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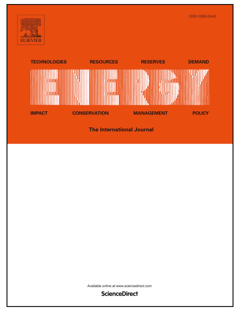

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Implementation of a strategy for low-temperature operation of radiator systems using data from existing digital heat cost allocators

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Abstract

Low-temperature district heating (LTDH) networks can integrate sustainable energy sources and waste industrial heat towards decarbonisation goals by 2050. LTDH networks can be realised through the low-temperature operation of heating systems in buildings. However, the low-temperature operation of heating systems is obstructed by inefficient radiator control by end-users or other technical errors. This study investigated the implementation of a strategy for low-temperature operation of radiator systems by calculating the minimum supply temperature and using an innovative treatment of data from electronic heat cost allocators to identify radiators not in use and locate the critical apartments with higher heat demands. According to the results, the low-temperature operation of radiator systems is possible. Although, the minimum supply temperature should be calculated based on the higher heat demand of the critical apartment identified to avoid complaints regarding poor thermal comfort. An energy weighted average supply temperature of 55 °C can be achieved, resulting in an average energy weighted return temperature of 31.3 °C in the system. Testing of a reduced supply temperature in the building case highlighted the

existence of critical apartments. The investigation highlighted that the increased heat loss to the poorly heated neighbouring apartments heavily influences the critical apartments.

1. Introduction:

1.1. Low-temperature district heating

According to the European Green Deal [1], to meet the decarbonisation goals by 2050, renewables, energy efficiency, and other sustainable solutions must be integrated across different sectors. District Heating (DH) can contribute in this direction by integrating renewable energy sources [2,3]. More specifically, fossil fuel-based sources that include excess heat from power generation, oil or natural gas boilers, and industrial heat must be replaced by geothermal heat, solar thermal heat, and large-scale heat pumps in DH networks by 2050 [4].

DH networks must operate at temperatures lower than the current state to integrate sustainable energy sources. These future low-temperature district heating (LTDH) networks must operate with supply and return temperatures below 55 °C and 25 °C, respectively [4–7]. The reduction in the operating temperatures would reduce the distribution heat loss [8], primary energy consumption [9], and the energy cost for heating [10] in the network. In Denmark, 2.2–2.6 billion Danish kroner will be saved annually by establishing LTDH networks [11].

LTDH networks can be realised through the low-temperature operation of heating systems in buildings. The network operator controls the supply temperature according to the heat demand. However, the return temperature limits the potential for reduction in the supply temperature. The return temperature is the outcome of the operation of heating systems controlled by end-users. As a result, the network operator has a clear interest in helping end-users achieve a low return temperature [12].

The most common heat emitters in multi-family buildings are water radiators. They have been designed for ambient conditions that rarely occur in recent years. In Denmark, the design [13] is based on an outdoor temperature of -12 °C, excluding solar and internal heat gains. As a result, they are sufficiently large to ensure thermal comfort under low-temperature operating conditions [14,15].

1.2. The digitalisation of heating systems

The digitalisation of heating systems would help DH operators gain insight into the operation of heating systems. Heat meters installed in DH substations, electronic heat cost allocators installed on each radiator, and return temperature sensors are currently available solutions. According to the EU directive [16], all new energy meters and heat cost allocators must be remotely readable by October 2020. Månsson et al. [17] showed that DH operators could identify malfunctions in heating installations using energy-meter data. Return temperature sensors can be placed in risers to identify malfunctions or inefficient control by the end-users in different apartments, which results in a higher local return temperature than the rest of the system [18].

Heat cost allocators are devices that measure the share of the energy consumption of each radiator according to its nominal capacity to the total energy consumption of the space heating system. Hence, their main function is to allocate the energy use for each apartment in multi-family buildings and provide the relative energy bill [19]. According to Cholewa et al. [20], the use of heat cost allocators for billing should be based on a 50% variable cost based on energy-efficient behaviour of the end-users, a minimum indoor temperature of 16 °C for heating charges to address the problem of heat transfer between neighbouring apartments. In addition, the end-users should be educated concerning good control practices. In recent years, heat cost allocators have been used in an innovative way for fault detection in heating systems, which is a novel approach.

1.3. Problem identification

Low-temperature operation of radiator systems is obstructed by inefficient radiator control by end-users. The most typical example is the usage of a few radiators in an apartment to compensate for the total heat demand of the apartment. The radiators in use are designed to provide only the heat demand for the rooms in which they are installed. When several radiators in other rooms are not used, heat transfer occurs between rooms until a similar indoor temperature is reached. As a result, the radiators must deliver the heat demand for unheated rooms. The heating capacity of the radiators cannot usually deliver the necessary heat demand for the entire apartment. As a result, the thermostatic radiator valve (TRV) that controls the flow through the radiators is fully open because the indoor temperature setpoint set by the valve cannot be met. This results in high flow and return temperatures from the radiators and complaints about low room temperature to the operator. To deliver the necessary heat for the entire apartment with only a few available radiators, a higher logarithmic mean temperature difference ($LMTD$) is required between the radiator and the surrounding. A higher $LMTD$ requires a combination of high supply and high return temperatures owing to a high mass flow rate through the radiators [21].

To overcome this problem, all the available radiators in each apartment should deliver the necessary heat demand to the end-users. This would result in a minimum $LMTD$ for every radiator, which can be secured by a minimum combination of supply and return temperatures. By implementing a minimum supply temperature in the system, the necessary heat demand at the apartment level can only be secured using all available radiators. If not, thermal discomfort may lead to complaints by the end-users.

The previous example refers to a uniform heating load on all radiators. However, there are critical apartments where the radiators have a higher load than in general in the building. The higher heating demand in these critical apartments may be due to higher comfort temperature set point in the critical apartment than in general. This will result in higher heat loss to the ambient and heat transfer to the neighbouring apartments. The critical apartments may require a higher supply temperature than the minimum required under uniform heating conditions. Several studies have shown a significant leak of heat for neighbouring apartments to poorly heated apartments [22].

The heating system operator needs to have information on the realistic minimum supply temperature and insight into using radiators to implement a low-temperature operation of the heating system.

