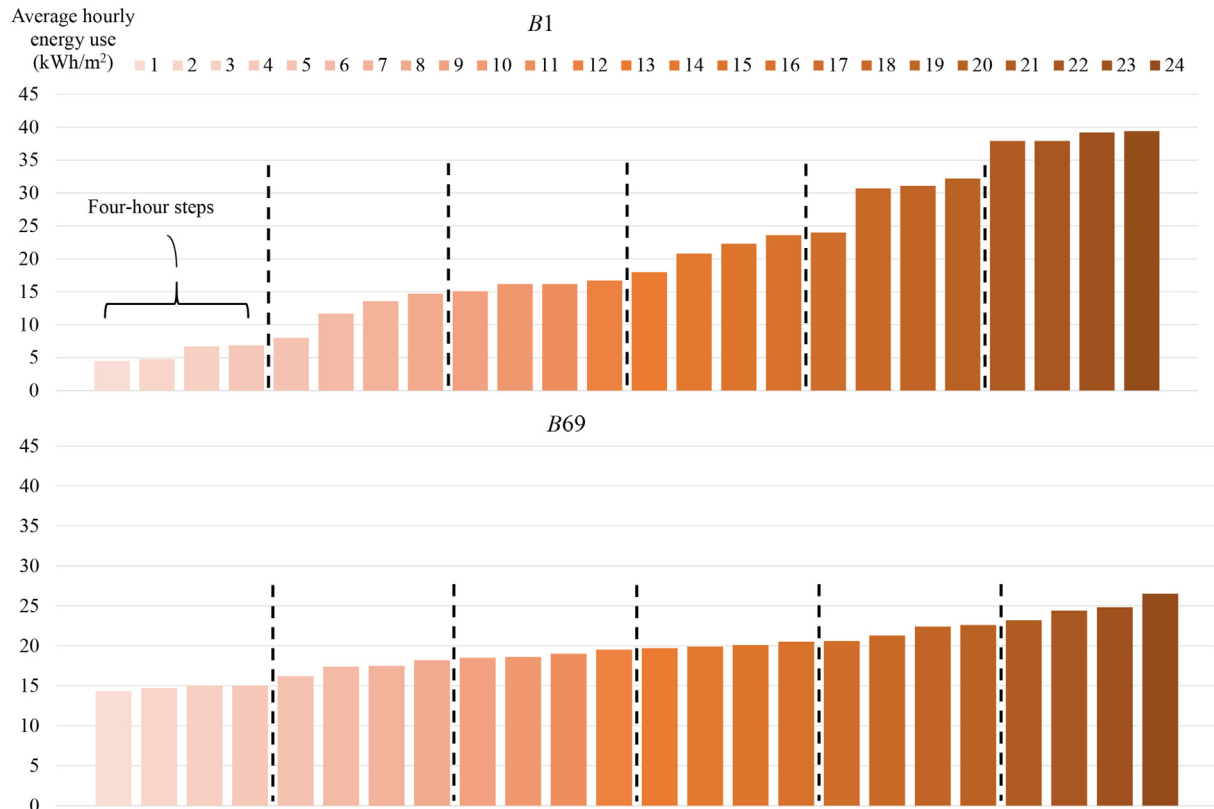
Average hourly
energy use
(kWh/m²) ■1 ■2 ■3 ■4 ■5 ■6 ■7 ■8 ■9 ■10 ■11 ■12 ■13 ■14 ■15 ■16 ■17 ■18 ■19 ■20 ■21 ■22 ■23 ■24

