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On the Minimum and Maximum Variable Cost of Heating of the Flat in Multifamily Building

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Abstract: Heat cost allocation is commonly used in existing buildings supplied by centralized sources of heating/cooling and provided with individual metering systems. However, this process is not always fair for the users, since "fairness" strongly depends on the methods established to allocate variable and fixed costs among the dwellings. That is why unrealistic cost for heating may be allocated for specific flats. However, there is a lack of evidence about procedures as to how maximum and minimum variable cost of heating may be calculated for specific flats in multifamily building for a specific heating season. This paper presents different methods for estimation of maximum and minimum variable cost of heating of flat in multifamily buildings, the use of which depends of the availability of input data for specific buildings. Evaluation of the proposed methods is made on the example of a case study multifamily building located in Poland. It was shown that the maximum variable costs of heat purchase for specific flats in the analyzed building were in the range from 169% to 256% of the average unit cost of heat, depending on the method used. The recommendation about the accuracy of proposed methods is also provided by the authors.

Keywords: heat allocation; heat cost allocator; heat metering; energy efficiency in buildings; multi-family buildings; residential sector; heating costs; thermostatic radiator valve

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1. Introduction

It is well-known that individual metering and heat cost allocation in multifamily buildings may contribute to decrease of energy consumption depending on the analyzed case by around 25–30% [1], 15–20% [2], or 20–35% [3]. In this regard, Calise et al. proposed and validated a method for proper calculation of energy savings owing to heat metering [4] or heat metering and thermostatic radiator valves [5].

Additionally, electronic heating cost allocators (HCAs) can be used to calculate the lowest possible supply temperature in the building's heating system [6], which leads to an increase in the energy efficiency of the space heating system [7].

However, the heat cost allocation may simultaneously generate problems [8,9], which are mainly connected with variable cost of heating and different assumptions used in this process [10]. One of the main issues is also the location of specific flats in a building [11], the heat transfer between apartments, and the ways (if and how) to include it in the heat cost allocation in the specified building [12,13]. In this regard, a model for developing credible heat accounting systems was proposed by Dell'Isola et al. [14]. The method proposed by Michnikowski and Cholewa [15] allows for the elimination of not technically-justified HCAs readings in individual flats. Ficco et al. [16] experimentally assessed the metrological efficiency of indirect systems and direct thermal energy meters for heat metering, emphasizing certain significant operative metrological effects related to the various available methods of heat accounting. To increase the fairness of heat cost allocation process by addressing room heat transfer, the game theory was used by Xue et al. [17]. As regard to fairness of heat cost allocation, Dell'Isola et al. [18] presented a new method for heat cost allocation based on the calculation of the extra-consumptions due to building inefficiencies. According to this method, energy-efficient retrofit interventions are encouraged by charging all tenants with extra-consumptions. Stauffer et al. [19] proposed a method for accurate indirect heat accounting in apartment buildings, which is based on the temperature difference between the heating medium and the indoor air. Because HCAs may also be used for other purposes, such as low-temperature operation of radiators system [7], it is crucial to omit wrong readings and have a valid and fair allocation process of heating costs. One such solution is, for example, the limits regarding the minimum and maximum variable cost of heating, which, in the Czech Republic, should be between 80% and 200% of average cost (related to m^2) for a building [20]. However, the above-mentioned percentage method does not take into account local conditions for a given building and apartment, which affect the maximum and minimum amount of heat supplied to a given apartment for heating purposes. For example, in Poland [21], if HCAs are used in heat allocation process, the building owner or manager should be able to estimate the minimum and maximum variable cost of heating for a specific apartment for each real heating season. In this regard, the maximum variable cost of heating should be calculated as the heat consumption for a given flat resulting from the technical possibility of supplying heat to the flat. The minimum variable cost of heating should be calculated as a value of heat consumption for heating necessary to maintain the indoor temperature not lower than minimum allowed temperatures [21] of the heated rooms. This is especially important for owners of the flats, who would like to know which kind of minimum and maximum cost of heating of their flat they may foresee in specific heating seasons. Such methods are not used in practice, but they may easily solve a lot of problems and misunderstandings which are presented by heat cost allocation.

That is why more accurate methods are needed in this regard. However, to the best of the authors' knowledge, there are no international publications which propose such detailed methods (taking into account energy characteristics, meteorological conditions, and social aspects) that may be used to estimate the minimum and maximum variable cost of heating for a specific apartment for each real heating season and in such a way to ensure fairness of the heat cost allocation process.

The objectives of this paper are to present and evaluate different methods for estimation of maximum and minimum variable cost of heating for specific flat in multifamily building in actual heating season. The availability of input data in existing buildings will also be taken into account by descriptions of specific methods in order to find cost-effective solutions for each building.

2. Methods

A number of different calculation methods can be used to determine the maximum and minimum variable cost of heat purchase depending on the specific consumption of flats in a given heating season. However, for a given calculation method to be successfully used in practice in existing buildings, it should be characterized by the following features: (i) the method should be as simple as possible to apply, and at the same time as accurate as possible and in accordance with the rules of technical knowledge applicable in this topic; (ii) the method should minimize additional costs and time (in relation to the existing condition in a given building), which are needed to obtain additional information for the purpose of possibly increasing the accuracy of the calculations performed; (iii) the method should be fully understandable to the person (also a person who does not have detailed technical knowledge and/or many years of practice in this field) who uses a given method in a specific facility or group of facilities, so that he or she can answer the questions from users that arise in the future and internally solve possible the problems that arise.

Most often, in practice, the entities dealing with the allocation of heating costs have the following information: flat surfaces; values of readings from heat cost allocators; type, size and power of radiators (based on the inventory of radiators installed in individual apartments); value of the average outdoor temperature in a given heating season; the duration of the heating season; heat consumption of the whole building during the heating season; design heat load of the entire building and individual flats (calculated in accordance with the EN 12831 standard [22]), which is used by these entities to calculate the compensation factors for heat consumption for heating resulting from the location of the flats in the building. Therefore, taking the above into account, selected methods for determining the maximum and minimum variable cost of heating depending on the specific consumption of flats, which mainly use the information held by entities dealing with the allocation of heating costs, are presented below.

The limitations of the proposed methods and their accuracy come from the availability and quality of information and data used in heat cost allocation. These methods do not calculate the exact heat used for heating of a specific flat in a particular heating season, but rather the maximum and minimum levels between which the heat used should be in order to ensure fairness of this process.

2.1. Methods for Determining the Maximum Variable Cost of Heating of a Particular Flat in a Multifamily Building

For the purposes of determining the maximum variable cost of heat depending on its consumption in the flats, it is recommended to determine the value of heat consumption for a given flat resulting from the technical possibilities of heat supply to the particular flat in a given heating season. For this purpose, various calculation methods can be used (including those using advanced simulation programs, e.g., TRNSYS, EnergyPlus); therefore, selected methods are presented below.

2.1.1. Method That Uses the Power of the Installed Radiators ($C_{max}{}^1$ Method)

For the purposes of determining the maximum cost, it is suggested to first use the method (marked as $C_{max}{}^1$), which is based on the thermal power of radiators ($\Sigma Q_{radiators}$), in a given apartment as the method by which the actual conditions in a given apartment can be mapped best.

In these cases, radiators cover the total heat losses related to heat transfer through building partitions, as well as those associated with heating the ventilation air (in the case of natural or mechanical exhaust ventilation commonly used in existing buildings). In the case of mechanical supply and exhaust ventilation with heat recovery, radiators usually do not provide thermal power for the purpose of heating the ventilation air, because the heating of the ventilation air is carried out centrally in the ventilation unit.

For the purposes of systematizing this method, three calculation stages were distinguished within it.

Stage 1—Determination of the thermal power of radiators in a given apartment ($\Sigma Q_{radiators}$).

The total heat output of radiators in a given apartment ($\Sigma Q_{radiators}$) should be determined for the current operating parameters of a given heating system in a building in a given heating season. Therefore, the heating power of the radiators should be assumed for the average temperature of the heating medium at the supply (t_{supply}) and return (t_{return}) in a given heating season and the design value of the indoor temperature (t_{indoor}) in a given heated room.

