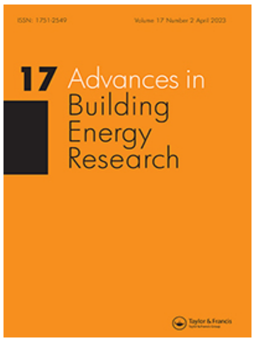

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Screening of thermal characteristics and assessment of comparative energy efficiency potential in a residential district

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ABSTRACT

By identifying buildings with poor thermal performance and prioritizing these in terms of energy efficiency potential, a sustainable transformation of the building stock may be accelerated. However, there is currently a lack of thermal characteristics (TCs) differentiating total energy use from hot water circulation (HWC), hot tap water (HTW) and space heating in large building portfolios. This research demonstrates a methodology based on a change-point model for identifying and prioritizing TCs, which also enables prediction of the Comparative Energy Efficiency Potential (CEEP). The change-point model allows for the differentiation of various processes, i.e. space heating, HWC and HTW, using only heating supply data and outdoor temperature. The studied district consists of 70 multi-family buildings in the Vasastaden district in Linköping, Sweden. The findings demonstrate that the proposed methodology allows for identifying and prioritizing TCs connected to HWC, HTW and space heating. The highest CEEP is in space heating, corresponding to a maximum of 2,016 MWh (16% of the district's energy use), followed by HWC, 699 MWh (6% of the district's energy use) and HTW, 520 MWh (4% of the district's energy use). Consequently, a total decrease of 3,235 MWh (26%) is made possible according to the studied energy efficiency targets.

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KEYWORDS
Thermal characteristics; Change-point model; Residential district; Building energy efficiency; Comparative energy efficiency potential

HIGHLIGHTS

- A methodology for the prediction of the Comparative Energy Efficiency Potential (CEEP) in a building portfolio based on the identification and prioritization of TCs is proposed
- The study is enabled by the use of a unique change-point model (*DTPC*) for differentiating TCs solely from digital heating supply data and outdoor temperature
- 70 multi-family buildings (total heated area of 121,692 m^2) in the Vasastaden district in Linköping, Sweden, are investigated
- The methodology is successful in identifying and prioritizing TCs related to HWC, HTW and space heating

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- The highest CEEP is in space heating calculated at a maximum of 2016 MWh, which corresponds to 16% of the district's total energy use

Nomenclature

E	Energy (Wh)
P	Hourly heating power supply (W)
$Q_{infiltration}$	Infiltration losses (W/°C)
Q_{total}	Total specific heat losses (W/°C)
$Q_{transmission}$	Transmission losses (W/°C)
$Q_{ventilation}$	Ventilation losses (W/°C)
T_b	Balance temperature (°C)
T_{in}	Indoor temperature (°C)
T_{out}	Outdoor temperature (°C)
ψ	Degree hours (°C·h)

List of abbreviations

CEEP	Comparative Energy Efficiency Potential
DTPC	Differentiating Thermal Power Characteristics
HTW	Hot tap water
HWC	Hot water circulation
TC	Thermal characteristics

1. Introduction

This section first describes the background to the research field. Then the objective and novelty of the research are presented.

1.1. Background

An important part in the quest for a highly energy-efficient and decarbonized building stock in the amended Energy Performance of Buildings Directive (EPBD) (2018/844/EU) (European Parliament, 2018) is decreased energy use in residential buildings. This applies in particular to heat supply for buildings located in Northern European countries since it is often highly resource-demanding due to a cold climate and a long heating period, as well as the fact that comfort cooling is still uncommon in residential buildings. In Sweden, the national renovation strategy emphasizes that many multi-family buildings have been overlooked in terms of maintenance and are, therefore, in need of renovation (The Swedish Government, 2019). As a foundation in the quest to improve the thermal status in multi-family buildings, it is important to have good knowledge of the status of the building stock and how it is used. The importance of understanding the thermal performance in a larger number of buildings to increase the rate of energy renovation is highlighted by Dall'O' et al. (2012).

To allow for an energy-efficient transformation of the building stock and minimize climate impact, it is important to identify and prioritize buildings with poor thermal performance. Moreover, there is a need to target thermal characteristics (TCs), such as space heating, with the highest energy efficiency potential to allow for a sustainable transformation of the built environment.

In order to allow for a time-effective investigation for prioritizing buildings in terms of the need for energy renovation, a computational approach is required. In addition, to map the thermal performance of a large number of buildings it is possible to process the heating power supply data, which allows for differentiation of various TCs. In Sweden, existing values of performance indicators, e.g. kWh/(m^2·year), are gathered in databases such as in the Swedish energy declaration register GRIPEN, which includes around 600,000 buildings (National Board of Housing, Building and Planning). Even though this type of overall data is interesting and an important piece of the puzzle in the work of determining building thermal status, it does not say anything explicit about the proportion that is related to total specific heat losses (Q_{total}) from transmission, ventilation and infiltration losses, hot water circulation (HWC) and energy use for hot tap water (HTW), or how occupants use the buildings, i.e. what internal heat gains arise from e.g. electrical appliances and human occupancy. One computational approach to solve this problem includes the use of change-point models, i.e. describing the building's thermal performance from a number of points, for example, Q_{total}, HWC and HTW, based on digital heating power supply data along with outdoor temperature. Hence, the main advantages of using change-point modelling include time-effective calculations of numerous TCs describing the thermal performance in buildings, as well as to investigate the effects from energy renovation measures (Claridge et al. 1992). Consequently, prioritization of buildings in terms of energy efficiency potential is made possible, which in turn can promote energy renovation. Nonetheless, it is important to be aware of other factors affecting energy renovation, such as profitability and environmental performance in terms of primary energy use and greenhouse gas emissions.

Several scientific studies have previously investigated residential districts with a focus on calculating thermal performance and energy efficiency potential. De Rubeis et al. (2021) highlighted the time-consuming effort to collect input data for analysis of energy performance and energy efficiency potential in a building portfolio. The study was based on 769 residential buildings in Central Italy using a bottom-up energy modelling tool. Nonetheless, it is stated that the increasing availability of data provides a beneficial outlook for these types of analysis in the future. Al Tarhouni et al. (2019) demonstrated how machine learning can be used to prioritize energy efficiency measures in a building portfolio of 139 residential buildings in the U.S. Midwest. Data in the form of geometrical and thermal characteristics, e.g. heated area, insulation thickness of building elements, types of windows and monthly energy use, were used. It was concluded that the approach allows for quantification of energy savings from various energy efficiency upgrades in the studied buildings, which include, among others, the replacement of windows and additional insulation of the external walls. Based on 36 archetype residential buildings in Austria, Heidenthaler et al. (2022) showed that it is possible to differentiate the studied buildings with regards to thermal performance and assess the energy efficiency potential. The archetype buildings varied in terms of the construction period, building condition and building type (single-family house or multi-family building) and were developed using energy performance certificates for 22,605 buildings. Also, using archetype residential buildings based on energy certificates, Mac Uidhir et al. (2020) investigated the energy savings potential in the Irish building stock. Building energy simulation was used to quantify the effects of various energy renovation measures, such as insulation of the attic and external walls. The study emphasized the consideration of the original thermal performance for better energy renovation strategies. In addition, it was shown that optimal energy renovation strategies differ by archetype building. This is in line with the results by Mattinen et al. who pointed out the variation in building thermal performance of 700 residential buildings in the Kaukajärvi district located in Tampere, Finland. These findings can be useful to identify hot spots in buildings portfolios, as well as for prioritization of buildings for energy renovation. The calculations were performed using quasi-steady state calculation according to EN ISO 13790. Examples of using change-point models for differentiating buildings' thermal performance also exist in the scientific literature. For example, Park et al. (2016) investigated 128 apartment complexes consisting of 52,731 housing units in Seoul, South Korea, with regard to thermal performance and energy savings potential. Input data included electricity used for electrical appliances and heating data, as well as building physical characteristic. The results showed that change-point modelling can be used for differentiating building in terms of thermal performance. Measures decreasing space heating corresponded to the highest energy efficiency potential. The possibilities of differentiating buildings with regards to thermal performance, i.e. specific heat losses, using change-point modelling were also demonstrated by Sjögren et al. (2007). More than 100 multi-family buildings constructed from 1900 to 1995 in Sweden were used as the study object. Sjögren et al. (2007) also stated that average consumption profiles for household electricity could successfully be used in rather large buildings during predictions of specific heat losses.