Fig. 14. Specific average energy use during July 2016 for B1 and B69 from the hour with the lowest average to the hour with the highest average.
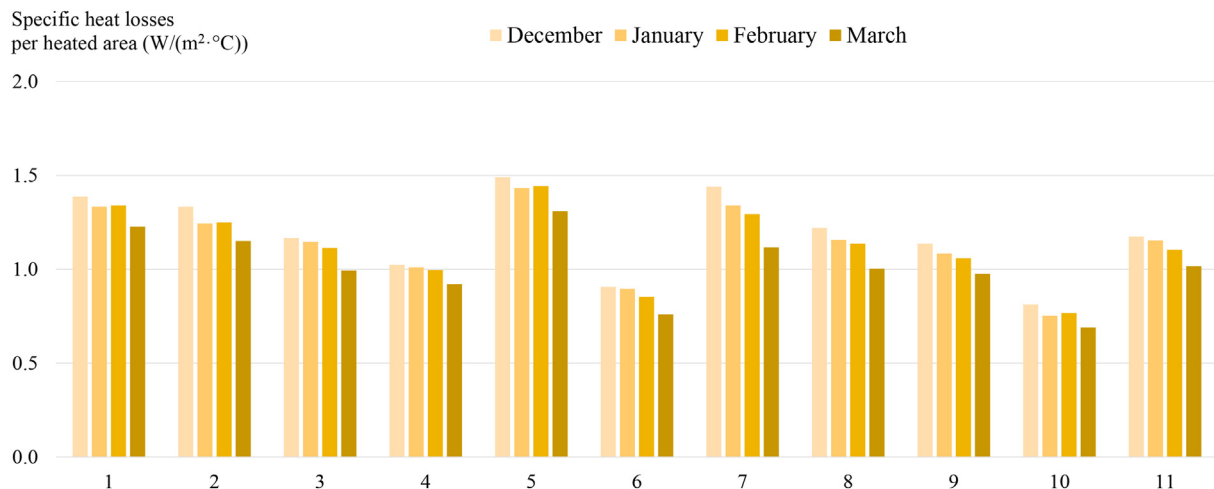
Specific heat losses
per heated area (W/(m²·°C)) ■ December ■ January ■ February ■ March

Fig. 15. Calculated specific heat losses per heated area when selecting December, January, February or March during the time period 00:00–05:00.

quence of variation in internal heat gains of ± 30% from the default of 4.4 W/m² is included with a step resolution of 10%. The data points in Fig. 17 are connected only for visualization purposes. Based on the aforementioned conditions in Fig. 17, the specific heat losses vary between 0.91 and 1.21 W/(m² □ °C) and the balance temperature between 14.7 °C and 18.7 °C. As can be observed in the figure, the heat losses decrease with a higher indoor temperature. This is a result of the power supplied to a building being able to maintain a higher indoor temperature but with the same amount of heating power supply, see Eq. (2). It can also be seen that higher internal heat gains result in a higher predicted heat loss factor. The heat gains contribute to indirect heating and therefore

help keep the indoor temperature at a fixed level. Concerning prediction of the balance temperature, higher indoor temperature corresponds to a higher balance temperature and more internal heat gains results in a lower balance temperature. The difference between maintaining an indoor temperature of 19 °C or 23 °C is on average 2.4 °C in predicted balance temperature, and the difference between 30% higher internal heat gains compared to 30% lower gains is on average 1.5 °C in predicted balance temperature.