The values of the heating power of the radiators under given operating conditions can be read from the catalogue of the given manufacturer and the given radiator, as well as the current operating parameters of the heating installation (t_{supply}/t_{return}) in a specific heating season, as well as for the design value of the indoor temperature (t_{indoor}) in a given heated room (assumed in most cases as t_{indoor} = 20 °C). The current values of the heating system operating parameters (in particular t_{supply}) in a given heating season can be read from the heating curve (t_{supply} dependence on $t_{outdoor}$, which is programmed in the weather-based controller of a given heat source) for the mean outdoor temperature in a specific heating season ($t_{outdoor}^{mean}$).

In addition, if the building has been thermally insulated (heat demand for heating has been reduced) but the existing radiators have not been replaced, they will still be able to transfer the heat power to the rooms for which they were previously selected.

Stage 2—Determination of the value of the maximum energy used for heating of given flats ($Q_{H,nd}^{max}$).

The value of the maximum usable energy to heat a given apartment in a given heating season to the maximum indoor temperature (t_{indoor}^{max}), i.e., the one that can be set on a thermostatic head or other local control device used in a given apartment, can be determined using Equation (1) [23], which allows for a simplified way to switch from thermal power to heat demand.

Therefore, it is necessary to check what maximum indoor temperature in a heated room can be set with the use of a given type of thermostatic heads in a given building. Most often, the maximum indoor temperature that can be set on commonly used thermostatic heads is 26 °C or 28 °C. Taking this into account, there are theoretically technical possibilities to ensure such indoor temperature inside a heated room (especially in the case of outdoor temperature higher than the design value in a given climatic zone). However, in the absence of the information on the type of installed thermostatic heads or lack of access to archival catalogue cards of the thermostatic heads used, t_{indoor}^{max} can be assumed at a minimum of 24 °C.

$$Q_{H,nd}^{max} = 8.64 \cdot HDD_{real}^{t_{indoor}^{max}} \cdot \frac{\sum Q_{radiators}}{t_{indoor} - t_{outdoor}} \cdot 10^{-5} \left[\frac{\text{GJ}}{\text{year}}\right] \tag{1}$$

where:

$HDD_{real}^{t_{indoor}^{max}}$—the number of degree days for maximum indoor temperature (t_{indoor}^{max}), calculated according to Equation (2), K·d/year,

$\Sigma Q_{radiators}$—thermal power of radiators used in a given apartment for the actual temperature of the heating medium on the supply and return at the design outdoor temperature in a given location of the building, W,

t_{indoor}—design indoor temperature in heated rooms in a given apartment, t_{indoor} = 20 °C,

$t_{outdoor}$—design outdoor temperature in a given location of the building, adopted depending on the climatic zone, °C.

$$HDD_{real}^{t_{indoor}^{max}} = L_{dsez} \cdot \left(t_{indoor}^{max} - t_{outdoor}^{real}\right) \ [\text{K} \cdot \text{d/year}] \tag{2}$$

where:

L_{dsez}—number of days of the heating season according to meteorological data, d/year,

t_{indoor}^{max}—maximum indoor temperature that can be set on the thermostatic head or other local control device used in a given apartment, °C,

$t_{outdoor}^{real}$—real, mean outdoor temperature in a particular heating season, °C.

The number of days of the heating season in a given building location (L_{dsez}) can be assumed on the basis of the actual start and end date of a given heating season, which results from the start and end date of heat supply for heating by the heat supplier for the analysed building. The actual, mean outdoor temperature in a particular heating season ($t_{outdoor}^{real}$) can be assumed on the basis of own measurements, the measurements carried out by the heat supplier, or the measurements carried out by a meteorological station, which is located in the closest possible location of a given building.

Stage 3—Determination of the maximum final energy used for heating the flats (Q_{kH}^{max})

Determination of the maximum final energy used for heating of a given apartment in a given heating season to the maximum indoor temperature (t_{indoor}^{max}) can be done using Equation (3).

$$Q_{kH}^{max} = \frac{Q_{H,nd}^{max}}{\eta_{system}} \left[\frac{\text{GJ}}{\text{year}}\right] \tag{3}$$

where:

η_{system}—the seasonal average overall efficiency of the building's heating system, which may be calculated using Equation (4).

$$\eta_{system} = \eta_{H,g} \cdot \eta_{H,s} \cdot \eta_{H,d} \cdot \eta_{H,e} \tag{4}$$

where:

$\eta_{H,g}$—mean seasonal efficiency of heat production,

$\eta_{H,s}$—mean seasonal efficiency of heat accumulation in capacitive elements of the heating system in building,

$\eta_{H,d}$—seasonal average efficiency of heat distribution from the heat source to the heated space,

$\eta_{H,e}$—average seasonal efficiency of regulation and use of heat in the heated space.

The values of specific average efficiency of the heating system (mentioned above) can be taken on the basis of, for example, EN 15316-2:2017 [24].

2.1.2. Method Using the Value of the Design Heat Load in the Flats (Method $C_{max}{}^2$)

For the purpose of determining the maximum cost of heating in a given apartment, when there is no information about the current power of installed radiators, a method (marked as $C_{max}{}^2$) can be used, which is based on the values of the design heat load (Φ_{HL}) determined for individual apartments in a given building. However, in the case of existing buildings, if the building is retrofitted but the heating curve has not been lowered, then Φ_{HL} should be assumed for pre-renovation conditions, as the radiators will still be able to transfer this heat output to the heated room. However, if the building is after thermal modernization and the heating curve has been lowered and/or radiators have been replaced with smaller ones, then Φ_{HL} should be assumed for the conditions after thermal insulation.

Stage 1—Determination of the heat output of radiators in a given apartment ($\Sigma Q_{radiators}$) based on the value of the design heat load in a given apartment (Φ_{HL})

Equation (5) was used to convert from the value of the design heat load in the flats (Φ_{HL}) to the heat output of the radiators ($\Sigma Q_{radiators}$).

$$\sum Q_{radiators} = 1.25 \cdot \Phi_{HL} \ [\text{W}] \tag{5}$$

The value of 1.25 in Equation (5) was adopted on the basis of technical knowledge used in the process of designing heating installations in buildings (in particular, the selection of convection heaters), because the selection of heaters takes into account the impact of using a thermostatic radiator valve by increasing the required heat output of the heater by 15%; the influence of the radiator cover (e.g., window sill), the average value of increasing the radiator's thermal power on this account was assumed at the level of 5%, and the impact of cooling the heating medium on the distance between heat source and radiators. The average value of increasing the heater's thermal power on this account was assumed at the level of 5%. In addition, it should be emphasized that designers of heating systems usually select the thermal power of radiators to be even higher than the calculated thermal power of the radiator. Therefore, in reality, the radiators may have a thermal power even higher than that estimated by the use of Equation (5).

After determining the thermal power of the radiators installed in a given apartment ($\Sigma Q_{radiators}$), further calculations should be made in the same way as presented in the method $C_{max}{}^{1}$, which is described in Section 2.1.1, in particular according to stage 2 and stage 3.