1.2. Contribution of the research

Researchers have applied change-point models to quantify the thermal performance of buildings in different types of contexts, such as before and after energy renovation (Park et al., 2016; Eriksson et al., 2020; Kim and Haberl, 2016). However, to the best of the authors' knowledge, there has been no analysis on using change-point models to identify and prioritize buildings with a need for energy renovation by using quantified TCs describing thermal performance from heating supply data, which consists of HWC, HTW and space heating. To illuminate the abovementioned unexplored field of research, the contribution of this paper is to develop a methodology to identify and prioritize TCs, as well as to assess the Comparative Energy Efficiency Potential (CEEP) in a residential district. This is fulfilled by the differentiation of TCs, which is allowed by the use of a proven, robust change-point model, titled *DTPC* (Differentiating Thermal Power Characteristics) (Milić et al., 2021). The change-point model allows for prediction of Q_{total}, P (HWC), P (HTW) and T_{b}, using digital heating supply data together with outdoor temperature data. Hence, there is no need for time-consuming collection of data connected to occupant behaviour. The key strength of the *DTPC* model is the use of selected time periods on the basis of dynamic patterns in occupant behaviour and climate. This means that the model allows for time-effective prediction of TCs in entire building districts and can consequently be used by authorities, as a tool for identifying and prioritizing buildings with poor thermal performance based on the actual building technical performance. Moreover, predictions of the CEEP related to different

TCs are allowed by predetermined energy efficiency targets based on the original performance in the studied building portfolio.

The novelty of the proposed research is to identify and prioritize TCs in a building district by differentiating TCs solely from digital heating supply data consisting of HWC, HTW and space heating. This is performed by using a proven, robust change-point model that considers dynamic patterns in occupant behaviour and climate in the algorithmic method (Milić et al., 2021). With the ongoing transformation of the building stock in both the EU and Sweden, and higher availability of heating supply data, change-point models are an increasingly important tool in mapping building TCs in a time-effective manner. Vasastaden, a residential district located in Linköping, Sweden, consisting of 70 multi-family buildings built between 1908 and 1945 is investigated in this research.

2. Theory

The following section presents the building thermal characteristics (TCs) that are of interest to this research. This is followed by a description of different types of change-point models, along with an overview of change-point models used in research studies.

2.1. Building thermal characteristics

By differentiating TCs from heating supply data, it is possible to generate a clearer picture of a building's thermal performance. In a Northern European climate, the energy use of a building depends on the HWC, HTW, specific heat losses (Q_{total}) and balance temperature.

The HWC is part of the building baseload and provides a rapid flow of domestic hot water at plumbing fixtures. HWC recirculation systems have an issue with heat losses occurring in pipes. These heat losses vary depending on the piping design. There are estimates of the energy use for HWC, but they vary greatly. As an example, an investigation performed by the Swedish Energy Agency (SEA) with 12 residential buildings stated HWC energy use between 2.3 and 28 kWh/(m^2·year) (BEBO, 2015). Similar figures, from 4 kWh/(m^2·year) to 25 kWh/(m^2·year), were found in a collaboration project between the largest residential property owners in Sweden and SEA (BELOK, 2017).

The energy use for HTW is connected to the behaviour of the occupants. Consequently, large variations may exist between different multi-family buildings. Moreover, this means each building's HTW energy use must be calculated separately. In terms of average figures for HTW, a study quantified the HTW energy use at 25 kWh/(m^2·year) based on 1,500 apartments, in Stockholm, Sweden (Sveby, 2020, November 27).

The specific heat loss, Q_{total}, is a mathematical description of building technical performance as a function of outdoor temperature and heating power supply. Hence, by determining Q_{total}, knowledge about a building's technical performance can be generated. Q_{total} includes transmission losses through the building envelope, as well as infiltration and ventilation losses.

A building's balance temperature, T_b, defines the temperature at which the heating system needs to be heated to. This means that the solar gains and internal heat gain amount to the heat losses from transmission, ventilation and infiltration. During these time periods, there is no need for additional heating of the building.

2.2. Description of change-point models

Using a change-point model, a description of a building's power demand in relation to the outdoor temperature is made possible. Linear regression is commonly applied to calculate the number of points that is directly dependent on the building energy balance. Standards for designing change-point models for building energy systems of different types have been established by ASHRAE (2002). A summary of these standards can be seen in Table 1.

The most common change-point models in residential buildings located in a cold climate as in Northern Europe are those with three points, with heating energy use required for space heating, HWC and HTW. It is important to be aware of that a quantification of these TCs are more descriptive with regards to building thermal performance compared solely data about energy use. Hence, change-point models allow for a better characterization of a building's thermal performance. A change-point model can be seen in Figure 1 with the energy use for HWC and HTW described by the baseload.

Since Q_{total} is a measure of a building's performance based on heat losses from transmission, ventilation, and infiltration, the effects of being able to quantify it are important. Hence, calculations of Q_{total} together with the building balance temperature allow for an assessment of the technical performance of the buildings, which is a key feature with change-point model. Then, using the actual outdoor temperature for the location, the energy use of a building (excluding the energy use for HWC and HTW) based on the actual technical performance can be formulated according to Equation (1).

$$E = \mathrm{Q}_{\mathrm{total}} \cdot \psi = (\mathrm{Q}_{\mathrm{transmission}} + \mathrm{Q}_{\mathrm{ventilation}} + \mathrm{Q}_{\mathrm{infiltration}}) \cdot \psi$$

where E corresponds to building energy use (Wh), Q_{total} the heat losses from transmission (i.e. heat losses through windows, roof, floor, external walls and cold bridges), ventilation and infiltration (W/°C) and ψ the degree hours (°C·h). Q_{total} can be divided into heat losses from transmission, $Q_{transmission}$ (W/°C), and the movement of heated air from indoors to outdoors, i.e. ventilation, $Q_{ventilation}$ (W/°C), and infiltration, $Q_{infiltration}$ (W/°C).