The results presented in this section show the significance of assessing different assumptions related to the input data. Therefore, the use of a sensitivity analysis is a key feature of the *DTPC* model. When investigating other districts, it is necessary to per-
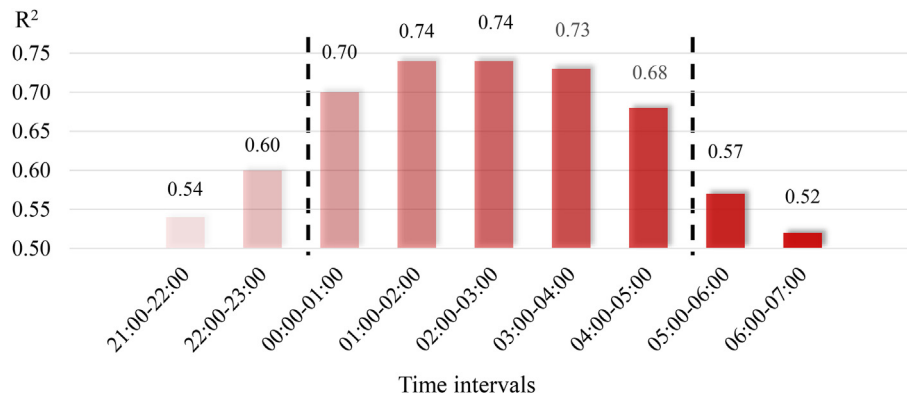
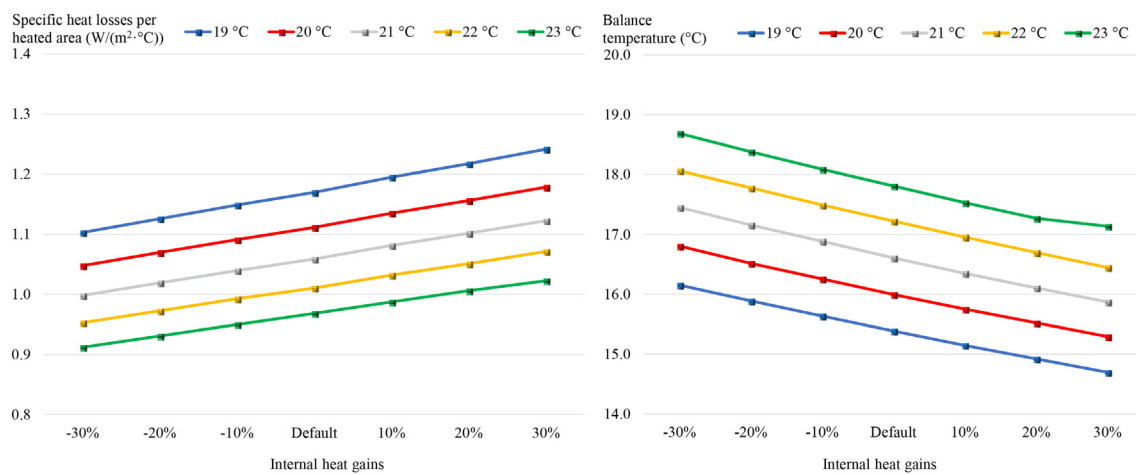**Fig. 16.** R^2 values depending on time intervals used when calculating Q_{total}.

Fig. 17. Specific heat losses per heated area (to the left) and balance temperature (to the right) with varying assumptions regarding indoor temperature and internal heat gains. The data points are connected only for visualization purposes.

form a similar sensitivity analysis in order to identify suitable time periods for the numerical procedure.

6. Conclusion

The thermal performance of buildings is often given as specific energy use (kWh/m²) annually. This metric is highly dependent on factors such as user behavior, as has been stated in numerous scientific investigations. Hence, using specific energy use to compare the thermal status of different buildings is often not appropriate. However, by using change-point models it is possible to describe the actual power demand of a building as a function of outdoor temperature. Consequently, this enables an assessment to be carried out of the building's technical performance. This paper presents a novel change-point model, titled *DTPC*, which has been developed using selected time periods based on time-dependent variations in climate and user behavior to predict building thermal power characteristics. The model is first and foremost adapted for investigating building districts due to the exclusive use of district heating data, which consists of space heating, HTW use and HWC, and there is no need for data describing the user behavior in the building. Seventy-three historic buildings located in the district of Vasastaden in Linköping, Sweden, are used as the study object.