1.4. Aim of the study

This study aims to present the implementation of a strategy for low-temperature operation of a radiator system by calculating the minimum supply temperature required in the system, stimulating the use of more radiators, and using data from electronic heat cost allocators to detect errors in the system and identify the critical apartments along with the reasons for the higher heat demand. Then, the supply temperature will be calculated based on the critical apartments' higher heat demand, resulting in a slightly higher supply temperature than the minimum required. The implementation of the strategy was performed in an actual building through actual tests and simulations.

1.5. State-of-the-art

Several studies have investigated the potential for a reduction in the operating temperature in heating systems and improvements in radiator systems' control. Østergaard et al. [23] investigated what should be the characteristics of a well-functioning radiator heating system. According to the analysis from three multi-family apartment buildings, the obtained return temperatures were in the range of 30-40 °C instead of the targeted DH return temperature of 25-30 °C.

Lauenburg et al. [24] investigated a control algorithm that can calculate an optimal combination of supply temperature and circulation flow to achieve a low return temperature in Swedish DH systems. The proposed algorithm centrally adjusts the operating conditions and does not require interaction with the end-users to improve the operation of the radiators.

Liu et al. [25] developed a novel numerical method to solve a coupled thermal-hydraulic model for simulating the multi-room radiator heating system's dynamic by comparing different indoor temperature control strategies. According to the results, efficient flow rate control may secure up to 13% energy savings. However, the reduction of the operating temperatures was not investigated.

Sun et al. [26] proposed a dynamic control strategy for substations based on online forecasting and indoor temperature measurements to predict the required supply temperature. The proposed strategy was tested in an actual system securing energy savings of approximately 6%. In another study [27], a new control strategy was proposed that integrates end-users control behaviour based on indoor temperature setpoints and combined control of feedforward and feedback to save energy up to 20%. In both studies, the use of electronic heat cost allocators to detect errors was not investigated.

Yuan et al. [28] proposed a model for predicting the secondary supply temperature based on the building's thermal inertia, solar radiation, outdoor temperature and the end-users behaviour. The results of the proposed model showed energy savings close to 6%. However, the study does not investigate the use of heat cost allocators to identify problematic end-users behaviour.

Dahlblom et al. [29] proposed a control strategy of the radiator supply temperature in multi-family buildings in Sweden, based on enhanced feedforward control of TRVs with a signal from indoor temperature sensors, to secure an indoor temperature less dependent on the outdoor temperature. However, the control did not consider potential problematic behaviour by the end-users like radiators not in use.

Jangsten et al. [30] investigated the potential to reduce DH temperatures in radiator systems in multi-family buildings in Gothenburg, Sweden, based on data from 109 buildings. According to the survey, 87% of the radiator systems were operated at a supply temperature below 55 °C for an outdoor temperature of 5 °C. In Sweden, it is not common to use heat cost allocators as a basis for individual heating bills for the tenants. In Denmark and most EU countries, heat cost allocator devises are mounted on the radiators in apartments and used for billing purposes. In the actual article, the data from the heat cost allocators are used to implement a low-temperature heating system operation.

Rønneseth et al. [31] investigated the possibility of reducing the supply temperature in apartment blocks in Norway to maintain a heating setpoint of 22 °C. According to the results, a low supply temperature of 60 °C can be achieved in buildings constructed after 1971. However, the investigation was performed through dynamic simulations considering the ideal operation of all radiators according to the heat demand. Although, under actual operating conditions, the operation of radiators is not ideal.

Østergaard et al. [32] concluded that single-family houses in Denmark could be heated by low-supply temperatures for most of the year. However, measurements from individual radiators showed that problematic local control by the end-users and malfunctioning TRVs might result in high return temperatures. This study did not investigate the use of electronic heat cost allocators to identify malfunctions but only return temperature measurements.

Alonso et al. [33] suggested that before reducing the DH supply temperature, it is essential to check whether the buildings can be adapted to low-operating conditions by increasing the circulation mass flow rate. However, the authors pointed out that even when the system's mass flow rate is doubled, thermal discomfort may occur for higher indoor temperature setpoints. As a result, the calculation of the reduced supply temperature must consider the maximum mass flow rate of the system and the increase in the heat demand due to higher indoor temperature setpoints.

Teli et al. [34] investigated the driving factors of the indoor temperature in multi-family buildings connected to DH. According to the results, in addition to the building characteristics, the central control strategy of the heating system and the lack of end-user engagement with the control influence the indoor temperature. The authors suggested that a better interaction between end-users and the heating system may maintain appropriate indoor temperatures.

In the past, heat cost allocators were used exclusively for the cost allocation and billing of the energy use in the different apartments in multi-family buildings. In recent years, the use of heat cost allocators has been expanded to identify the operating parameters of the radiator systems. Several studies investigated the potential of using the electronic heat cost allocators as a tool to identify errors and radiators not in use in multi-family apartment buildings. Østergaard et al. [35] investigated electronic heat cost allocators to identify errors in the radiator system. More specifically, data from heat cost allocators were used to calculate the return temperature from each radiator and consequently identify radiators with high return temperatures. However, the results were susceptible to assumptions and the proposed method required further development.

Benakopoulos et al. [21] presented a strategy to stimulate the use of all available radiators by securing a minimum supply temperature and using data from electronic heat cost allocators to identify radiators not in use in the different apartments. The proposed strategy was analysed using only a thermal/hydraulic model of the radiator systems and considering a uniform heating load on all radiators. Data from the actual heat cost allocators of the building case were used to estimate the number of radiators in use under the current operation of the heating system without identifying the critical apartments with higher heat demand.

Cholewa et al. [36] identified through experimental studies that the use of heat cost allocators in multi-family buildings may result in energy savings compared to buildings where the billing is based on the proportional heated area, due to the increased interest of the end-users to regulate the energy use through the TRVs. In another study, Cholewa et al. [37] assessed the influence of heat cost allocators on the energy use and operating parameters through parallel tests in two identical multi-family buildings with and without heat cost allocators, respectively. Measurements of the energy use and the supply and return temperature of the radiator systems were performed in the heat exchanger of the two buildings. In addition, the end-users were trained to regulate the indoor temperatures by using the TRVs properly. According to the results, there was a 24% lower energy use in the building with the heat cost allocators due to the flow regulation through the optimal use of the TRVs by the end-users compared to the building without heat cost allocators. Consequently, there was a potential to reduce the supply temperature in the building with the heat cost allocators to take advantage of the 24% potential for increasing the flow rate. According to the results of both studies, the heat cost allocators were not used to locate radiators not in use or address errors and problems regarding the behaviour of the end-users.