2.1.3. Method Based on Characteristic of Radiator (Method $C_{max}{}^{3}$)

This method assumes the lack of rational use of the heat supplied by the radiators installed in the flats in the case of intensive, over-standard ventilation. The first step in this method is the current inventory of radiators for the most frequently used heating medium parameters 90/70/20 °C [25]. The power of the installed radiators can also be calculated for other parameters. The following relationships are used to determine the maximum variable cost in frame of this method, namely:

- the dependence of the heat load on the change in outdoor temperature (Equation (6)).

$$Q_{radiators}^{average} = Q_{radiators}^{max} \frac{t_{indoor} - t_{outdoor}^{real}}{t_{indoor} - t_{outdoor}} \text{ [W]} \tag{6}$$

- the dependence of thermal power of radiator on changes in the average heating medium temperature (Equation (7)) [23].

$$\frac{Q_{radiators}^{average}}{Q_{radiators}^{max}} = \left(\frac{\Delta t}{\Delta t_{max}}\right)^{k} \tag{7}$$

where:
$\Delta t = t_{radiators}^{average} - t_{indoor}$ [K]
$t_{radiators}^{average} = \frac{t_{supply}+t_{return}}{2}$ or $\frac{t_{supply}+t_{return}}{\ln\frac{t_{supply}-t_{indoor}}{t_{return}-t_{indoor}}}$ for small flows
$\Delta t_{max} = \frac{t_{supply}+t_{return}}{2} - 20^{o}\ for\ example = \frac{90+70}{2} - 20\ ^{o}\mathrm{C} = 60\ \mathrm{K}$
k—exponent depending on the type of radiator
Transforming the Equation (7) to the form of Equation (8).

$$Q_{radiators}^{average} = Q_{radiators}^{max} \left(\frac{\Delta t}{\Delta t_{max}}\right)^{k} \text{ [W]} \tag{8}$$

Afterwards, it is possible to determine the maximum amount of heat delivered to the flats during the τ heating period, taking into account the actual power of the radiators installed for the case of intensive ventilation. Then, the demand for heat in the flats exceeds the values obtained for the so-called design conditions. This relationship has the form presented in Equation (9).

$$Q_{H,nd}^{max} = Q_{radiators}^{max} \left(\frac{\Delta t}{\Delta t_{max}}\right)^{k} \tau \text{ [Wh]} \tag{9}$$

Depending on Equation (9), the mean temperature of the heating medium $t_{radiators}^{average}$ for the average outdoor temperature of the heating season $t_{outdoor}^{real}$, which is ensured in heating system by weather-based control in the building, is unknown. That is why it can be determined from Equation (10), describing the operation characteristics of the weather-based control for a given slope of the heating curve.

$$\Delta t = 60 \left(\frac{t_{indoor} - t_{outdoor}^{real}}{t_{indoor} - t_{outdoor}}\right)^{1/k} \text{ [K]} \tag{10}$$

2.2. Methods for Determining the Minimum Variable Cost of Heating Specified Flats in a Multifamily Building

For the purposes of determining the minimum variable cost of heat supplied to the flats in order to maintain the minimum indoor temperature in it (e.g., in Poland t_{indoor}^{min} is equal to 16 °C [26]), different computational methods may also be used. Therefore, selected ones (depending on the available input data) are presented below.

The minimum indoor temperature level (t^{min}_{indoor} = 16 °C) is connected with the requirement (for example, valid in Poland) that TRVs in multifamily buildings should not allow the indoor temperature to decrease below 16 °C.

2.2.1. Method That Uses the Value of the Annual Demand for Heat in Given Flats ($C_{min}{}^{1}$)

Within this method, 3 stages can also be distinguished, which are presented below.

Stage 1—Determining the value of the minimum usable energy to heat a given apartment ($Q_{H,nd}$) in a standard heating season

The seasonal demand for usable energy for heating and ventilation ($Q_{H,nd}$) in a given apartment for the minimum indoor temperature (t^{min}_{indoor} = 16 °C) is calculated for the data from the standard heating season in a given location in accordance with [27] or in accordance with [28], which is still used in the calculation process conducted with the use of many computer programs.

In the calculation of the seasonal demand for usable energy for heating and ventilation ($Q_{H,nd}$) of a given apartment, the amount of heat needed to heat the ventilation air is also taken into account (in the case of natural or mechanical exhaust ventilation commonly used in existing buildings). The value of the ventilation air stream adopted for the calculations should be in accordance with relevant guidelines that are in force in a given country. For example, in Poland, in the case of natural ventilation, the ventilating air stream can be determined, assuming an air exchange rate of 0.5 1/h, which is indicated in the standard [22]. In the majority of existing buildings (after replacing the window), there are significant problems with the proper operation of natural ventilation, and the air exchange rate may be lower than calculated. In these calculations, it is also possible to assume ventilation air flow (especially in the case of using mechanical exhaust ventilation in the kitchen and bathroom in a given building) for example on the basis of the standard [29]. In this case, it is assumed that the ventilation air flow is equal to the air flow removed from the rooms in the following amounts, e.g.,: bathroom (with or without toilet): 50 m^3/h; toilet: 30 m^3/h; kitchen with a window and a gas or coal stove: 70 m^3/h; kitchen with a window and an electric cooker: 30 m^3/h in an apartment for up to 3 people; 50 m^3/h in an apartment for more than 3 people; kitchen without a window but with an electric cooker: 50 m^3/h.

Stage 2—Determination of the minimum usable energy to heat the flats ($Q^{min}_{H,nd}$) in a given heating season

After determining the seasonal demand for usable energy for heating and ventilation ($Q_{H,nd}$) in the flats for the minimum indoor temperature (t^{min}_{indoor} = 16 °C) in the standard heating season, which is most often done using the software supporting engineering calculations, it is necessary to switch from the seasonal demand for usable energy for heating and ventilation ($Q_{H,nd}$) in a given apartment in the standard heating season to the value of the seasonal demand for usable energy for heating and ventilation ($Q^{min}_{H,nd}$) in a given apartment in a given (current) heating season using Equation (11).

$$Q^{min}_{H,nd} = Q_{H,nd} \cdot \frac{HDD^{t^{min}_{indoor}}_{real}}{HDD^{t^{min}_{indoor}}_{standard}} \left[\frac{\text{GJ}}{\text{year}}\right] \tag{11}$$

where:

$Q_{H,nd}$—seasonal demand for usable energy for heating and ventilation in a given apartment for the minimum indoor temperature (t^{min}_{indoor} = 16 °C) in a standard heating season, GJ/year,

$HDD^{t^{min}_{indoor}}_{real}$—the number of degree days for the minimum indoor temperature (t^{min}_{indoor}) in a given (current) heating season, calculated in accordance with Equation (12), K·d/year,

$HDD_{standard}^{t_{indoor}^{min}}$—the number of degree days for the minimum indoor temperature (t_{indoor}^{min}) in a standard heating season, calculated in accordance with Equation (13), K·d/year,

$$HDD_{real}^{t_{indoor}^{min}} = L_{dsez} \cdot \left(t_{indoor}^{min} - t_{outdoor}^{real} \right) \text{ [K·d/year]} \quad (12)$$

where:

L_{dsez}—number of days of the heating season according to meteorological data in a given (current) heating season, d/year,

t_{indoor}^{min}—minimum indoor temperature that can be set on a thermostatic head or other local control device used in a given apartment, t_{indoor}^{min} = 16 °C,

$t_{outdoor}^{real}$—real, average outdoor temperature in a given heating season, °C.

$$HDD_{standard}^{t_{indoor}^{min}} = L_{dsez}^{standard} \cdot \left(t_{indoor}^{min} - t_{outdoor}^{standard} \right) \text{ [K·d/year]} \quad (13)$$

where:

L_{dsez}^{st}—number of days of the heating season according to meteorological data in a standard heating season (please see Section 2.1), d/year,

$t_{outdoor}^{standard}$—average outdoor temperature in a standard heating season, °C.

Stage 3—Determination of the value of the minimum final energy used for heating of the flats (Q_{kH}^{min}) in a given heating season

Determination of the minimum final energy to heat a given apartment in a given heating season to an indoor temperature of t_{indoor} = 16 °C can be determined using Equation (14).

$$Q_{kH}^{min} = \frac{Q_{H,nd}^{min}}{\eta_{system}} \left[\frac{\text{GJ}}{\text{year}} \right] \quad (14)$$

2.2.2. Method Using the Value of the Design Heat Load in Flats ($C_{min}{}^2$)

Stage 1—Determination of the design heat load in given flats (Φ_{HL})

For the purpose of determining the minimum cost of heating of given apartment, when it is not possible to calculate the seasonal demand for usable energy for heating and ventilation ($Q_{H,nd}$) in a given apartment (see Section 2.2.1), the $C_{min}{}^2$ method can be used, which is based on the values of the design load (Φ_{HL}) determined for individual flats in a given building (according to the standard [22]) for calculation conditions and, most often, indoor temperature equal to 20 °C.