The results show that the *DTPC* model is an effective way to describe a building's thermal performance. This is because the model provides additional information compared to specific

energy use (kWh/m²) as reported in GRIPEN [5]. This information can be used by housing companies to get an overview of the thermal performance of buildings in a district. In addition, it is shown that by using *DTPC*, buildings with deviating thermal performance are easily identified in a district. The robustness of the algorithm is satisfactory based on a comparison of quantified building thermal power characteristics using three years of hourly DH data: 2014, 2015 and 2016. It is found that, overall, predictions of building thermal power characteristics are independent of which year's DH data is used with the exception of energy use for HTW. The observed variations in the energy use for HTW can be attributed to user behavior and are a dynamic building characteristic. Concerning energy use for HWC, an in-depth analysis of the average hourly energy use during July shows that the baseload occurs for approximately four to five hours, demonstrating a suitable selection of the time steps included in the *DTPC* model. Based on the preset model assumptions in terms of internal heat gains and set indoor temperature, the average specific heat loss for the district is 1.06 W/(m² ∘ °C), with generally low volatility in the data. The average standard deviation is less than 0.11 W/(m² ∘ °C) for the building district. Quantifying the R^2 value shows that the selected time period for predictions of the specific heat losses, i.e., night time between 00:00–05:00, correspond to an average R^2 value of 0.70 for the district. When including time steps before 00:00 or after 05:00, it is concluded that the dependency from outdoor temperature on heat power supply is decreased, which is shown by a significantly lower R^2 as well as higher specific heat losses. This

can be attributed to occupants waking up in the morning and using energy for HTW, for example. Predictions of the balance temperature show that, using heating power supply data from three different years, the average variation width is 0.9 °C for the buildings in the interquartile range. In the district 84% of the buildings have a variation width equal to or less than 2.0 °C. Since predicting the balance temperature is the final step in the prediction process, this shows that *DTPC* is largely independent of which year of heating power supply data was used.

The key potentialities of the *DTPC* model lays on the possibility for a time-effective description of the thermal power characteristics of buildings in a residential district using only heating supply data and outdoor temperature. In addition, the model allows for a differentiation between the thermal power characteristics related to the building's technical performance and the HTW use. This means that buildings may be ranked depending on energy savings potential based on actual technical performance. Hence, the advantages with *DTPC* allow for the model to be useful for decision-making in large-scale energy renovation. In any event, it is important to be aware of the limitations with the model. Since the model is developed for districts in a Northern European climate, the current version of *DTPC* is limited to buildings with only heating supply and no comfort cooling. In addition, the model is limited to analysis of residential buildings. Further development of the model will include differentiation between transmission losses and ventilation and infiltration losses from Q_{total}. This may be performed by searching for patterns in the heating supply data related to the correlation between wind speed data and heat losses. In addition, it is possible to develop the model for investigation of districts consisting of different building types, such as office buildings and schools. In this case, it is likely necessary to include an additional parameter for space cooling in the change-point model since these buildings often have comfort cooling.

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.