Understanding the drawbacks of change-point models for describing building thermal performance is important. This includes, for example, the need for precise data related to heating supply and information about behaviour from occupants. A defective heating system means that the building heating supply data will not accurately describe the thermal performance. Problems connected to occupant behaviour may include airing affecting the heat output and variations in the use of electrical appliances, which

Table 1. Summary of ASHRAE standards for designing change-point models.

Type of change-point model (no. of points)	Building energy system	Characteristics
2	Comfort cooling	Slope and break point
3	Heating	Slope, break point and baseload, which includes HTW and HWC
4	Heating with heat recovery	Corresponding characteristics to the three-point change-point model, but with a slope after the balance temperature
5	Heating and comfort cooling	A baseload, two break points (one for heating and one for cooling) and two slopes

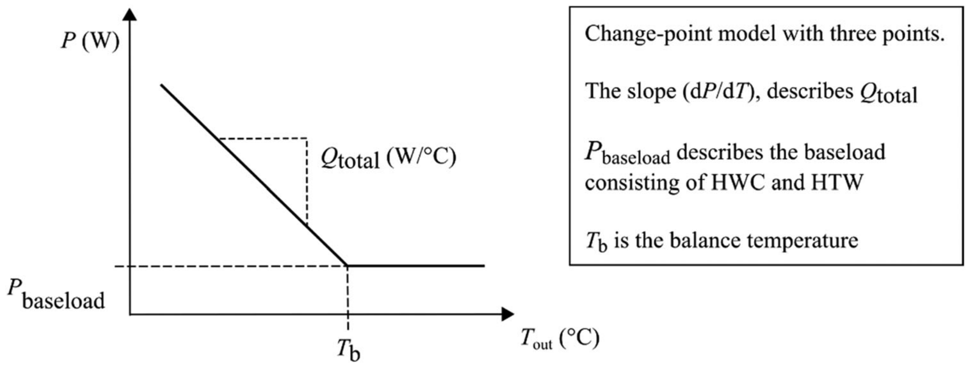

Figure 1. Illustration of a change-point model with three points.

impacts the balance temperature of a building. In light of the time-varying patterns of occupant behaviour and unique occupancy schedules for all buildings, this causes complexity in the development a change-point model with no information about occupant behaviour.

2.3. Overview of change-point models in scientific literature

Hammarsten's study from 1987 (Hammarsten, 1987) is one of the first publications in the research area of change-point models. Hammarsten (1987) described how a change-point model for building technical performance could be designed and studied the effect of different temporal resolutions. The findings demonstrated that a change-point model is appropriate for determining the energy performance of a building. Another early paper on the development of change-point models from actual energy use is the work from Claridge et al. (1992). The findings were in line with the results from Hammarsten (1987). In addition, Claridge et al. (1992) shed light on the possibilities of evaluating efficiency measures with change-point models.

With the recent increase in digital data, there has been increased interest in the potentialities of calculating performance indicators related to building energy performance with the use of change-point models. Some listed research on the potentialities of using change-point models to calculate building energy performance is presented in Table 2. There is a general consensus on the benefits of using change-point models for quantifying thermal power characteristics in a robust manner which can be seen in e.g. (Park et al., 2016; Eriksson et al., 2020; Kim and Haberl, 2016; Farmer et al., 2016; Vesterberg et al., 2014). As an example, Eriksson et al. (2020) highlight the possibilities of deducing more data on building operation from the use of only heating supply data. This view is supported by Sjögren et al. (2009) who questioned the figure kWh/(m^2·year) as an indicator of thermal performance because of the high correlation with internal heat gains. Another interesting conclusion by Sjögren et al. (2009) is that to allow for determining Q_{total} accurately, information describing the use of household electricity use and indoor temperature is required. This was also highlighted in the research by Park et al. (2016). However, Milić et al. (2021) have previously shown the potential to differentiate performance indicators without any data about occupant behaviour by the use of selected time

Table 2. Examples of research on calculating building energy performance with change-point modelling.

Research objective	Case study	Main findings	Reference
Estimate energy savings potential of a residential building stock using change-point modelling	128 representative apartment complexes of the buildings located in Seoul, South Korea, and built between 1971 and 2009	- Allows for quantification of the thermal performance in the building stock - Calculations of optimal efficiency measures made possible	Park et al. (2016)
Study the robustness of method based on linear regression to determine transmission losses above ground	Two multi-family buildings situated in Umeå, Sweden, from 1970/1971 with heated areas around 900 m^2	- Robustness of the method confirmed with specific heat losses varying <2% based on data from two different years - May assist in calibration process of building energy simulation model	Vesterberg et al. (2014)
Develop a change-point model with three points to improve a simulation model using data of building energy use and weather parameters	Three single-family houses located in Texas, USA, built between 1990 and 2002	- More realistic modelling of the thermal performance post-calibration - Assists in determining appropriate energy renovation measures	Kim and Haberl (2016)
Study the impact on Q_{total} from different time periods, as well as heat gains from insolation and internal heat gains, using a change-point model	Nine multi-family buildings situated in Stockholm, Sweden, and built during 1998–2003	- For accurate calculations of Q_{total}, data describing the use of household electricity and indoor temperature levels is needed - kWh/(m^2·year) is questioned as indicator for thermal performance since this is strongly dependent on internal heat gains	Sjögren et al. (2009)
Develop and validate new method to find change-point model with three points	Multi-family building in Gävle, Sweden, from the 1970s with a heated area of 2674 m^2 before energy renovation and 2830 m^2 after	- Possible to deduce more data about building operation from using heating supply data - Good agreement between change-point model and building energy simulation model	Eriksson et al. (2020)
Present methodology for determining heat loss coefficient using linear regression	Three single-family houses with integrated co-heating in the United Kingdom from 2009 to 2012 with heated areas between 90 and 155 m^2	- Enables a more representative view of a building's technical performance in-use - The methodology could be used to identify problems related the heating system	Farmer et al. (2016)

periods on the basis of dynamic patterns in occupant behaviour and climate. It should be noted that this approach will be used in the proposed research.

3. Description of the methodology

The developed methodology includes three steps. In Step *I*, the *DTPC* model is implemented for predictions of performance indicators, which include total specific heat losses (Q_{total}), energy use for HWC and HTW, and balance temperature. This is performed using selected time periods based on time-dependent variations in occupant behaviour and climate. In addition, building energy usage is calculated in this step using the quantified performance indicators. Step *II* consists of identifying and prioritizing TCs for the

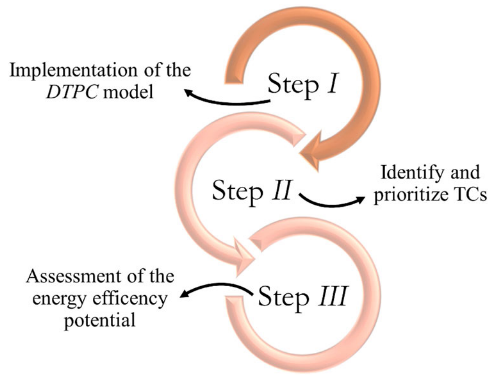

Figure 2. Schematic of the methodology.

buildings. In Step *III*, an assessment of the energy efficiency potential in the residential district is performed. A schematic of the proposed methodology can be seen in Figure 2.