Stage 2—Determination of the value of the minimum usable energy to heat the flats ($Q_{H,nd}^{min}$) in a given heating season

The minimum value of usable energy to heat a given flats ($Q_{H,nd}^{min}$) in a given heating season can be determined using Equation (15).

$$Q_{H,nd}^{min} = 8.64 \cdot HDD_{real}^{t_{indoor}^{min}} \cdot \frac{\Phi_{HL}}{t_{indoor} - t_{outdoor}} \cdot 10^{-5} \left[\frac{\text{GJ}}{\text{year}} \right] \quad (15)$$

where:

Φ_{HL}—design heat load for the flats at the design outdoor temperature at the building location and t_{indoor} = 20 °C, W,

t_{indoor}—design indoor temperature in heated room, t_{indoor} = 20 °C,

$t_{outdoor}$—design outdoor temperature in a given location of the building, assumed depending on the climatic zone, °C.

After determining the value of the minimum usable energy to heat the flats ($Q_{H,nd}^{min}$) in a given heating season, further calculations are performed (stage 3) similarly to the $C_{min}{}^1$ method described in Section 2.2.1.

2.2.3. Method That Uses the Value of Seasonal Heat Demand of a Building and Compensation Factors (CFs) for Heating ($C_{min}{}^{3}$)

As part of this method, the seasonal demand for usable energy for heating and ventilation ($Q_{H,nd}^{building}$) should be determined for the building at the minimum indoor temperature (t_{indoor}^{min} = 16 °C) and not for individual flats, as was the case in the method $C_{min}{}^{3}$.

Stage 1—Determining the value of the minimum usable energy to heat the building ($Q_{H,nd}^{building}$) in a standard heating season

The value of $Q_{H,nd}^{building}$ at the minimum indoor temperature (t_{indoor}^{min} = 16 °C) can be determined using the software supporting engineering calculations or taken, for example, from an energy audit (if available for the analysed building). The details regarding the assumptions of the amount of ventilation air are provided in Section 2.1.

Stage 2—Determining the value of the minimum usable energy to heat the building ($Q_{H,nd}^{building}$) in a given heating season

After determining the seasonal demand for usable energy for heating and ventilation ($Q_{H,nd}^{building}$) of the given building for the minimum indoor temperature (t_{indoor}^{min} = 16 °C) in the standard heating season, the value of the seasonal energy demand for heating and ventilation of the given building in the given (current) heating season should be estimated using Equation (16).

$$Q_{H,nd}^{min,\ building} = Q_{H,nd}^{building} \cdot \frac{HDD_{real}^{t_{indoor}^{min}}}{HDD_{standard}^{t_{indoor}^{min}}} \left[\frac{\text{GJ}}{\text{year}}\right] \tag{16}$$

where:

$Q_{H,nd}^{building}$—seasonal demand for usable energy for heating and ventilation of a given building for the minimum indoor temperature (t_{indoor}^{min} = 16 °C) in a standard heating season, GJ/year.

Stage 3—Determining the value of the minimum final energy used for heating of the building ($Q_{kH}^{min,building}$) in a given heating season

The minimum seasonal demand for final energy for heating and ventilation of the building can be determined from Equation (17).

$$Q_{kH}^{min,building} = \frac{Q_{H,nd}^{min,\ building}}{\eta_{system}} \left[\frac{\text{GJ}}{\text{year}}\right] \tag{17}$$

Stage 4—Determination of the minimum value of the unit heat consumption for the purpose of heating a given apartment in a given heating season

The minimum value of $q_{j,minB}$ [GJ/(m^2·year)] for the building in relation to the heated area of the building (A) was determined from Equation (18).

$$q_{j,minB} = \frac{Q_{kH}^{min,building}}{A} \quad [\text{GJ}/(\text{m}^2\cdot\text{year})] \tag{18}$$

In turn, the minimum value of the $q_{j,minL}$ [GJ/(m^2·year)] for a given apartment, taking into account the compensation factors (*CFs*) for heat consumption for heating purposes related to the location of a given apartment in the building, can be determined from Equation (19).

$$q_{j,minL} = q_{j,minB} \cdot \frac{1}{CF} \quad [\text{GJ}/(\text{m}^2\cdot\text{year})] \tag{19}$$

Compensation factors for heat consumption for heating purposes (*CFs*), taking into account the location of a given apartment in the building, can be adopted on the basis of calculations of the demand for usable energy (recommended method) [30] or calculations of the design heat load. *CFs* may be determined based on a calibrated simulation method, as was presented by Ling et al. [31].

2.3. The Minimum and Maximum Variable Cost of Heat Used for Heating Flats in a Multi-Unit Building in the Case of Using CFs in Heat Cost Allocation Process

The above methods (see Sections 2.1 and 2.2) of determining the minimum and maximum heat consumption for the purposes of determining the minimum and maximum variable heating costs are particularly useful when the calculation of heating costs does not include the compensation factors (*CFs*), which take into account the location of the flats in building.

However, if in the process of heating costs allocation, heat consumption compensation factors for heating purposes (*CFs*) are used, this allows for taking into account the specific location of each apartment in a given building block and thus adjusting heat consumption for the needs of heating in a given building to the average unit level of heat consumption for the needs of heating in a given building expressed in [GJ/(m^2 year)]. Therefore, taking into account that the indications of heating cost allocators are corrected (by the use of *CFs*) in this process due to the location of the flats in the building, it is also possible to determine the maximum level of heat consumption for heating purposes in a given building ($Q_{kH}^{max,building}$) using the methods described in Section 2.1, as well as the minimum level of heat consumption for heating purposes in a given building ($Q_{kH}^{min,building}$) using the methods described in Section 2.2. Hence, there is no need to carry out detailed calculations in this regard for each apartment, which greatly simplifies the calculation process.

Thus, having the values of $Q_{kH}^{max,building}$ or $Q_{kH}^{min,building}$, the unit value of the maximum (Equation (20)) and the minimum (Equation (21)) heat consumption level for a building in relation to the heated area of a given building (A) are determined.

$$q_{j,max} = \frac{Q_{kH}^{max,building}}{A} \ [\mathrm{GJ/(m^2 \cdot year)}] \tag{20}$$

$$q_{j,min} = \frac{Q_{kH}^{min,building}}{A} \ [\mathrm{GJ/(m^2 \cdot year)}] \tag{21}$$

The next step is to determine the maximum and minimum heat consumption for a given apartment in a building using Equations (22) and (23), respectively, and taking into account the heated area of a given apartment in the building (A_{local}).

$$Q_{max}^{local} = q_{j,max} \cdot A_{local} \ [\mathrm{GJ/year}] \tag{22}$$

$$Q_{min}^{lok} = q_{j,min} \cdot A_{local} \ [\mathrm{GJ/year}] \tag{23}$$

3. Case Study

In order to analyze the correctness of the presented calculation methods and the adopted simplifying assumptions, calculations were made in the *Audytor OZC* software [32] for an existing building before and after thermorenovation. The building is a four-story multi-family building with a basement and ventilated roof, made using large slab technology (Figure 1). The building has 16 apartments—there are 4 flats on each floor, with the areas in the range of 54.32 m^2 to 82.40 m^2. The total area of apartments is 1019.66 m^2. The kitchens in the flats are equipped with gas cookers, two apartments on each floor have bathrooms, and two have additional separate toilet rooms. The building is located in Gliwice (in Poland), where the design outdoor temperature is −20 °C. There is natural gravitational ventilation, executed through individual ventilation channels in the building. The building has a heating substation without an accumulation tank and is powered by the municipal heating network. The central heating installation is equipped with thermostatic radiator valves.

Figure 1. View of the analyzed building.

During the thermorenovation, the building was adapted to the state required in Polish technical conditions for residential buildings [26]. Building partitions were insulated so that the heat transfer coefficients were in accordance with the applicable Polish standards. The efficiency of the heating installation was increased. Efficiency values of the heating system were adopted in accordance with the Regulation [33]. It was assumed that the insulation of the pipelines in the basement and the thermostatic valves were replaced as part of the modernization of the central heating installation. As a result, the efficiency of heat transfer in pipelines and control efficiency increased.