1.6. Novelty

The novelty of this study is the innovative use of data from electronic heat cost allocators to identify critical apartments and poor control by end-users and to implement low-temperature operation without complaints regarding poor thermal comfort in existing buildings with radiators connected to DH networks. No work has been reported in the literature on finding the extra high demand in critical apartments based on the use of data from heat cost allocators and using the critical apartments as a basis to calculate the minimum supply temperature curve for use in the weather compensation controller in order to implement low-temperature heating in existing multi-storey residential buildings. This is why the actual article presents new knowledge.

2. Methods

The investigation started considering uniform heating for the different apartments in the multi-family building case. The uniform heating assumed that the heat demand in each apartment could be delivered by using all the available radiators in the rooms where thermal comfort is required based on a specific indoor temperature setpoint. Hence, it was calculated a new minimised supply temperature curve required to secure the thermal comfort in each apartment considering the measured heat demand for the building and the heat capacity of all radiators installed.,

A gradual reduction of the supply temperature was tested in the building case. The purpose of the test was first to investigate if reducing the supply temperature close to the minimum supply temperature would secure thermal comfort in the different apartments by stimulating the use of more radiators. Second, to investigate if potential complaints due to poor thermal comfort would occur for critical apartments with higher heat demand that the minimum supply temperature could not fulfil.

The data from electronic heat cost allocators were used to identify if the assumption of uniform heating was correct and obtain a detailed overview of the actual operation of all radiators. This allowed pinpointing the radiators not in operation and the heat demand distribution among all apartments. In this way, the minimum supply temperature curve, calculated under the uniform heat distribution, was improved to secure the usual indoor comfort by considering the actual operation of the space heating systems.

2.1. Calculation of the minimum supply temperature

First, the total heating degree days ($HDD(T)$) of a heating period with minimum solar gains. The temperature difference ($\Delta T(T)$) at each daily average outdoor temperature (T) between −12 °C and 12 °C can be calculated using Equation 1:

$$\Delta T(T) = T_{in} - T \tag{1}$$

where T_{in} is a realistic indoor temperature (°C) setpoint used in the building, and T is the daily average outdoor temperature between −12 °C and 12 °C. The $HDD(T)$ for each outdoor temperature between −12 °C and 12 °C can be calculated from Equation 2:

$$HDD(T) = \Delta T(T) \cdot n_{days}(T) \tag{2}$$

where $n_{days}(T)$ is the number of days of the heating season in which each outdoor temperature between −12 °C and 12 °C occurs. The number of days $n_{days}(T)$ for each daily average outdoor temperature can be obtained from the available weather data of the building area and the actual measuring period.

The total heating degree hours (HDH) of the year in Kh can be calculated as the sum of the $HDD(T)$ for each outdoor temperature between −12 °C and 12 °C multiplied by 24 hours per day, according to Equation 3:

$$HDH = \sum_{-12℃}^{12℃} HDD(T) \cdot 24 \tag{3}$$

The heat loss coefficient (L) for each outdoor temperature in kW/K can be calculated by dividing the annual heat loss ($E_{heatloss}$) by the total heating degree hours (HDH) of the year, according to Equation 4:

$$L = \frac{E_{heatloss}}{HDH} \tag{4}$$

The annual heat loss ($E_{heatloss}$) is the sum of the measured energy delivered to the space heating system and the energy due to internal heat gains (G).

The heating demand ($Q(T)$) in kW at each outdoor temperature between −12 °C and 12 °C to be delivered by the radiators is calculated by multiplying the heat loss coefficient (L) by the temperature difference ($\Delta T(T)$) at each outdoor temperature (T), and subtracting the internal gains (G) in kW, according to Equation 5:

$$Q(T) = \big(L \cdot \Delta T(T)\big) - G \tag{5}$$

The logarithmic mean temperature difference ($LMTD(T)$) between the radiator temperature and the indoor temperature at each outdoor temperature between −12 °C and 12 °C can be calculated using Equation 6:

$$\frac{Q(T)}{Q_{tot}} = \left(\frac{LMTD(T)}{LMTD_0}\right)^n \tag{6}$$

where $LMTD_0$ is the logarithmic mean temperature difference (°C) at the reference temperature, and Q_{tot} is the heating capacity (kW) at the reference temperature.

The minimum supply temperature required for each outdoor temperature ($T_{sup}(T)$) between −12 °C and 12 °C can be calculated by solving the system of equations (7) and (8):

$$LMTD(T) = \frac{T_{sup}(T) - T_{ret}(T)}{ln\left(\frac{T_{sup}(T) - T_{in}}{T_{ret}(T) - T_{in}}\right)} \tag{7}$$

$$\Delta T_{rad}(T) = T_{sup}(T) - T_{ret}(T) \tag{8}$$

where $\Delta T_{rad}(T)$ is the magnitude of cooling of the water in the radiator system, and $T_{ret}(T)$ is the estimated return temperature at each outdoor temperature between −12 °C and 12 °C.

The cooling of the water in the radiator system $\Delta T_{rad}(T)$ can be estimated by measuring the actual temperature difference between the supply and return temperatures for different outdoor temperatures. Using Equation 9, the actual circulation flow ($\acute{m}$) can be calculated for different outdoor temperatures to identify the maximum possible circulation flow of the system. The measured heating demand ($Q(T)$) during the measurement time duration can be used as an input for the calculation of the circulation flow ($\acute{m}$).

$$Q(T) = \dot{m} C_p \Delta T_{rad}(T) \quad (9)$$

For a constant circulation flow in the system ($\dot{m}$), the cooling of the water in the radiator system $\Delta T_{rad}(T)$ is proportionally reduced according to the reduction in the heating demand ($Q(T)$) as the outdoor temperature is increased from −12 °C to 12 °C.

2.2. Data from electronic heat cost allocators to detect radiators not in use and to locate the critical apartments with higher heat demands

Electronic heat cost allocators measure the relative heat emitted by each radiator according to their nominal capacity, compared to the total heat emitted. Besides the typical use for cost allocation, the electronic heat cost allocators can be used innovatively to locate the critical apartment and the critical radiators by relating the share of the energy used by the radiator with the share of the radiator's heating capacity. Furthermore, the absence of measurements can also highlight radiators not in operation. This can also contribute to the non-uniform heat distribution among all apartments.