A key feature in the proposed research is the use of the *DTPC* model. Therefore, it should be noted that the robustness of the change-point model has been investigated in a previous study by Milić et al. (2021). The results concluded robust-satisfying algorithm based on a comparison of predicted performance indicators using three different years of data for heating supply.

3.1. Step I – implementation of the DTPC model

In this section, the implementation of the *DTPC* model is presented, which consists of five main parts. A more detailed description of the model can be seen in Milić et al. (2021). Part 1 consists of the collection of heating power supply with hourly resolution for the studied buildings and outdoor temperature during the studied time period. To allow for an assessment of building TCs per m^2, data in terms of heated area is collected from GRIPEN (National Board of Housing, Building and Planning).

In Part 2, specific time periods are selected on the basis of seasonal and daily patterns in climate and occupant behaviour. For example, more space heating is required during months with colder outdoor temperatures compared to months with higher outdoor temperatures. Hence, selection of time periods based on such patterns allows for differentiating and identifying performance indicators without using any information about building occupant behaviour, which is also one of the main advantages of the change-point model. The time periods used for predicting building performance indicators is presented in Figure 3. It should be emphasized that the research presented in Milić et al. (2021) showed a good robustness in the selected time periods, which is also the case for the model assumptions in Part 3. An example of the good robustness is that the average R^2 is 0.70 for predictions of specific heat losses. In addition, a sensitivity analyses concluded that the selected time steps and months correspond to the highest R^2 value.

In Part 3, a number of assumptions are made because only heating power supply data is used in the change-point model. First, there is no comfort cooling in or supplied to the buildings. This is because comfort cooling is unusual in multi-family buildings situated in cold climate. Second, during the quantification of Q_{total}, internal heat gains from residents

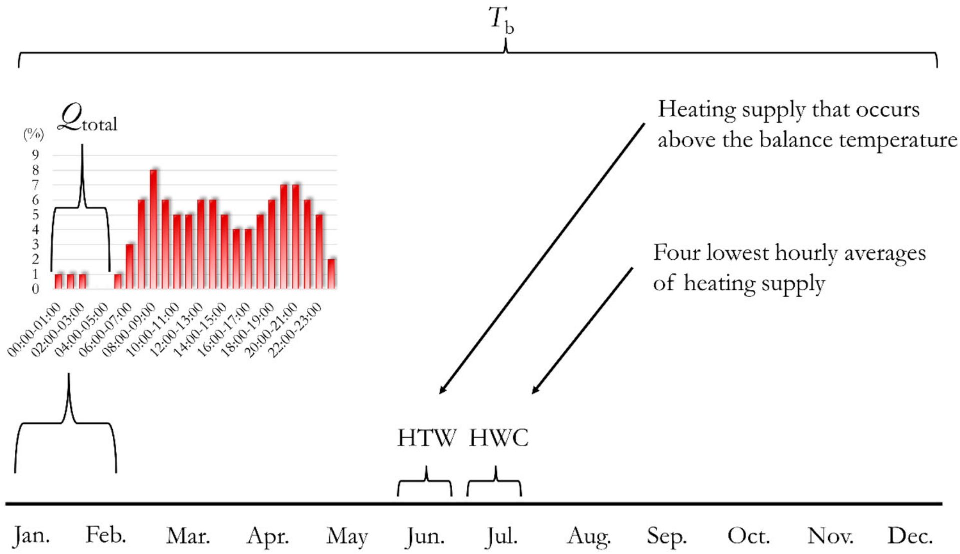

Figure 3. Time periods used for prediction of building performance indicators. Inspired by Milić et al. (2021).

and electrical appliances are considered. Third, it is assumed the building indoor temperature is constant, based on figures from the Public Health Agency of Sweden (2014). Moreover, the model assumptions are necessary for a time-effective analysis of building portfolios without the use of data related to occupant behaviour. Despite that data related to heat gains from occupants are based on occupancy density for the city of Linköping and that internal heat gains from electrical appliances are estimated using figures from the Swedish construction and real estate industry, one should bear in mind that these figures are approximations and not actual figures for the studied district. Nonetheless, these assumptions provide a rather good representation of the internal heat gains from occupants and electrical appliances.

Part 4 consists of the algorithmic method in the change-point model, which is implemented using MATLAB R2020b. The change-point model takes less than one minute of CPU time on a 12-core desktop with a 3.7 GHz processor for the multi-family buildings in the studied district. A schematic of the algorithmic method can be seen in Figure 4.

The algorithmic method for predicting performance indicators starts by calculating the energy use for HWC. The individual average power for each hour of the day, $\overline{\mathrm{P(HWC)}}$ is considered for all days in July, and the average for each hour is calculated by dividing the sum by 31 (the no. of days in July). The average of the four hours with the lowest averages with regard to heating power supply, P(HWC), is set as the HWC. Following, the specific heat losses, Q_{total}, are predicted. This is based on $P_{\cdot j}$, the hourly heating supply to the building at hour j that is subtracted by P(HWC), constituting the nominator. The nominator is divided by the temperature difference between the indoor and outdoor temperature, $T_{out,j}$, at hour j, constituting the denominator. Q_{total} is then set as the average based on the calculations during the selected time period (January–February between 00:00–05:00) by considering the number of time steps, k.

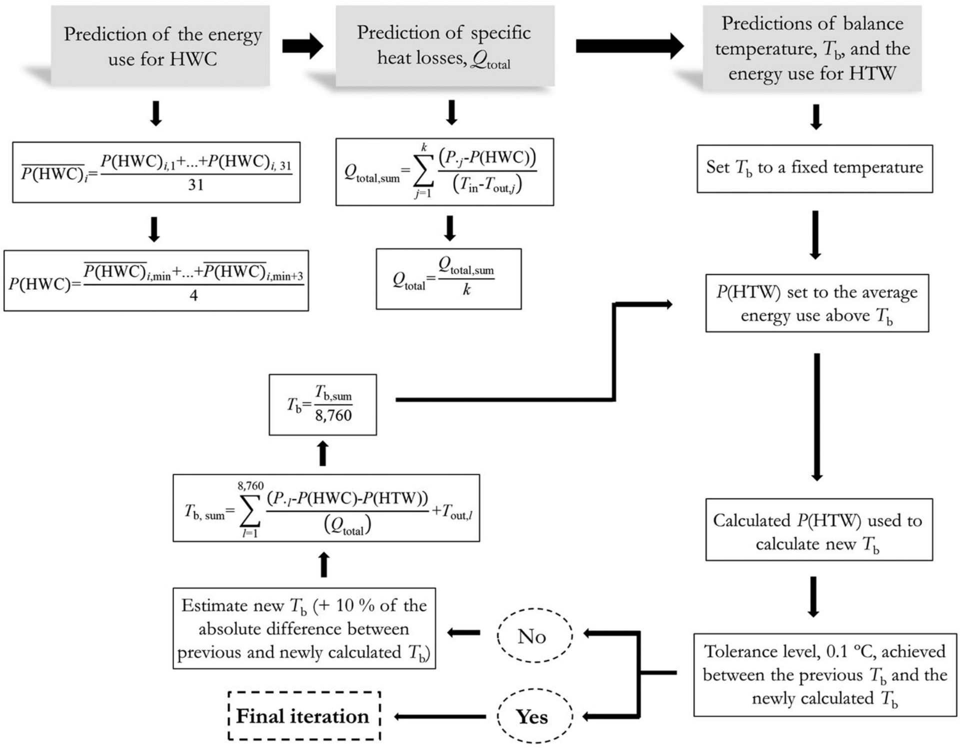

Figure 4. Schematic of the algorithmic procedure.