3.1. Materials and Methods

Calculations of the maximum and minimum unit final energy consumption for heating and ventilation purposes of individual apartments were performed in order to determine the maximum and minimum variable cost of heat purchase for each flat in the analyzed building during the standard heating season. The weighted average temperature of the standard heating season for Gliwice is 3.14 °C and the duration of the season is 222 days (all days in the period from October to April and 5 days in September and May, according to [34]).

Calculations of the design heat load of flats Φ_{HL} were made in accordance with the standard [22], and the calculations of the seasonal heat demand for heating and ventilation purposes $Q_{H,nd}$ (usable energy demand) in the standard heating season in accordance with the procedure of EN 13790 [28]. The *Audytor OZC* [32] engineering calculation software was used. In all apartments, standard conditions were assumed: the design indoor temperature equals 20 °C [26] and ventilation air flow rates [22,28]. To calculate final energy consumption Q_{kH}, the central heating system efficiencies were taken from the tables in Regulation [33]. The total energy efficiency of the heating system was 0.70 before thermorenovation and 0.74 after thermorenovation.

One method of determining the maximum heating cost for the apartment was analyzed, i.e., the $C_{max}{}^2$ method (described in Section 2.1) using the value of the calculated design heat load for individual apartments, as the information on the thermal power and types of installed radiators was not available.

The maximum design temperature in the flats was assumed to be 26 °C (as the temperature possible to be set on the heads of thermostatic valves) and the maximum usable energy demand values for heating and ventilation for each apartment $Q_{H,nd}^{max}$ were calculated by using the equations presented in Section 2.1.

The maximum unit final energy consumption for each apartment $q_{Kj,max}$ was calculated as the value of the final energy Q_{kH}^{max} for each apartment related to the area of each one.

Three methods of determining the minimum heating cost for individual apartments were analyzed (i.e., methods described in Section 2.2). The minimum indoor temperature of flats was assumed to be 16 °C (as the minimum temperature in rooms in multi-family buildings supplied from the heating network, in accordance with Regulation [26]).

In the $C_{min}{}^1$ method, the demand for usable energy for heating and ventilation for each apartment for the assumed internal minimum temperature $Q_{H,nd}^{min}$ was calculated directly using the software [32].

In the $C_{min}{}^2$ method, the minimum demand for usable energy $Q_{H,nd}^{min}$ in order to maintain the minimum temperature of 16 °C for each apartment was calculated (according to method presented in details in Section 2.2) using the design heat load Φ_{HL} of individual apartments. The design heat load Φ_{HL} was calculated in the software [32], assuming an indoor temperature of 20 °C.

In the $C_{min}{}^3$ method, the usable energy demand in the entire building $Q_{H,nd}^{building}$ was calculated for the indoor temperature of 16 °C, using the software [32]. The calculations were made for the whole building without division into individual apartments. Then, the usable energy demand $Q_{H,nd}^{min}$ was calculated for each apartment using the equations presented in Section 2.2 and compensation factors (*CFs*). The *CFs* resulting from the location of the flats in the building body were calculated based on the design heat load of individual apartments (calculated for the design indoor temperature equal 20 °C). Then, the unit minimum final energy consumption Q_{kH}^{min} in each apartment was determined based on the calculated minimum values of the usable energy demand for each apartment and the total efficiency of the heating system. The minimum unit final energy consumption in each apartment $q_{Kj,min}$ was calculated, taking into account their area.

The values of the maximum and minimum unit final energy consumption are the basis for calculating the maximum and minimum variable cost for each apartment.

The percentage share of the unit minimum and maximum final energy consumption in individual premises in the value of the average unit final energy consumption for the entire building was also calculated. The calculated average unit final energy consumption for the entire building (assuming the indoor temperature equal 20 °C in the building) before thermorenovation is equal to 0.65 GJ/m^2 per year; in turn, after thermorenovation, it is equal to 0.44 GJ/m^2 per year.

3.2. Results and Discussion

The results of calculations of the unit maximum final energy consumption for determining the maximum heating cost in the individual apartments before and after thermorenovation of the building are presented in Figure 2 and Table A1 (Appendix A).

On the basis of the calculations of the unit maximum consumption of final energy, it can be concluded that the maximum unit variable cost of heat purchase for each flat depending on heat consumption in the analyzed building (determined by the $C_{max}{}^2$ method) was in the range from 169% to 249% of the average unit cost of heat purchase in the building before thermorenovation and from 191% to 256% of the average unit cost of heat purchase in the building after thermorenovation (%*AV* values).

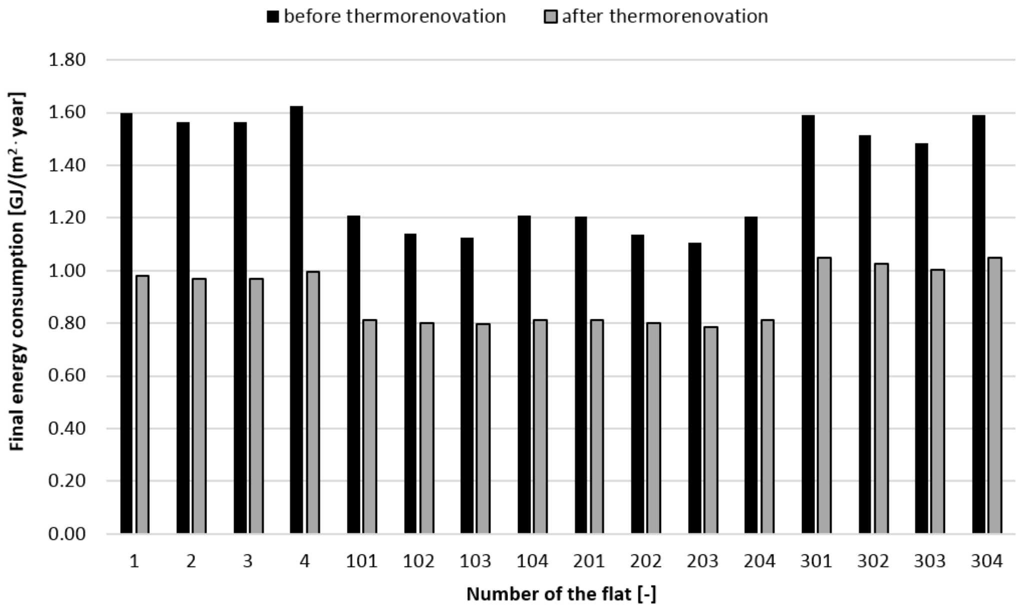

Figure 2. Unit maximum final energy consumption in the individual apartments of the analyzed building before and after thermorenovation.

The calculation results of the unit minimum final energy consumption for determining the minimum heating cost in the individual apartment (calculated using three different methods) are presented in Figure 3 and Table A2 (before thermorenovation) and in Figure 4 and Table A3 (after thermorenovation).

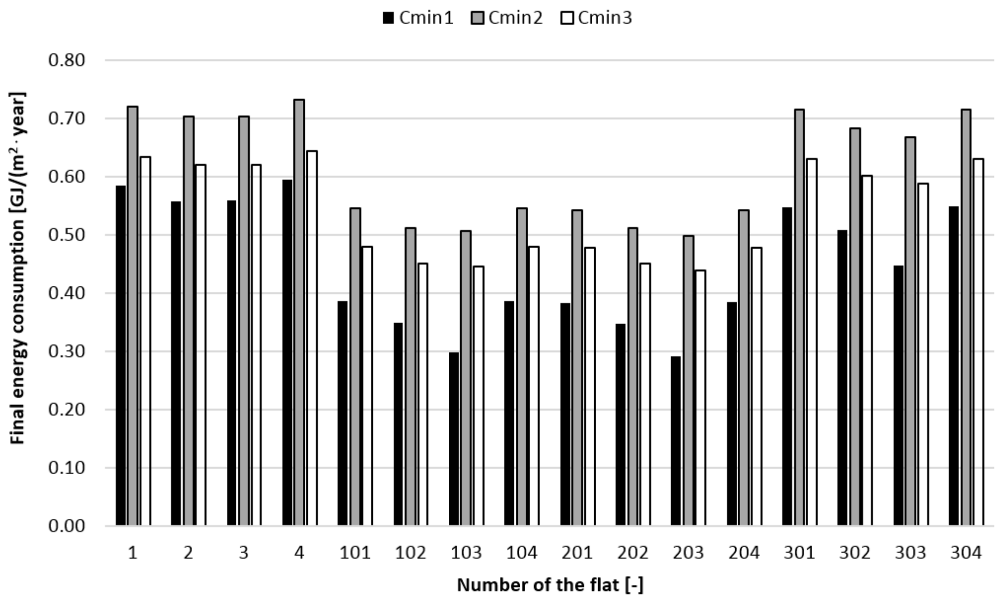

Figure 3. Unit minimum final energy consumption in the individual apartments of the studied building before thermorenovation for analyzed methods.