2.3. Theoretical analysis of the higher heat demand in the critical apartments

Due to the higher share of external surfaces, apartments located on the top floor of multi-family buildings may require higher heating demand than apartments in the middle of the building. Moreover, in the case of poorly heated neighbouring apartments, the critical apartment's heat demand may be even higher due to the increased heat loss to these apartments. In addition, older people with low activity levels may require higher indoor temperatures than 22 °C. The higher indoor temperature may result in an extra heat loss from the critical apartments. The effect of the different parameters on the heat demand of the critical apartments was theoretically investigated through energy simulations.

3. Implementation of low-temperature operation in an existing building connected to district heating

3.1. Description of the building and measuring system

The building was a multi-family building in Viborg, Denmark, constructed in 1992, consisting of 42 apartments distributed on either two or three floors in different sections of the building with 235 radiators.

The apartments were distributed in seven staircases across the building on the left and right sides of each staircase.

The water radiators in each room were connected to a manifold in each apartment by PEX pipes placed between the concrete deck and wooden flooring. Each radiator had a wireless heat cost allocator that transmitted measurements every 2 min to the online database of the heat cost allocator company through an antenna located in the building.

Two DH meters measured the total heat supplied to the building and the heat supplied to the DHW system. The heat supplied to the space heating system was the difference between the two heat meters.

3.2. Calculation of the minimum supply temperature considering uniform heating

Table 1 presents all the inputs and intermediate calculated parameters required to calculate the minimum required supply temperature for the building considering a uniform heating demand among the different apartments. The data were obtained during the heating period between December 2020 and the end of January 2021.

Table 1. Inputs and the intermediate calculated parameters are required to calculate the minimum required supply temperature for the building from 1/12/2020 to 31/1/2021.

Parameter	Uniform heating
The energy delivered for space heating during the period from 1/12/2020 to 31/1/2021.	86 MWh
Internal energy gain during the period from 1/12/2020 to 31/1/2021. Calculated based on a typical internal gain of 5 W/m^2 and a heated area.	24 MWh
Heated area.	3270 m^2
Heat loss from the building during the period from 1/12/2020 to 31/1/2021. Sum of energy for space heating and internal gain.	110 MWh
Nominal heating capacity of all the radiators in the building at 90/70/20 °C.	270 kW
Nominal heating capacity of the master bedrooms at 90/70/20 °C.	54 kW
Extra heating capacity due to heat loss from pipes to radiators inside apartments at 90/70/20 °C.	57 kW

Corrected heating capacity of the radiators, excluding radiators in the master bedrooms and including the pipes to the radiators at 90/70/20 °C.	273 kW
The heating degree days ($HDD(T)$) during the period from 1/12/2020 to 31/1/2021, based on an indoor temperature of 22 °C and daily average outdoor temperature from Danish Meteorological Institute for the actual period and location [40].	1197
The calculated heat loss coefficient (L).	3.9 kW/K
Circulation flow used to find the temperature difference of the supply and the return temperature for different heating power.	2.5 kg/s

According to the calculation process described in Section **Error! Reference source not found.** the calculation of the minimum supply and return temperatures, along with the energy required for heating at each outdoor temperature between −12 °C and 12 °C considering a uniform heat demand in the different apartments and the maximum flow in the system of 2.5 kg/s according to the capability of the circulation pump are illustrated in Figure 1**Error! Reference source not found.**.

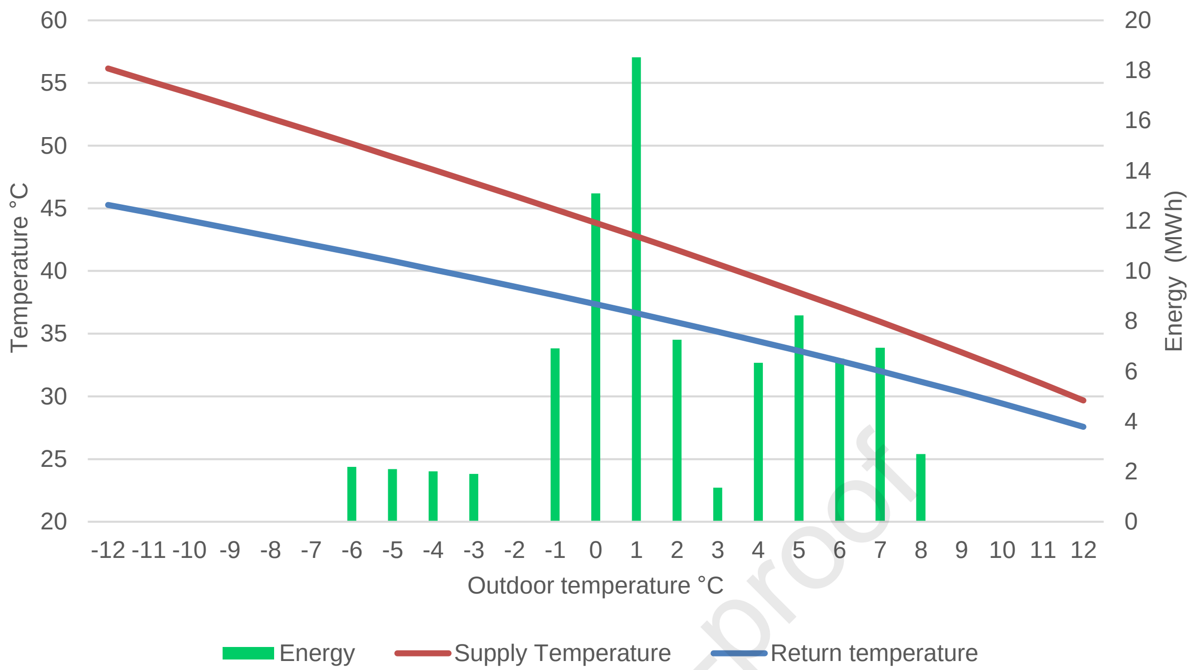

Figure 1. The minimum supply and temperature required in the building along with the energy required for heating at each outdoor temperature between −12 °C and 12 °C, considering uniform heating of the building, during the period between 1/12/2020 and 31/1/2021, based on a higher circulation flow of 2.5 kg/s.

According to Figure 1, the calculated energy-weighted average supply and return temperature are 41.6 °C and 35.9 °C, respectively.

3.3. *Test of lower supply temperature in the actual building case*

The test of the methodology in the building was performed to investigate whether the low-temperature operation of the radiator system could be achieved. As shown in Figure 2, the supply temperature of the system was reduced between 26/2/2021 and 1/3/2021 by changing the setting of the weather compensation control in the system. The recorded outdoor temperature from the DMI [40] fluctuated between 5 °C and 11 °C during the test period.