Following the calculations of Q_{total} and P(HWC), are the predictions of the balance temperature, T_b, and the energy use for HTW, P(HTW). The algorithmic method is performed through an iterative calculation process in which the balance temperature is set to a fixed temperature in the first iteration. This enables calculation of the P(HTW) use by setting the average energy use that occurs during outdoor temperatures above T_b, as P(HTW), during June. Using the calculated P(HTW), a new T_b is calculated as the average of all hourly balance temperatures, i.e. by subtracting $P_{.l}$, the hourly heating supply to the building at hour l by P(HTW) and P(HWC). The nominator is then divided with Q_{total}. The quota is added with the outdoor temperature, $T_{out,l}$, at hour j. Next, the new T_b is calculated as the average of all hourly balance temperatures during the year. For each iteration, a new balance temperature is estimated to the calculated $T_b + 10\%$ of the absolute difference between the calculated T_b and the previously estimated T_b. The calculation procedure is carried out until the tolerance level (< 0.1°C), i.e. the difference between the last two balance temperatures, is attained. Lastly, the prediction of the balance temperature and specific heat losses allows for quantification of the energy used for space heating.

The results are interpreted and analysed in Part 5 of the change-point model. A sensitivity analysis can be performed concerning the model assumptions and selected time periods in order to investigate the model robustness, as well as the impact from e.g. variations in internal heat gains.

3.2. Step II – identify and prioritize TCs

Step *II* of the proposed methodology consists of identifying and prioritizing buildings that are object for energy efficiency related to HWC, HTW and space heating. For this purpose, the quantification of TCs generated in Step *I* is used. Following this procedure, the buildings' TCs are sorted in ascending order in terms of specific energy use. Three energy efficiency targets are established for each TC that allows for identifying and prioritizing TCs for energy renovation in the studied district, as well as for assessment of the energy efficiency potential (see Section 3.3). This is allowed by quantifying the Comparative Energy Efficiency Potential (CEEP) for different TCs for each building, i.e. the energy efficiency potential compared to predetermined energy efficiency targets. The investigated energy efficiency targets in this research are energy efficiency targeting the 75th percentile of the original energy performance in the studied district, energy efficiency targeting the median, and energy efficiency targeting the 25th percentile.

3.3. Step III – assessment of the energy efficiency potential

This step consists of assessing the energy efficiency potential for decreasing energy use related to HWC, HTW and space heating. The assessment is performed based on the three energy efficiency targets earlier presented in Section 3.2. Moreover, Step *III* allows for analyzing the energy efficiency potential for individual buildings related to different TCs, as well as the potential for the entire district.

4. Description of the studied district

Seventy multi-family buildings located in the Vasastaden district in Linköping, Sweden, are studied in this research. The geographic co-ordinates of Linköping are latitude 58.42 and longitude 15.61. The vast majority of the built environment in Vasastaden is multi-family buildings. In total, the district has around 6,000 residents. Vasastaden is characterized by a rather old building stock with many buildings built before 1945.

All buildings in the studied district are constructed between 1908 and 1945. The buildings have three to six stories. 35 (50%) buildings are detached, 20 (29%) are semi-detached, and 15 (21%) are terraced. Multi-family buildings constructed in this time period generally have brick walls with a thickness between 25 cm and 45 cm. Moreover, the buildings are connected to the local district heating network. Hourly energy use data for the studied buildings during three years have been collected at the municipal multi-utility company Tekniska Verken AB, as well as the corresponding outdoor temperatures obtained from the Swedish Meteorological and Hydrological Institute (SMHI). The quantification of energy use for the studied buildings is based on the quantified TCs together with outdoor temperatures for 2020. Moreover, the register GRIPEN (National Board of Housing, Building and Planning) has been used to gather heated areas for the buildings. The heated areas of the studied buildings vary between 446 m^2 and 4,433 m^2, and the total heated area of the district is 121,692 m^2. Photos of six buildings in the studied district can be seen in Figure 5.

Figure 5. Photos of multi-family buildings in the studied district.

5. Results and discussion

This section presents the results together with an associated discussion.

5.1. Prediction of energy use for HWC, HTW and space heating

By the use of the *DTPC* change-point model, it is possible to predict performance indicators describing building thermal characteristics (TCs). Consequently, this allows for identifying and prioritizing TCs related to HWC, HTW and space heating, which will be presented in this section below.

The total heated area in the studied district distributed by the specific energy use for HWC, HTW and space heating can be seen in Figures 6–8, respectively. Each TC also includes the figure corresponding to the 25th percentile, median and 75th percentile in accordance with Sections 3.2–3.3. The energy use for HWC varies between 4.5 kWh/(m^2·year) and 36.3 kWh/(m^2·year), with a median of 13.4 kWh/(m^2·year). This is similar to figures obtained from two other Swedish studies (BEBO, 2015; BELOK, 2017), in which the energy use for HWC ranged between 2.3 and 28 kWh/(m^2·year). As shown in Figure 7, the energy use for HTW (corresponding to a part of the baseload) varies between 4.3 and 30.1 kWh/(m^2·year), with a median of 11.9 kWh/(m^2·year). These figures are somewhat low in comparison with a study analyzing the HTW energy use in Stockholm, Sweden, which calculated the HTW energy use at 25 kWh/(m^2·year) (Sveby, 2020, November 27). However, the energy use for HTW is strongly correlated with the occupant behaviour. Considering the energy use related to space heating, the figures vary between 42.7 and 202.1 kWh/(m^2·year). The median is found to be 75.3 kWh/(m^2·year), as shown in Figure 8.

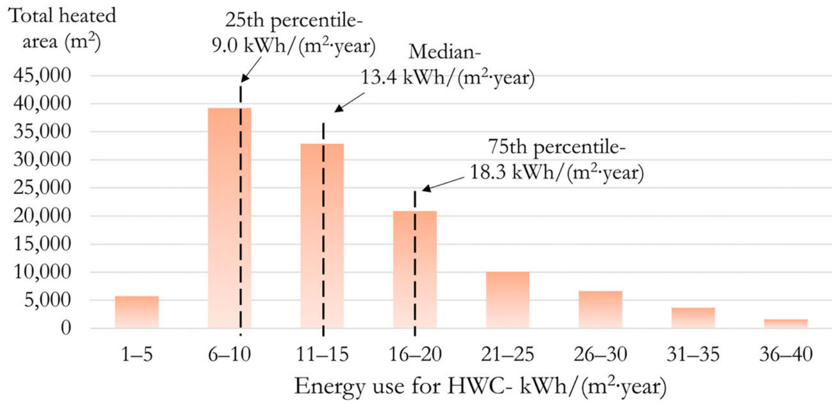

Figure 6. Total heated area distributed by energy use for HWC – kWh/(m^2·year).