Due to the fact that the $C_{min}{}^1$ method is based on accurate calculations of the minimum usable energy demand, it is considered to be the most accurate of the three presented methods. It served as a reference point when evaluating the other two methods, $C_{min}{}^2$ and $C_{min}{}^3$. It can be seen that higher values of the minimum unit final energy consumption were obtained from the calculations using the $C_{min}{}^2$ and $C_{min}{}^3$ methods in comparison to the $C_{min}{}^1$ method.

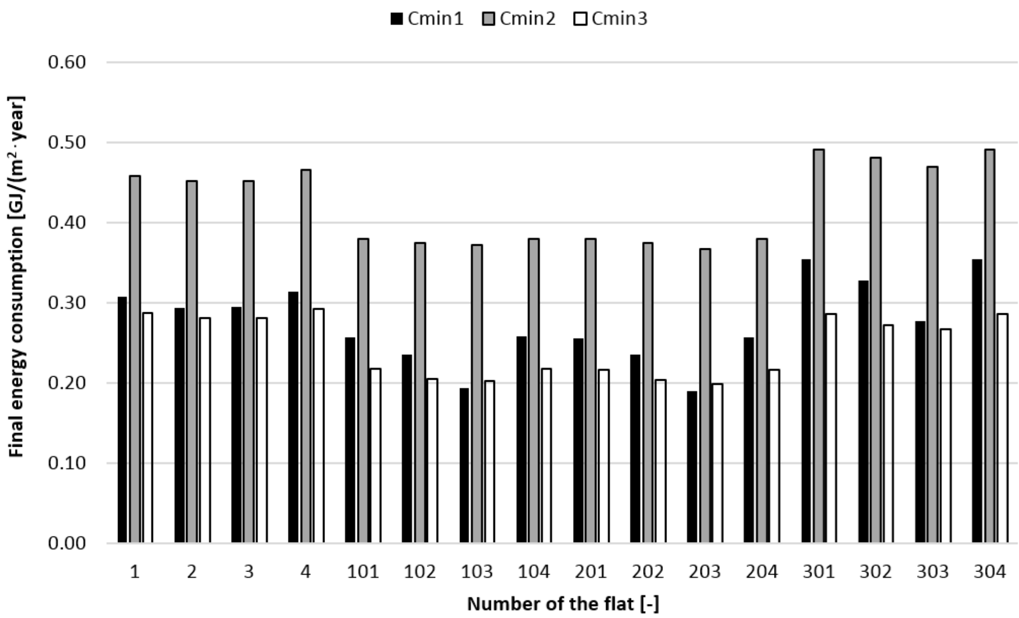

Figure 4. Unit minimum final energy consumption in the individual apartments of the studied building after thermorenovation for the analyzed methods.

It was calculated that the relative error δ for the $C_{min}{}^2$ method is in the range of 23% to 71% (average error of 40%) for the building before thermorenovation and in the range of 38% to 93% (the average error of 56%) for the building after thermorenovation. The relative error δ for the $C_{min}{}^3$ method is in the range of 8% to 51% (average error of 23%) for the building before thermorenovation and in the range of 4% to 19% (the average error of 11%) for the building after thermorenovation.

When analyzing the results, it is not recommended to use the $C_{min}{}^2$ method in engineering practice when calculating the unit minimum variable cost of heat purchase for an apartment depending on heat consumption.

On the basis of the calculations of the minimum unit final energy consumption, it can be concluded that the minimum unit variable cost of heat purchase depending on heat consumption in the apartments in the analyzed building (determined by the $C_{min}{}^1$ method) ranged from 44% to 91% of the average unit cost of heat purchase in the building before thermorenovation and from 46% to 87% of the average unit cost of heat purchase in the building after thermorenovation. The minimum unit variable cost of heat purchase, depending on heat consumption in the apartments in the analyzed building (determined using the $C_{min}{}^3$ method), ranged from 67% to 99% of the average unit purchase cost of heat in the building before thermorenovation and from 49% to 71% of the average unit purchase cost heat in the building after thermorenovation (values %*AV*). For the non-recommended $C_{min}{}^2$ method, the corresponding values are much larger.

4. Conclusions

This work proposes different methods (depending on availability of input data) for calculation of maximum and minimum variable cost of heating of specific flat in multifamily building, which may be used as part of the heat cost allocation process in such buildings.

It was shown that maximum variable costs of heat purchase for specific flats in the analyzed building were in the range from 169% to 249% and from 191% to 256% of the average unit cost of heat for the building before and after thermorenovation, respectively. In the case of minimum variable costs of heat purchase for specific flat, it is recommended to use the methods which are based on minimum demand for usable energy $Q_{H,nd}^{min}$ (methods $C_{min}{}^1$ and $C_{min}{}^3$) and not on design heat load Φ_{HL}. Owing to these methods, the calculated, minimum unit variable cost of heat ranged from 44% to 91% and from 67% to 99% of the average unit cost of heat for the analyzed building before thermorenovation for the $C_{min}{}^{1}$ and $C_{min}{}^{3}$ method, respectively.

In the buildings where *CFs* are included in heat cost allocation process (because of location of a particular flat in the building), the method for calculation of minimum and maximum variable cost of heating may be simplified, especially if there is a lack of detailed input data for calculation, because the calculation may be limited to the building as a whole.

The presented methods for calculating minimum and maximum costs of heating may be helpful to properly carry out the process of heat cost allocation in multifamily buildings and avoid complaints from the users.

Future research work may be needed to develop a cost-effective method which will take into account all the aspects related to heat used for the heating of specified flats in multifamily buildings and allow for fair allocation of heating costs.

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Nomenclature

A	Heated area of a building (m^2)
HDD	The number of degree days (K·d/year)
k	Exponent depending on the type of a radiator
L_{dsez}	Number of days of the heating season according to meteorological data, d/year
Q	Heat consumption (GJ/year)
$Q_{H,nd}$	Seasonal demand for usable energy for heating and ventilation (GJ/year)
Q_{kH}	Seasonal demand for final energy for heating and ventilation (GJ/year)
$Q_{radiator}$	Thermal power of a radiator (W)
q_j	Unit value of the heat consumption (GJ/(m^2·year))
t_{indoor}	Indoor temperature (°C)
$t_{outdoor}$	Outdoor temperature (°C)
t_{return}	Average temperature of the working medium at the return (°C)
t_{supply}	Average temperature of the working medium at the supply (°C)
Δt	Average arithmetic the difference of temperature, (K)
$\eta_{H,d}$	Average seasonal efficiency of heat distribution from the heat source to the heated space (-)
$\eta_{H,e}$	Average seasonal efficiency of regulation and use of heat in the heated space (-)
$\eta_{H,g}$	Average seasonal efficiency of heat production (-)
$\eta_{H,s}$	Average seasonal efficiency of heat accumulation in capacitive elements of the heating system in building (-)
η_{system}	Average seasonal overall efficiency of the building's heating system (-)
Φ_{HL}	Design heat load (W)
Acronym	
CFs	Compensation factors for heat consumption for heating space (-)

Appendix A

Table A1. The results of the unit maximum final energy consumption in the individual apartments of the analyzed building before and after thermorenovation.