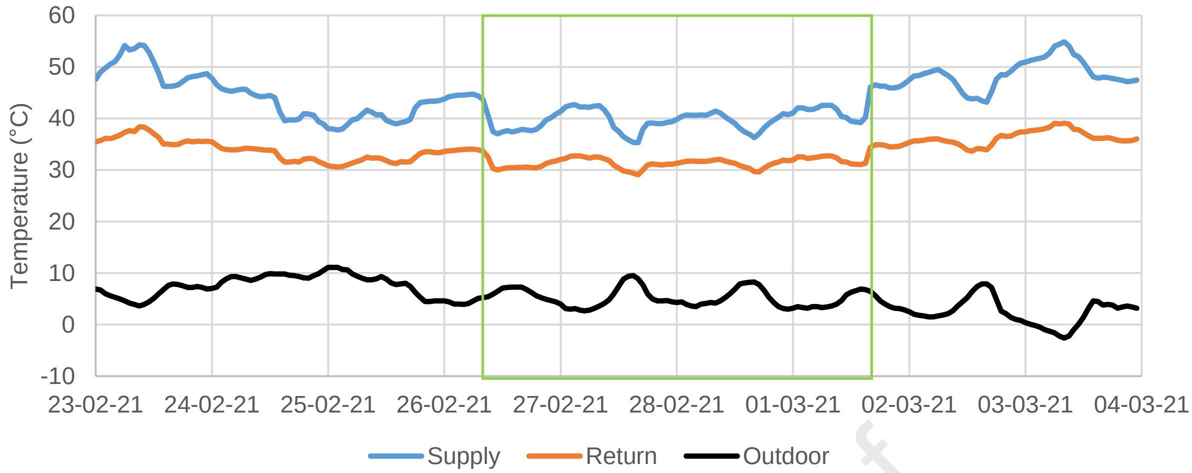

Figure 2. The radiator system recorded the supply, return, and outdoor temperatures between 23/2/2021 and 3/3/2021. In the green box, the period of reduced temperature is illustrated.

The reduction in the supply temperature resulted in a reduction in the overall return temperature of the radiator system below 35 °C, as illustrated in Figure 2. Particular attention was posed during the test to the end-users experience due to the low-temperature operations. It was found that only 3/42 apartments were experiencing some level of discomfort. Plotting the measured hourly supply temperature during the test in Figure 3, it was clear that the supply temperature was reduced close to the minimum calculated supply temperature under uniform heating.

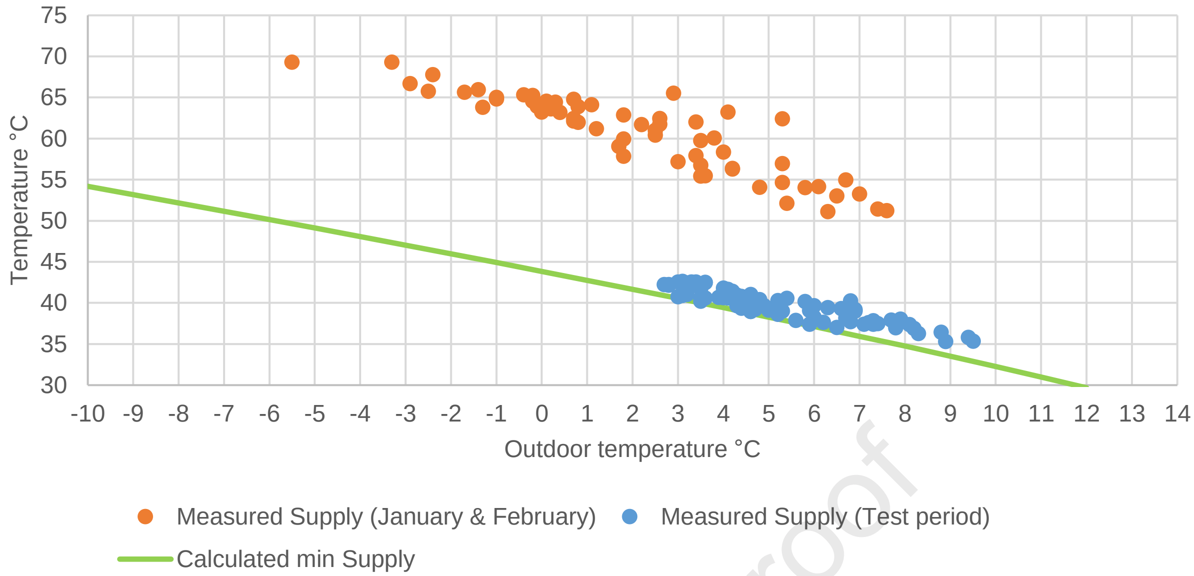

Figure 3. Measured supply temperature related to the outdoor temperature between 1/12/2020 and 31/1/2021 (before the test) and the testing period between 26/2/2021 and 1/3/2021, along with the calculated minimum supply curve for the system under uniform heating.

The test results highlighted two main elements: despite reducing the supply temperatures, the majority of the apartments did not experience any discomfort; hence, it is possible to meet the space heating demand with lower temperatures in the existing building. However, the three complaints suggested that the assumption of uniform heating among all apartments should be revised by considering the critical apartments' heat demand when calculating the minimum supply temperature. This can help secure the expected comfort in all apartments in the building.

3.4. Data from heat cost allocators to estimate the number of radiators not used in the system.

During the test of the minimum supply temperature in the building case, data from the heat cost allocators were used to detect the number of radiators not in use by identifying radiators with no new recording each day. By comparing the number of radiators not in use before and during the test, it could be possible to examine if the supply temperature reduction could increase the radiators in use in rooms where thermal comfort is essential.

Figure 4 shows the number of radiators not in use in the system for each day between 23/2/2021 and 3/3/2021, which is illustrated as a percentage of the total radiators in different apartments, excluding one radiator in one bedroom in each apartment. The radiator in the bedroom was excluded because end-users in Denmark typically do not heat their bedrooms.