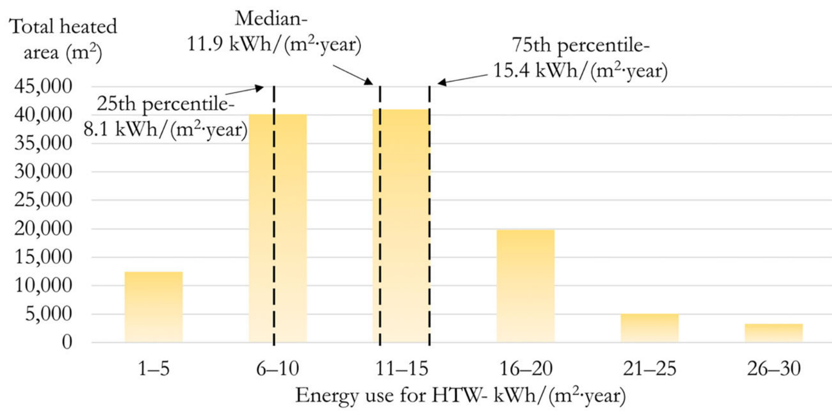

Figure 7. Total heated area distributed by energy use for HTW – kWh/(m^2·year).

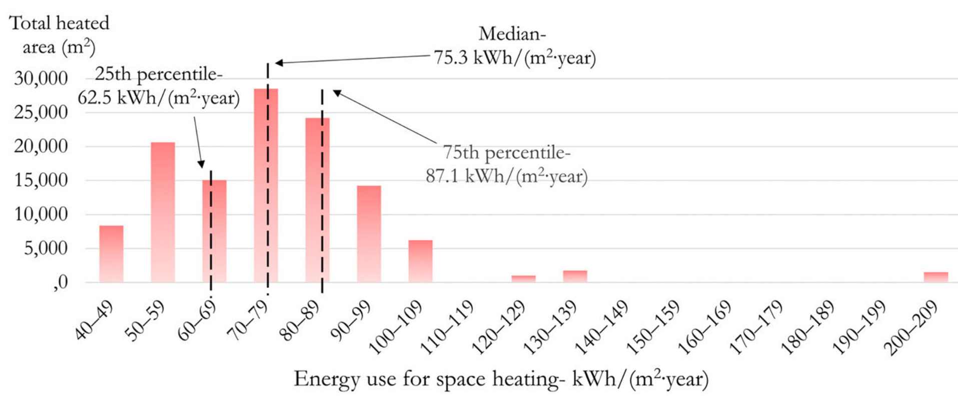

Figure 8. Total heated area distributed by energy use for space heating – kWh/(m^2·year).

When analyzing the total energy use for HWC, HTW and space heating in the studied district, which corresponds to a median of 100.6 kWh//(m^2·year), the specific energy use is 24% lower compared to the average figure (132 kWh/(m^2·year)) in Östergötland County (Swedish Energy Agency, 2022, December 2). This difference can be attributed to a number of factors such as performed energy renovation and occupant behaviour. Moreover, the impact from different geographic locations in Östergötland County on building energy usage is minimal since the distance from the north to the south is approximately 100 km. However, the reader should bear in mind that detailed analysis of the abovementioned factors is beyond the scope of this research.

5.2. Identification and prioritization of TCs in the building district

Current practices in the building industry have shown that stakeholders' decision-making process for prioritizing energy renovation projects has a tendency to be based on factors such as personal intuition and heuristic decision-making (Medal and Amy, 2017). Along with the issue of sub-optimal building energy renovation, there is a need to identify and prioritize buildings and TCs with the highest energy efficiency potential during large-scale energy renovation. By identifying and prioritizing TCs based on the three energy efficiency targets presented in Section 3.2, it is possible to identify and rank buildings in the studied district with regard to energy efficiency potential based on actual technical performance. Such a procedure can be useful for stakeholders as a tool during decision-making in energy renovations of large building portfolios, which has also been highlighted by Chen et al. (2017).

The Comparative Energy Efficiency Potential (CEEP) in prioritized order of buildings related to total energy use from space heating, HTW and HWC when targeting the preset energy efficiency targets, i.e. the 75th percentile, the median and 25th percentile, can be seen in Figures 9–11, respectively. By prioritizing the buildings with regard to total energy use, and not separately considering each TC for the energy efficiency targets, there will be a varying number of TCs selected in each energy efficiency target. Energy efficiency targeting space heating is the most common in the studied group of buildings. 14 buildings are target for energy efficiency related to space heating in the 75th percentile energy efficiency target, and 47 buildings in the 25th percentile energy efficiency target. The corresponding figures for HWC are 8 and 41 buildings, respectively. For HTW, 7 buildings are target for energy efficiency in the 75th percentile energy efficiency and 39 building in the 25th percentile energy efficiency target. The highest CEEP is related to the improvement of the building envelope, i.e. space heating. The average potential corresponds to between 23.3 and 24.9 kWh/(m^2·year) considering the preset energy efficiency targets. However, as shown in Figure 9–11 there is a large difference between the buildings' energy efficiency potential related to space heating. In all three cases, the difference between the highest and lowest potential corresponds to more than 100 kWh/(m^2·year). The average CEEP related to HTW and HWC for the three energy efficiency targets correspond to 7.7 and 10.6 kWh/(m^2·year), respectively. The difference between the highest and lowest potential for HTW ranges between 11.1 and kWh/(m^2·year) and 22.0 kWh/(m^2·year) considering the three targets, and between 10.6 and 27.2 kWh/(m^2·year) for HWC. This is a significantly lower variation compared to space heating. The reason for this is the higher proportion of total energy use related to the specific

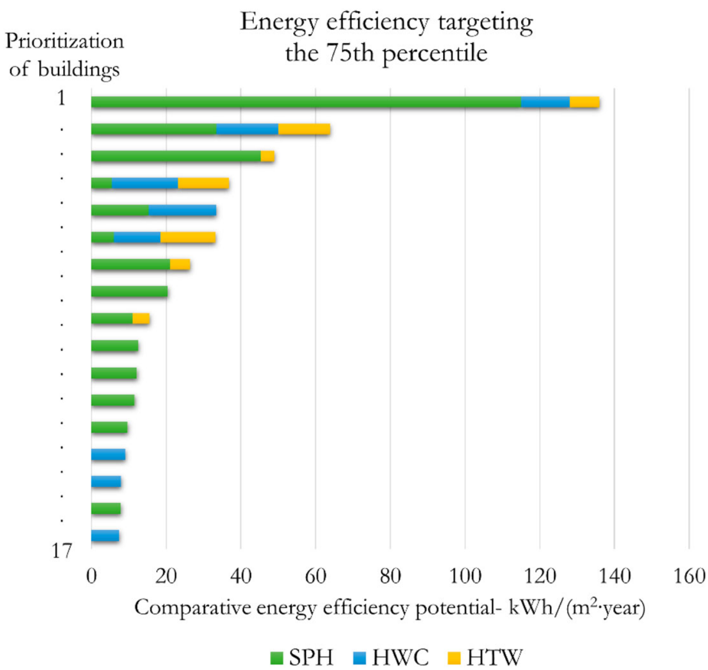

Figure 9. Comparative energy efficiency potential in prioritized order of buildings connected to space heating, HTW and HWC when targeting the 75th percentile.