Apartment		Before Thermorenovation					After Thermorenovation				
-	A_{local}	Φ_{HL}	$Q_{H.nd}$	$Q_{H.nd}{}^{max}$	$q_{Kj.max}$	$\%AV$	Φ_{HL}	$Q_{H.nd}$	$Q_{H.nd}{}^{max}$	$q_{Kj.max}$	$\%AV$
-	m^2	W	GJ/Year	GJ/Year	GJ/(m^2·Year)	%	W	GJ/Year	GJ/Year	GJ/(m^2·Year)	%
1	54.32	4412	32.73	60.45	1.60	245	2893	18.80	39.64	0.98	239
2	67.76	5379	39.18	73.70	1.56	239	3562	22.52	48.81	0.97	236
3	67.76	5379	39.27	73.70	1.56	239	3562	22.57	48.81	0.97	236
4	53.42	4412	32.80	60.45	1.63	249	2893	18.84	39.64	1.00	243
101	54.32	3340	21.59	45.76	1.21	185	2399	15.72	32.87	0.81	198
102	67.76	3918	24.52	53.68	1.14	174	2946	18.10	40.37	0.80	195
103	82.40	4706	25.78	64.48	1.12	172	3565	18.36	48.85	0.80	194
104	54.32	3340	21.65	45.76	1.21	185	2399	15.76	32.87	0.81	198
201	54.32	3326	21.45	45.57	1.21	184	2399	15.65	32.87	0.81	198
202	67.76	3909	24.41	53.56	1.14	174	2946	18.04	40.37	0.80	195
203	82.40	4627	25.14	63.40	1.11	169	3514	18.01	48.15	0.78	191
204	54.32	3326	21.51	45.57	1.21	184	2399	15.69	32.87	0.81	198
301	54.32	4385	30.26	60.08	1.59	243	3100	21.31	42.48	1.05	256
302	67.76	5216	35.19	71.47	1.52	232	3786	24.75	51.88	1.03	251
303	82.40	6202	37.94	84.98	1.48	227	4499	25.71	61.65	1.00	245
304	54.32	4385	30.33	60.08	1.59	243	3100	21.36	42.48	1.05	256
sum	1019.66	70,262	463.75	962.73			49,962	311.19	684.58		
min					1.11	169				0.78	191
max					1.63	249				1.05	256
avg						209					221

Table A2. The results of the unit minimum final energy consumption in the individual apartments of the analyzed building before thermorenovation.

Apartment		$C_{min}{}^1$ Method			$C_{min}{}^2$ Method				$C_{min}{}^3$ Method			
-	A_{local}	$Q_{H.nd}{}^{min}$	$q_{Kj.min}$	$\%AV$	$Q_{H.nd}{}^{min}$	$q_{Kj.min}$	$\%AV$	δ	$Q_{H.nd}{}^{min}$	$q_{Kj.min}$	$\%AV$	δ
-	m^2	GJ/Year	GJ/(m^2·Year)	%	GJ/Year	GJ/(m^2·Year)	%	%	GJ/Year	GJ/(m^2·Year)	%	%
1	54.32	22.06	0.58	89	27.21	0.72	110	23	23.96	0.63	97	9
2	67.76	26.31	0.56	85	33.17	0.70	108	26	29.21	0.62	95	11
3	67.76	26.38	0.56	86	33.17	0.70	108	26	29.21	0.62	95	11
4	53.42	22.11	0.59	91	27.21	0.73	112	23	23.96	0.64	99	8
101	54.32	14.57	0.39	59	20.60	0.55	83	41	18.14	0.48	73	24
102	67.76	16.43	0.35	53	24.16	0.51	78	47	21.28	0.45	69	30
103	82.40	17.09	0.30	46	29.02	0.51	77	70	25.56	0.45	68	50
104	54.32	14.61	0.39	59	20.60	0.55	83	41	18.14	0.48	73	24
201	54.32	14.47	0.38	59	20.51	0.54	83	42	18.06	0.48	73	25
202	67.76	16.35	0.35	53	24.10	0.51	78	47	21.23	0.45	69	30
203	82.40	16.65	0.29	44	28.53	0.50	76	71	25.13	0.44	67	51
204	54.32	14.51	0.38	59	20.51	0.54	83	41	18.06	0.48	73	24
301	54.32	20.69	0.55	84	27.04	0.72	109	31	23.81	0.63	96	15
302	67.76	23.94	0.51	78	32.16	0.68	104	34	28.33	0.60	92	18
303	82.40	25.63	0.45	68	38.24	0.67	102	49	33.68	0.59	90	31
304	54.32	20.74	0.55	84	27.04	0.72	109	30	23.81	0.63	96	15
sum	1019.66	312.54			433.26				381.57			
min			0.29	44		0.50	76	23		0.44	67	8
max			0.59	91		0.73	112	71		0.64	99	51
avg				69			94	40			83	24

Table A3. The results of the unit minimum final energy consumption in the individual apartments of the analyzed building after thermorenovation.

Apartment		$C_{min}{}^1$ Method			$C_{min}{}^2$ Method				$C_{min}{}^3$ Method			
- -	A_{local} m^2	$Q_{H.nd}{}^{min}$ GJ/Year	$q_{Kj.min}$ GJ/(m^2·Year)	$\%AV$ %	$Q_{H.nd}{}^{min}$ GJ/Year	$q_{Kj.min}$ GJ/(m^2·Year)	$\%AV$ %	δ %	$Q_{H.nd}{}^{min}$ GJ/Year	$q_{Kj.min}$ GJ/(m^2·Year)	$\%AV$ %	δ %
1	54.32	12.45	0.31	75	18.55	0.46	112	49	11.65	0.29	70	6
2	67.76	14.86	0.29	72	22.84	0.45	110	54	14.20	0.28	69	4
3	67.76	14.91	0.30	72	22.84	0.45	110	53	14.20	0.28	69	5
4	53.42	12.49	0.31	77	18.55	0.47	114	49	11.65	0.29	71	7
101	54.32	10.41	0.26	63	15.38	0.38	93	48	8.82	0.22	53	15
102	67.76	11.90	0.24	58	18.89	0.37	91	59	10.35	0.20	50	13
103	82.40	11.90	0.19	47	22.86	0.37	91	92	12.43	0.20	49	4
104	54.32	10.44	0.26	63	15.38	0.38	93	47	8.82	0.22	53	16
201	54.32	10.36	0.26	62	15.38	0.38	93	48	8.78	0.22	53	15
202	67.76	11.86	0.23	57	18.89	0.37	91	59	10.32	0.20	50	13
203	82.40	11.65	0.19	46	22.53	0.37	90	93	12.22	0.20	49	5
204	54.32	10.39	0.26	63	15.38	0.38	93	48	8.78	0.22	53	15
301	54.32	14.34	0.35	87	19.88	0.49	120	39	11.58	0.29	70	19
302	67.76	16.55	0.33	80	24.28	0.48	117	47	13.77	0.27	67	17
303	82.40	17.00	0.28	68	28.85	0.47	115	70	16.38	0.27	65	4
304	54.32	14.37	0.36	87	19.88	0.49	120	38	11.58	0.29	70	19
sum	1019.66	205.88			320.35				185.54			
min			0.19	46		0.37	90	38		0.20	49	4
max			0.36	87		0.49	120	93		0.29	71	19
avg				67			103	56			60	11