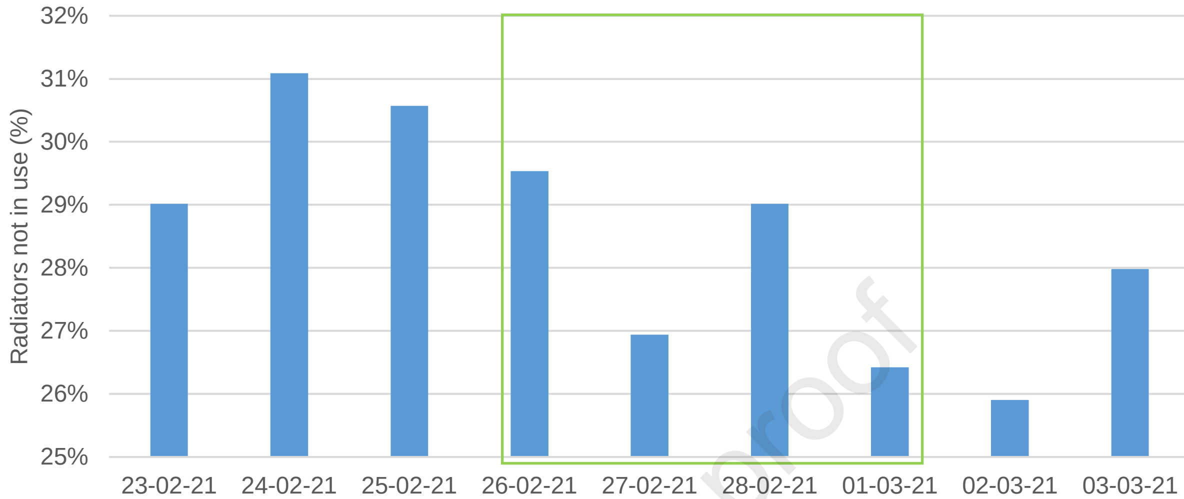

Figure 4. Percentage (%) of the radiators not in use in the system, excluding the radiators in one bedroom in each apartment, for each of the days between 23/2/2021 and 3/3/2021. In the green box, the period of reduced temperature is illustrated.

According to Figure 4, the number of radiators not in use before the test was close to 30%. The majority of the radiators not in use were small radiators located either at the entrance or in the bathroom, where thermal comfort is not critical at all times. Additionally, a lower indoor temperature might not affect the thermal comfort in critical rooms such as the living room. As a result, the specific building represents a well-operated system. During the reduced supply temperature period, there was a small increase in the radiators in use up to 3%. As a result, the reduction in the supply temperature stimulated the use of a few more radiators, even in this efficient operating system.

3.5. Data from heat cost allocators to address complaints regarding thermal comfort by end-users

During the reduced supply temperature between 26/2/2021 and 1/3/2021, the end-users of the three apartments complained of poor thermal comfort. Unlike the past, the electronic heat cost allocators can now help address the complaints from different apartments.

In Apartment 1 – located on the middle floor of the buildings, according to the data from heat cost allocators, all the available six radiators in the different rooms were used during the whole test period. The complaint was that the resident of the specific apartment preferred a higher indoor temperature than the standard 22 °C, which was not possible due to the low supply temperature. According to the data from the heat cost allocators, Apartment 1 was critical in the building.

In Apartment 2 – located on the ground floor of the building case, according to the data from heat cost allocators, all the available five radiators in the different rooms were in use.

In Apartment 3 – located on the ground floor of the building, according to the data from heat cost allocators, only two radiators were not in use during the test period: the radiators in the bathroom and entrance.

The complaints regarding the poor thermal comfort highlighted the necessity of identifying the critical apartments with higher heating demand. To fulfil the thermal comfort in these apartments, it is necessary to estimate the minimum supply temperature required in these apartments compared to the rest of the building. Finally, to achieve the potential for a minimum supply temperature in the heating system, it is necessary to investigate the reasons for the higher demand in these apartments and address them.

3.6. Data from heat cost allocators to identify the critical apartments and the calculation of the minimum supply temperature required based on the higher heat demand

Using data from the heat cost allocators between 4/1/2021 and 7/1/2021, the critical apartment of the building was identified along with the critical radiator of the apartment.

Table 2 presents all the inputs and intermediate calculated parameters required to calculate the minimum required supply temperature for the building considering the heating demand of the critical apartment identified. The data were obtained between 4/1/2021 and 7/1/2021 with a constant outdoor temperature of 0 °C and a constant temperature difference between supply and return temperature of 24 C. Under this temperature difference and by knowing the highest possible flow in the system, of 2.5 kg/s, the calculated total heating power in the specific period is 3-4 times higher than the calculated one from the actual energy measured. Consequently, it would be realistic to assume that the critical radiator gets a relatively high flow and a small temperature difference to deliver the required heat demand. A 5 °C temperature difference in the critical radiator was assumed that resulted in a flow of 0.058 kg/s based on the actual part-load operation of the critical radiator calculated by using data from the heat cost allocators.

Table 2. Inputs and the intermediate calculated parameters are required to calculate the minimum required supply temperature for the building during the period between 4/1/2021 and 7/1/2021, according to the critical radiator of the critical apartment.

Parameter	Critical radiator
The energy delivered for space heating according to data from heat cost allocators between 4/1/2021 and 7/1/2021.	0.12 MWh
Heated area.	10 m^2
Heat loss from the building between 4/1/2021 and 7/1/2021. Sum of energy for space heating and an internal gain of 5 W/m^2 and a heated area.	0.004 MWh
Nominal heating capacity of all the radiators in the critical apartment at 90/70/20 °C.	2.26 kW
Corrected heating capacity of the radiators, excluding radiators in the master bedroom and including the pipes to the radiators at 90/70/20 °C.	2.74 kW
The heating degree days ($HDD(T)$) between 4/1/2021 and 7/1/2021 based on an indoor temperature of 22 °C and daily average outdoor temperature from Danish Meteorological Institute for the actual period and location [40].	88
The calculated heat loss coefficient (L).	0,059 kW/K
Circulation flow used to find the temperature difference of the supply and the return temperature for different heating power.	0.058 kg/s

According to the calculation process described in Section **Error! Reference source not found.** the calculation of the minimum supply temperature to secure thermal comfort in the critical apartment is illustrated in Figure 5, along with the calculated return temperature of the system due to the potential optimal control of radiators in different apartments are also illustrated at each outdoor temperature between −12 °C and 12 °C.