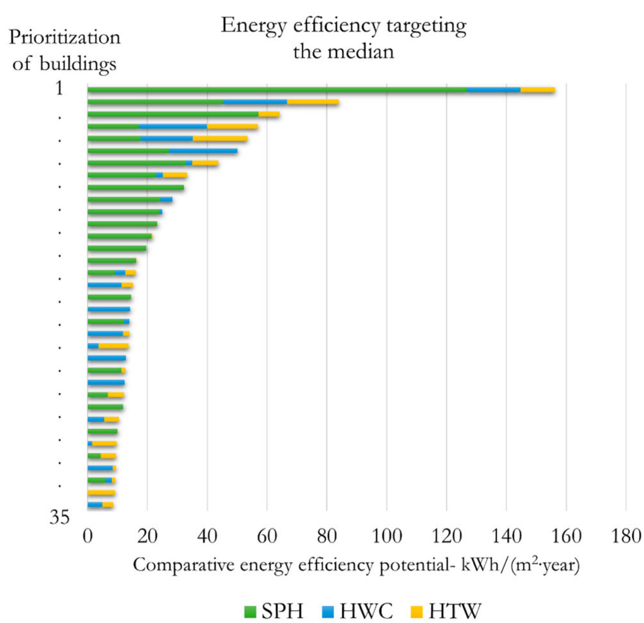

Figure 10. Comparative energy efficiency potential in prioritized order of buildings connected to space heating, HTW and HWC when targeting the median.

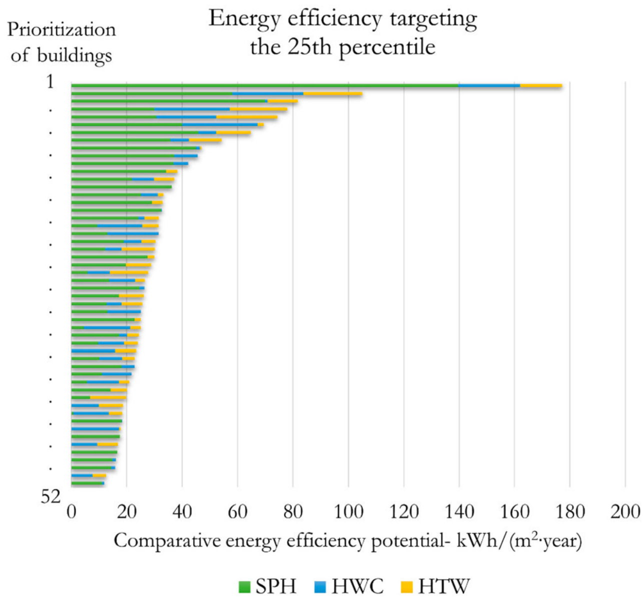

Figure 11. Comparative energy efficiency potential in prioritized order of buildings connected to space heating, HTW and HWC when targeting the 25th percentile.

heat losses due to a long heating season in a Northern European climate, as well as the fact that the district is constructed between 1908 and 1945 when there were no specific building energy requirements. Nonetheless, it should be noted that some of the buildings may have undergone some energy renovation, especially when considering that the average specific energy use is 24% lower compared to the average figure in Östergötland County for multi-family buildings (see Section 5.1).

The findings presented in this section show that our research can be important in elucidating the possibilities in generating a prioritization of TCs by using only digital heating supply data together with outdoor temperature data, with no need for on-site visits at the studied buildings, as well as without data related to occupant behaviour. By the use of a change-point model implemented in computational software, this can be performed in a time-effective manner for a portfolio of buildings. Moreover, it is important to address the possibilities and limitations of energy renovation related to space heating, HWC and HTW, although this aspect is not within the frame of the proposed research. Measures targeting space heating are in some way connected to the improvement of the thermal performance of the building envelope, such as additional insulation, replacement of windows, weather-stripping, etc. In absolute figures, these types of measures hold the highest energy efficiency potential due to a long heating season in a Northern European climate and often poor thermal performance of the building envelope in older buildings. However, it should be noted that measures related to decreasing space heating are often associated with high expenditures, such as additional insulation of the external walls and window replacenemt. This is in contrast to measures connected to HTW, which consist of energy-efficient taps and shower heads. Such measures are often linked with low investment costs, but also with rather low energy savings compared with energy renovation targeting the building envelope. Considering decreasing the energy use related to HWC, it is possible either to insulate the HWC piping, decrease the amount of loop piping or increase the efficiency of the pump. From a practical point of view, measures that require access and change of the HWC loop are difficult to implement, and, therefore, costly. Hence, in many cases replacement to an energy-efficient pump is preferable.

5.3. Comparative energy efficiency potential related to space heating, hot water circulation and hot tap water

By quantifying relevant TCs describing building thermal performance in the studied district, a prediction of the CEEP is allowed. In this research, this prediction is based on three different energy efficiency targets as mentioned in Section 3.2. In addition, it is possible to investigate how the heated area varies in different ranges of specific energy use when targeting the investigated energy efficiency targets. This is visualized by the total heated area distributed on specific energy use for HWC, HTW and space heating when targeting the 75th percentile, the median and 25th percentile, in Figures 12–14, respectively.

As seen in Figure 12, the change in a total heated area varies between 22,000 m^2 (75th percentile and 18.3 kWh/(m^2·year)) and 76,000 m^2 (25th percentile and 9.0 kWh/(m^2·year)). This corresponds to 18–62% of the heated area in the Vasastaden district. Moreover, analysis of the total energy efficiency potential related to HWC shows a decrease between 179 MWh (10%) and 699 MWh (40%) considering the entire district. Hence, by targeting the 25th percentile as an energy efficiency target for HWC, it is possible to decrease the total energy use of the district by 6%, and by 1% when targeting the 75th percentile. In terms of specific energy use, the potential varies between 7.5 and 8.3 kWh/(m^2·year).

Considering the total CEEP related to HTW, it is calculated at between 119 MWh (8%) and 520 MWh (36%). This corresponds to a change in a heated area between 28,000 m^2 when targeting 15.4 kWh/(m^2·year), i.e. the 75 h percentile, and 69,000 m^2 when targeting 8.1 kWh/(m^2·year), i.e. the 25th percentile, as shown in Figure 13. The change in specific energy use is 5.1–6.5 kWh/(m^2·year) according to the specified energy efficiency targets. Consequently, the overall potential related to HTW corresponds to 1–4% of the district's total energy usage.

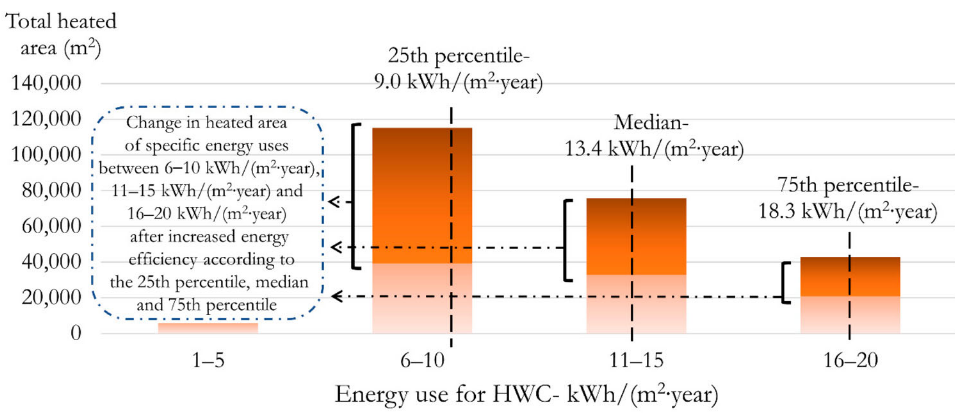

Figure 12. Total heated area distributed by specific energy use for HWC after energy efficiency targeting the 25th percentile, median and 75th percentile.