Acknowledgements

References

[1] International Energy Agency, Transition to Sustainable Buildings. Strategies and Opportunities to 2050. ISBN: 978-92-64-20241-2, 2013.
[2] European Parliament, "The Energy Efficiency Directive (2012/27/EU)", 2012.
[3] M. Santamouris, Cooling the buildings – past, present and future, Energy Build. 128 (2016) 617–638.
[4] Boverket, "Energi i bebyggelsen – tekniska egenskaper och beräkningar – resultat från projektet BETSI", ISBN: 978-91-86559-83-0, 2010
[5] National Board of Housing, Building and Planning, National Energy Audit Program for Buildings (GRIPEN).
[6] S. Hammarsten, A Critical Appraisal of Energy-Signature Models, Appl. Energy 26 (1987) 97–110.
[7] CARRIER, A United Design Technologies Company, "System Design Manual".
[8] BELOK, "Energy efficient tap water systems in facilities (in Swedish)", 2017.
[9] BEBO, "Audit of heat losses from hot water circulation in residential buildings-measurements in 12 residential buildings (in Swedish)", 2015.
[10] F. Philip and P. Danny, "A review of hot water draw profiles used in performanceanalysis of residential domestic hot water systems. FSEC-RR-56-04 ", Florida Solar Energy Center, 2004.
[11] Sveby. User input housing facilities. Available: http://www.sveby.org/wp-content/uploads/2012/10/Sveby_Brukarindata_bostader_version_1.0.pdf (in Swedish) (Last accessed: 2020, November 27).
[12] ASHRAE, "ASHRAE GUIDELINE- Measurement of Energy and Demand Savings", 2002.
[13] D. Claridge, J. Haberl, R. Sparks, R. Lopez, K. Kissock, Monitored Commercial Building Energy Data: Reporting the Results, presented at the ASHRAE Transactions Symposium Paper, 1992.
[14] J. Vesterberg, S. Andersson, T. Olofsson, Robustness of a regression approach, aimed for calibration of whole building energy simulation tools, Energy Build. 81 (2014) 430–434.
[15] K.H. Kim, J.S. Haberl, Development of a home energy audit methodology for determining energy and cost efficient measures using an easy-to-use simulation: Test results from single-family houses in Texas, USA, Build. Simul. 9 (2016) 617–628.
[16] R. Hitchin, Monthly utilisation factors for building energy calculations, Build. Serv. Eng. Res. Technol. 38 (2017) 318–326.
[17] D. Farmer, D. Johnston, D. Miles-Shenton, Obtaining the heat loss coefficient of a dwelling using its heating system (integrated coheating), Energy Build. 117 (2016) 1–10.
[18] J.-U. Sjögren, S. Andersson, T. Oloffson, An approach to evaluate the energy performance of buildings based on incomplete monthly data, Energy Build. 39 (2007) 945–953.
[19] J.S. Park, S.J. Lee, K.H. Kim, K.W. Kwon, J.-W. Jeong, Estimating thermal performance and energy saving potential of residential buildings using utility bills, Energy Build. 110 (2016) 23–30.
[20] J.-U. Sjögren, S. Andersson, T. Oloffson, Sensitivity of the total heat loss coefficient determined by the energy signature approach to different time periods and gained energy, Energy Build. 41 (2009) 801–808.
[21] Q. Meng, M. Mourshed, Degree-day based non-domestic building energy analytics and modelling should use building and type specific base temperatures, Energy Build. 155 (2017) 260–268.
[22] B. Arregi, R. Garay, "Regression analysis of the energy consumption of tertiary buildings", presented at the CISBAT 2017 International Conference – Future Buildings & Districts – Energy Efficiency from Nano to Urban Scale, Lausanne, Switzerland, 2017.
[23] Statistics Sweden (SCB). Persons absent from work aged 15-74 (LFS)/hours of absence during the reference week by reason for absence, sex and age. Available: http://www.statistikdatabasen.scb.se/pxweb/en/ssd/START__AM__AM0401__AM0401K/NAKUFranvOrsakM/?rxid=471f3e0a-e639-4735-b0aa-3af776a1e209 (Last accessed: 2019, April 4).
[24] J. Widén, M. Lundh, I. Vassileva, E. Dahlquist, K. Ellegård, E. Wäckelgård, Constructing load profiles for household electricity and hot water from time-usedata—Modelling approach and validation, Energy Build. 41 (2009) 753–768.
[25] European Commitee For Standardization, "EN 12831-3. Energy performance of buildings - Method for calculation of the design heat load - Part 3: Domestic hot water systems heat load and characterisation of needs", 2017.
[26] J. de Santiago, O. Rodriguez-Villalón, B. Sicre, The generation of domestic hot water load profiles in Swiss residential buildings through statistical prediction, Energy Build. 141 (2017) 341–348.
[27] Public Health Agency of Sweden, "Common Advice About Indoor Tempeatures. FoHMFS 2014:17", 2014 (in Swedish).
[28] Statistics Sweden. Average living area per person depending on region, residential type and living form. Available: http://www.statistikdatabasen.scb.se/pxweb/sv/ssd/START__HE__HE0111/HushallT23/?rxid=8f159a66-e78c-434a-854a-73965f712f46 (in Swedish) (Last accessed: 2020, February 7).