References

1. Cholewa, T.; Siuta-Olcha, A. Long term experimental evaluation of the influence of heat cost allocators on energy consumption in a multifamily building. *Energy Build.* **2015**, *104*, 122–130. [CrossRef]
2. Terés-Zubiaga, J.; Pérez-Iribarren, E.; González-Pino, I.; Sala, J.M. Effects of individual metering and charging of heating and domestic hot water on energy consumption of buildings in temperate climates. *Energy Convers. Manag.* **2018**, *171*, 491–506. [CrossRef]
3. Slijepcevic, S.; Mikulic, D.; Horvat, K. Evaluation of the Cost-Effectiveness of the Installation of Heat-Cost Allocators in Multifamily Buildings in Croatia. *Energies* **2019**, *12*, 507. [CrossRef]
4. Calise, F.; Cappiello, F.; D'Agostino, D.; Vicidomini, M. Heat metering for residential buildings: A novel approach through dynamic simulations for the calculation of energy and economic savings. *Energy* **2021**, *234*, 121204. [CrossRef]
5. Calise, F.; Cappiello, F.L.; D'Agostino, D.; Vicidomini, M. A novel approach for the calculation of the energy savings of heat metering for different kinds of buildings. *Energy Build.* **2021**, *252*, 111408. [CrossRef]
6. Tunzi, M.; Benakopoulos, T.; Yang, Q.; Svendsen, S. Demand side digitalisation: A methodology using heat cost allocators and energy meters to secure low-temperature operations in existing buildings connected to district heating networks. *Energy* **2023**, *264*, 126272. [CrossRef]
7. Benakopoulos, T.; Tunzi, M.; Salenbien, R.; Hansen, K.K.; Svendsen, S. Implementation of a strategy for low-temperature operation of radiator systems using data from existing digital heat cost allocators. *Energy* **2022**, *251*, 123844. [CrossRef]
8. Andersen, S.; Andersen, R.K.; Olesen, B.W. Influence of heat cost allocation on occupants' control of indoor environment in 56 apartments: Studied with measurements, interviews and questionnaires. *Build. Environ.* **2016**, *101*, 1–8. [CrossRef]
9. Cholewa, T.; Siggelsten, S.; Balen, I.; Ficco, G. Heat cost allocation in buildings: Possibilities, problems and solutions. *J. Build. Eng.* **2020**, *31*, 101349. [CrossRef]
10. Canale, L.; Dell'Isola, M.; Ficco, G.; Cholewa, T.; Siggelsten, S.; Balen, I. A comprehensive review on heat accounting and cost allocation in residential buildings in EU. *Energy Build.* **2019**, *202*, 109398. [CrossRef]
11. Li, Y.; Xue, P.; Yang, F.; Li, B.; Zhao, R.; Zhang, N.; Xie, J.; Liu, J. Location correction factor for household heat metering and its influencing factors. *J. Build. Eng.* **2023**, *64*, 105639. [CrossRef]
12. Siggelsten, S. Reallocation of heating costs due to heat transfer between adjacent apartments. *Energy Build.* **2014**, *75*, 256–263. [CrossRef]
13. Michnikowski, P. Allocation of heating costs with consideration to energy transfer from adjacent apartments. *Energy Build.* **2017**, *139*, 224–231. [CrossRef]
14. Dell'Isola, M.; Ficco, G.; Arpino, F.; Cortellessa, G.; Canale, L. A novel model for the evaluation of heat accounting systems reliability in residential buildings. *Energy Build.* **2017**, *150*, 281–293. [CrossRef]

15. Michnikowski, P.; Cholewa, T. On the Use of Base Temperature by Heat Cost Allocation in Buildings. *Energies* **2021**, *14*, 6346. [CrossRef]
16. Ficco, G.; Celenza, L.; Dell'Isola, M.; Vigo, P. Experimental comparison of residential heat accounting systems at critical conditions. *Energy Build.* **2016**, *130*, 477–487. [CrossRef]
17. Xue, P.; Li, Y.; Yang, F.; Fan, C.; Zhao, R.; Miao, Q.; Zhang, N.; Rong, Q.; Xie, J.; Liu, J. Research on three-part heating cost method based on heating consumption reallocation and game theory. *Energy Build.* **2022**, *261*, 111961. [CrossRef]
18. Dell'Isola, M.; Ficco, G.; Canale, L.; Frattolillo, A.; Bertini, I. A new heat cost allocation method for social housing. *Energy Build.* **2018**, *172*, 67–77. [CrossRef]
19. Stauffer, Y.; Saba, F.; Carrillo, R.E.; Boegli, M.; Malengo, A.; Hutter, A. Smart sensors network for accurate indirect heat accounting in apartment buildings. *J. Build. Eng.* **2022**, *46*, 103534. [CrossRef]
20. Castellazzi, L. *Analysis of Member States' Rules for Allocating Heating, Cooling and Hot Water Costs in Multi-Apartment/Purpose Buildings Supplied from Collective Systems*; Technical Reports; JRC, European Commission: Brussels, Belgium, 2017.
21. Regulation of the Minister Climate and the Environment of 7 December 2021 on the Conditions for Determining the Technical Feasibility and Profitability of Using Heat Meters, Heating Cost Allocators and Water Meters for Measuring Domestic Hot Water, Conditions of Selection of Methods for Allocation of Heat Purchase Costs and the Scope of Information Contained in Individual Settlements, (in Polish); Journal of Laws 2021, Item 2273. Available online: https://isap.sejm.gov.pl (accessed on 20 November 2022).
22. *EN 12831:2017*; Heating Systems in Buildings-Method for Calculation of the Design Heat Load. European Committee for Standardization: Brussels, Belgium, 2017.
23. Recknagel, H.; Sprenger, E.; Honmann, W.; Schramek, E.R. *Guidebook Heating and Air Conditioning*; EWFE: Gdańsk, Poland, 1994. (In Polish)
24. *EN 15316-2:2017*; Energy Performance of Buildings-Method for Calculation of System Energy Requirements and System Efficiencies—Part 2: Space Emission Systems (heating and Cooling). European Committee for Standardization: Brussels, Belgium, 2017.
25. *EN 834:2013*; Heat Cost Allocators for the Determination of the Consumption of Room Heating Radiators-Appliances with Electrical Energy Supply. European Committee for Standardization: Brussels, Belgium, 2013.
26. Regulation of the Minister of Infrastructure of 12 April 2002 on the Technical Conditions to Be Met by Buildings and Their Location, (in Polish); Journal of Laws 2022, item 1225. Available online: https://isap.sejm.gov.pl (accessed on 20 November 2022).
27. *EN ISO 52016-1:2017*; Energy Performance of Buildings—Energy Needs for Heating and Cooling, Internal Temperatures and Sensible and Latent Heat Loads—Part 1: Calculation Procedures. ISO: Geneva, Switzerland, 2017.
28. *EN ISO 13790: 2008*; Energy Performance of Buildings—Calculation of Energy Use for Space Heating and Cooling. ISO: Geneva, Switzerland, 2008.
29. *PN-B-03430:1983/Az3:2000*; Ventilation in Residential, Collective Housing and Public Buildings. Requirements. Polish Committee for Standardization: Warsaw, Poland, 1983 and 2000. (In Polish)
30. Specjał, A. Method of Determining Equalization Coefficients of Heat Consumption for Heating Resulting from the Location of the Premises in the Body of the Building. *Dist. Heat. Heat. Vent.* **2022**, *53*, 3–8. (In Polish) [CrossRef]
31. Ling, J.H.; Li, Q.; Xing, J.C. The influence of apartment location on household space heating consumption in multi-apartment buildings. *Energy Build.* **2015**, *103*, 185–197. [CrossRef]
32. *Audytor OZC 6.7 Pro: Program for Calculating the Design Heat Load of a Building and Seasonal Energy Consumption, As Well As Preparing Energy Performance Certificates for Buildings and Apartments*; SANKOM: Delémont, Switzerland, 2022.
33. Regulation of the Minister of Infrastructure of 27 February 2015 on the Methodology for Calculating the Energy Performance of a Building or Part of a Building and Energy Performance Certificates (in Polish); Journal of Laws, 2015 year, Item. 376. Available online: https://isap.sejm.gov.pl (accessed on 20 November 2022).
34. Regulation of the Minister of Infrastructure of 17 March 2009 on the Detailed Scope and Forms of the Energy Audit and Part of the Renovation Audit, Templates of Audit Cards, as well as the Algorithm for Assessing the Profitability of a Thermomodernization Project Journal of Laws 2009 No 43 Item 346 and Journal of Laws 2015 item 1606. Available online: https://isap.sejm.gov.pl (accessed on 20 November 2022).