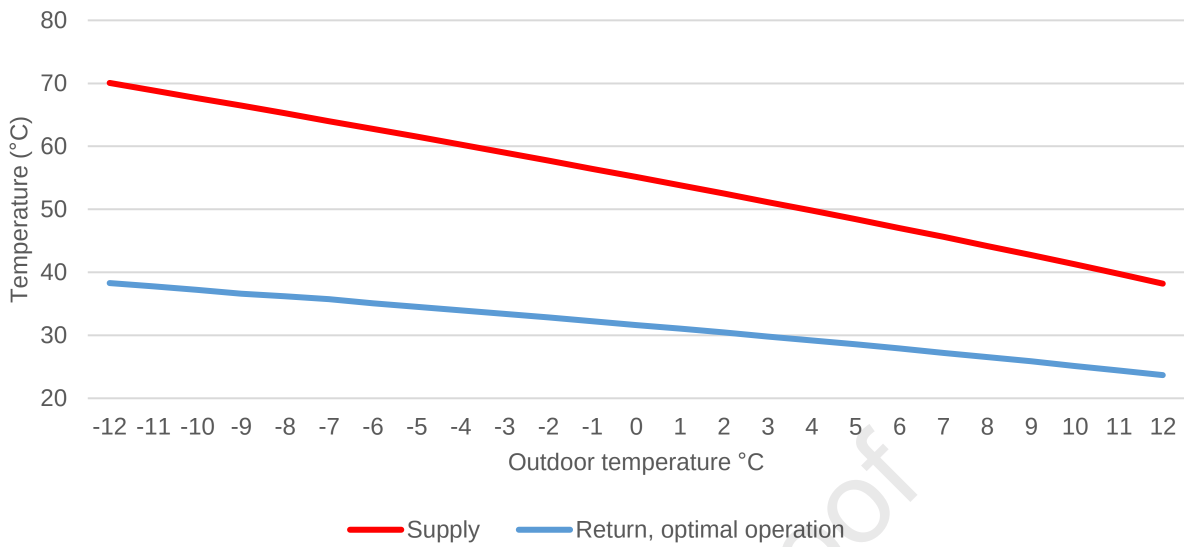

Figure 5. The minimum supply temperature required to secure thermal comfort by the critical apartment and consequently in the whole system, along with the calculated higher return temperature of the critical radiator and the calculated reduced return temperature due to possible control of radiators in other apartments.

According to the results, the minimum supply temperature required to secure thermal comfort in the critical apartment is relatively higher than the minimum supply temperature calculated under uniform heating of the building in Figure 1. According to Figure 5, an energy weighted average supply temperature of 55 °C can be achieved, resulting in an average energy weighted return temperature of 31.3 °C in the system.

3.7. Theoretical investigation of the higher heat demand in critical apartments

To identify the reasons for the higher heating demand in the critical apartments, a theoretical analysis was performed through detailed simulations by using IDA ICE [38] software. A section of the building of three identical apartments on three floors was modelled in IDA ICE, along with sections of the neighbouring apartments to estimate the vertical and horizontal heat transfer between the apartments. The apartment on the top floor of the buildings was assumed to be critical due to the higher external surface compared to the others. There were six rooms in each apartment: The section of the building modelled in the IDA ICE is illustrated in Figure 6. The areas of each room are listed in Table 3. The U-values of the building envelopes used in IDA ICE are presented in Table 4.

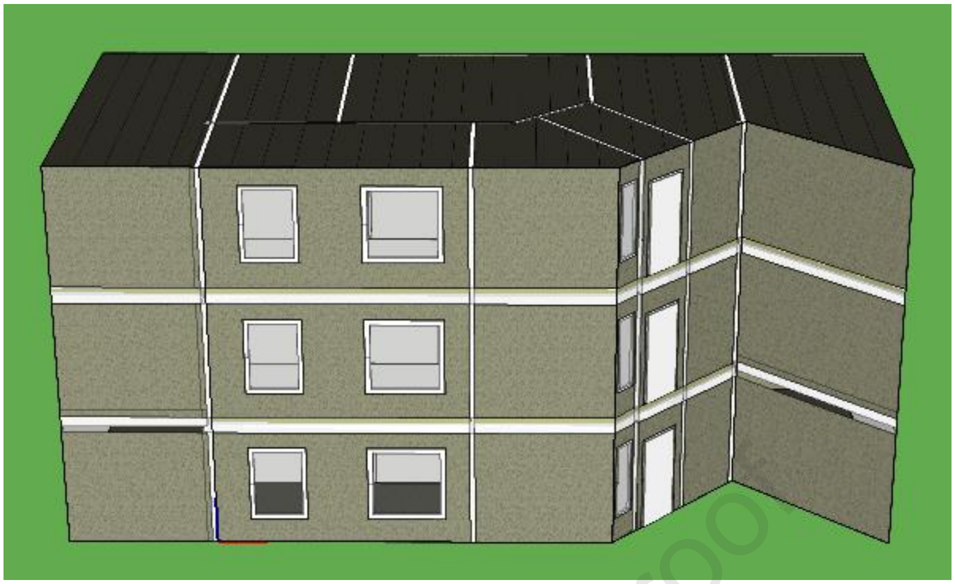

Figure 6. Section of the building modelled in IDA ICE.

Table 3. Areas of different rooms and the total area of each of the three identical apartments of the building section modelled in IDA ICE.

Room	Area (m^2)
Living room	20.6
Kitchen	12.4
Bathroom	6.1
Entrance	3.9
Master-bedroom	13.0
Bedroom	10.4
Total	66.4

Table 4. Thickness (m) and the U-value ($W/m^2\,K$) of the different elements of the building envelope used in IDA ICE for modelling the section of the building.

Elements of the building envelope	Thickness (m)	U-value ($W/m^2\,K$)
External Wall	0.35	0.20

Internal wall	0.10	2.60
Internal floors	0.35	0.48
External slab	0.37	0.28
Roof	0.35	0.18
Window glazing	-	2.9
Window frame	-	2.5

An ideal heater was implemented in every room to deliver the required heat. The size of the different ideal heaters was sufficient to maintain the selected heating setpoint in each zone during the dynamic annual simulation. In addition to the ideal heaters, internal gains of 5 W/m^2 were assumed in each room. The energy use for heating in the critical apartment was calculated under five different scenarios between 1/12/2020 and 31/1/2021. The weather data used to calculate the heat demand were according to the Danish Reference Year (DRY) conditions from 2001 to 2010 used in Denmark [39]. The following five scenarios were investigated to identify the increase in the heating demand of the critical apartment on the top floor.