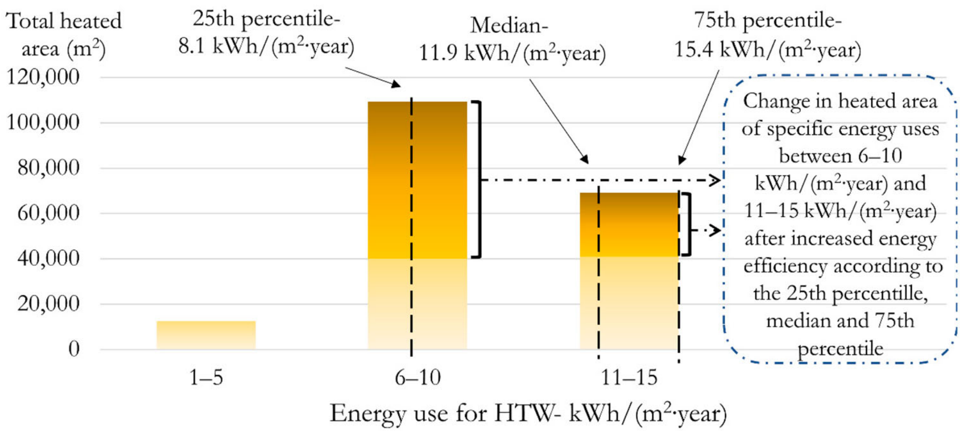

Figure 13. Total heated area distributed by specific energy use for HTW after energy efficiency targeting the 25th percentile, median and 75th percentile.

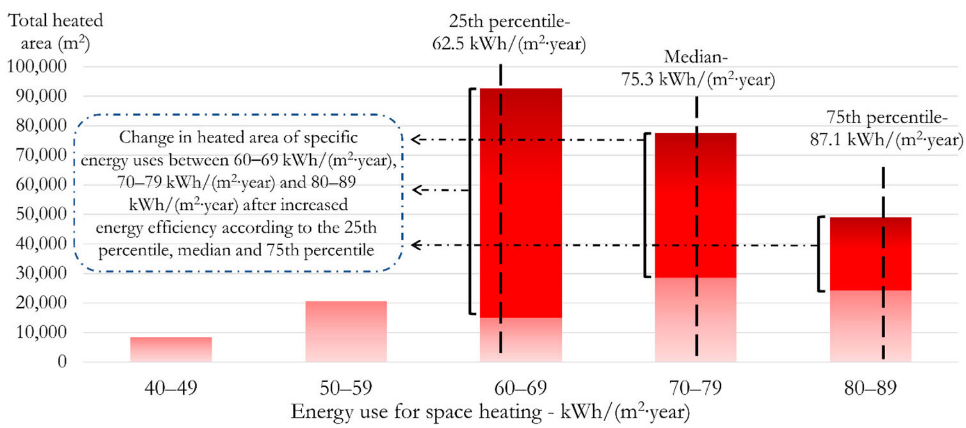

Figure 14. Total heated area distributed by specific energy use for space heating after energy efficiency targeting the 25th percentile, median and 75th percentile.

The highest CEEP of the investigated TCs is decreased energy use for space heating. Energy use for space heating is predicted to be 9,329 MWh in the district prior to any energy efficiency. A potential decrease of 501 MWh (5%) is calculated when targeting the 75th percentile, 991 MWh (11%) when targeting the median, and 2,016 MWh (22%) when targeting the 25th percentile. The change in specific energy use is 19.7–23.2 kWh/(m^2·year). As shown in Figure 14, these figures correspond to a change in a heated area of 25,000 m^2 when targeting 87.1 kWh/(m^2·year), i.e. the 75 h percentile, 49,000 m^2 when targeting 75.3 kWh/(m^2·year), i.e. the median, and 78,000 m^2 when targeting 62.5 kWh/(m^2·year), i.e. the 25th percentile. Analysis of the impact of energy efficiency related to space heating according to the studied energy efficiency targets shows a potential decrease in the total energy use of the district between 4% and 16%.

6. Conclusion

One main problem in increasing the rate of energy renovation in building portfolios is the lack of data describing thermal performance divided into different processes such as space heating, HWC and HTW. To speed up the pace of energy renovation, it is necessary to identify and prioritize buildings with poor thermal performance. Consequently, time is of the essence to minimize the climate impact from the building stock and tackle ongoing climate change. This means that a large number of buildings cannot be analysed on a building-by-building basis due to a time-consuming process and large amounts of data needed, but instead by a computational approach. This research has presented a unique methodology for identifying and prioritizing TCs, and to predict the Comparative Energy Efficiency Potential (CEEP). The objective is fulfilled by the use of a proven robust change-point model, titled *DTPC*. The *DTPC* model allows for prediction of energy use for space heating, HWC and HTW, with no need for data connected to occupant behaviour. In this research, 70 multi-family buildings (total heated area of 121,692 m^2) in the Vasastaden district in Linköping, Sweden, are investigated.

The results show that by predicting TCs it is possible to identify and prioritize buildings with regard to energy use related to HWC, HTW and space heating in the studied district. To enable identification and prioritization of TCs according to the predetermined energy efficiency targets in this research (75th percentile, the median and 25th percentile), it is necessary to calculate the energy use for HWC, HTW and space heating of the buildings in the district. The total energy use of the district prior to any energy efficiency is calculated at 12,485 MWh (median specific energy use of 100.6 kWh/(m^2·year)) of which 1,726 MWh (median specific energy use of 13.4 kWh/(m^2·year)) is related to HWC, 1,429 MWh to HTW (median specific energy use of 11.9 kWh/(m^2·year)) and 9,329 MWh (median specific energy use of 75.3 kWh/(m^2·year)) to space heating. The differentiation of different processes from the use of solely digital heating supply data is a key benefit of the proposed methodology, which is a prerequisite for the later prioritization of TCs. Consequently, ranking of TCs in a building portfolio can be made based on actual building technical performance. The maximum CEEP is found to be 3,235 MWh (26%). Space heating corresponds to the highest CEEP, decreasing the district's energy use by up to 16% (2,016 MWh). The potential in energy efficiency related to HWC is calculated at a maximum of 6% of the district's energy use (699 MWh) and 4% (520 MWh) for HTW.

The present study contributes to existing knowledge on energy efficiency in buildings by providing a unique methodology for identifying and prioritizing TCs in a residential district using only heating supply data. This means that there is no need for data related to occupant behaviour. Collecting this kind of data is often time-consuming, especially when studying a larger group of buildings. The key strengths of the research include time-effective screening of the thermal performance described by different TCs in building portfolios and prediction of the CEEP from various TCs. Hence, the developed methodology can contribute to the sustainable transformation of the built environment.

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Disclosure statement

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