Table 5. The different scenarios investigated in IDA ICE to investigate the increase of the heating demand in the critical apartment due to different heating setpoints between 1/12/2020 and 31/1/2021.

Scenario	Heating setpoint for the critical apartment (°C)	The heating setpoint of the neighbouring apartments (°C)	Calculated heat demand of the critical apartment (kWh)
1	22	22	2466
2	24	24	2763
3	24	22	2996
4	24	20	3239
5	24	18	3490

According to the results in Table 5, the heat demand increased by 12% from scenario 1 to scenario 2 due to higher heat loss to the outdoor environment because of the higher heating setpoint in all apartments. The increased heat demand from scenario 2 compared to scenarios 3, 4 and 5 due to higher heat loss to the poorly heated neighbouring apartments by 2 °C, 4 °C and 6 °C was 8%, 17% and 26%, respectively. The results highlight that the heat loss to the poorly heated neighbouring apartments may strongly influence the critical apartment's larger heat demand than the heat loss to the outdoor environment. This clearly suggests that the critical apartment can be located even in the middle of the building if the neighbouring apartments are not heated. Consequently, it is essential to use data from heat cost allocators to locate critical apartments in the building and calculate the minimum supply temperature required in the buildings based on the higher heat demand of these apartments.

4. Discussion

The calculation of the minimum supply temperature based on the critical apartment is relevant for multi-family buildings equipped with remotely readable heat cost allocators and energy meters. Although many buildings connected to DH systems or with central heating in different countries may not be currently equipped with digital metering devices, this situation will improve in the coming years in Europe. The last European Energy Efficiency Directive is binding member states to install heat cost allocators in multi-storey buildings with central heating to secure billing transparency for the end-users and replace existing meters with remotely readable ones by January 2027 [16].

The calculation of the minimum supply temperature was based on a heat loss coefficient considering the internal heat gain of 5 W/m^2. The calculation of the minimum supply temperature under the assumption of uniform heating or based on the critical apartment was performed during a selected period during December and January to minimise the effect of solar gains regarding the heat loss. As a result, the effect of solar gains was not considered in the calculation process. Moreover, the effect of the wind velocity on the natural ventilation of the different rooms was only included in the calculation of the heat loss coefficient as an average value. The heat loss may increase on days with an extra high wind velocity and hence, a slightly higher supply temperature may be required.

The test results highlighted that low temperatures could secure the expected comfort for the end-users, but the preliminary assumption of uniform heating distribution among all apartments needed to be improved. One of the three complaints during the test of the strategy in the building occurred because the residents preferred a higher heating setpoint than the typical value of 22 °C in their apartment, which was difficult to achieve with the minimised supply temperature in the system. Moreover, in the apartments where complaints occurred, almost all the radiators were in use, but it was still impossible to secure thermal comfort.

The improved minimum supply temperature based on the heat demand of the critical apartment, identified by using the data from heat cost allocators, was the solution to compensate for the non-uniform distribution of the heat demand and ensure thermal comfort. Due to the higher heat demand of the critical apartment, the new supply temperature shifted the curve up compared to the one calculated under uniform heating. Hence, this would secure comfort to all other apartments and, consequently, lower return from all other radiators due to the lower heat demand in the other apartments, as illustrated in Figure 5.

The investigation performed by dynamic simulations showed that the neighbouring poorly heated apartments may be more significant in relation to the higher heat demand than the heat loss to the outdoor environment. It is not rare to have unheated apartments due to a long absence of tenants – i.e. long holidays or very low indoor setpoints. , In this situation, the heat transfer among apartments might be significant and even cause thermal discomfort issues. This problem should be addressed to secure the expected comfort with low operating temperatures and fair heat distribution among apartments.

The investigation also showed that the reduction in the supply temperature in the system resulted in a small increase in the number of radiators in use. There was at least one radiator in each room in the specific building, even in areas such as the entrance. In the rooms where thermal comfort was required, all the radiators were continuously used, even before the reduction in the supply temperature on 26/2/2021. In buildings having common areas with more than one radiator to deliver the required heat demand, usually, one of the available radiators was used. In such buildings, the implementation of the strategy may increase the number of radiators in use.

Data from the electronic heat cost allocators proved to be an innovative solution to get insights about the operations of the space heating systems, detect the number of radiators not in use in different apartments, and locate the critical apartments in the building with higher heat demand. These can be of great support for building managers to correctly serve the heating systems and secure the comfort to the end-users with the lowest operating temperature possible.

5. Conclusions

This article presents a methodology to implement a strategy for low-temperature operation of a radiator system by calculating the required minimum supply temperature of the system and the innovative use of data from electronic heat cost allocators to detect radiators not in use and potential critical apartments with higher heat demand.

Implementing the methodology in a multi-family building case in Denmark showed that low-temperature operation is possible. However, the supply temperature should be calculated based on the radiators in the critical apartment with higher heat demand to secure the required thermal comfort. The results highlighted that an energy weighted average supply temperature of 55 °C was possible, resulting in an average energy weighted return temperature of 31.3 °C in the building. Hence, this investigation suggests that there are good potentials for low-temperature operation in the well-controlled heating system in existing buildings by accepting a slightly higher supply temperature to cover the larger heat demand in the critical apartments. This will also result in low return temperatures from all the radiators in the non-critical apartments due to the lower heat demand.

The test showed that the majority of the apartments were comfortably heated with lower supply temperatures, as well as an increase of 3% of the radiators in use in different apartments. However, the complaints regarding poor thermal comfort from three apartments showed that uniform heating could not be expected in multi-family apartment buildings.

The innovative use of data from the heat cost allocators is promising and helped pinpoint the critical apartments in the building and the radiators not in use in the system. Further investigations are necessary to make the data available to the building service personnel to address errors and complaints in the different apartments and secure an optimal operation of the heating systems.

Finally, the theoretical investigation performed by using dynamic simulations highlighted that the influence of poorly heated neighbouring apartments had the higher impact in increasing the heat demand of the critical apartments compared to the heat loss to the outdoor environment due to the higher external surface or the higher indoor temperature setpoints required by the end-users.

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- A Strategy for implementing a low-temperature operation of radiator system
- Calculation of the minimum required supply temperature based on critical flats
- Electronic heat cost allocators to detect errors in the system and critical flats
- Stimulating the use of more radiators by the end-users
- Heat loss to poorly heated neighbouring flats influences critical flats

Declaration of interests

☒ 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.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: