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Article

A Method of Multi-Criteria Assessment of the Building Energy Consumption

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Abstract: The aim of this study is to develop a universal method for the unequivocal selection of the optimal combination of components determining the energy efficiency of buildings by means of an introduced global building energy consumption indicator. The basis of this method is a multi-criteria optimization of the components influencing the energy efficiency of buildings. The method requires the development of a detailed description of the set of components influencing the energy efficiency of buildings and the definition of the analysis criteria. The following analysis criteria were adopted: relative annual demand for final energy, cost, durability, and investment outlays payback time. The normalized values of these criteria are calculated in relation to the structure of a reference building. The proposed method makes it possible to explicitly indicate the most advantageous solution from the point of view of the weighted share of the individual criteria. The verification of the method was presented on the basis of the thermo modernization case study analysis for the adopted reference building. As a result, the most advantageous variant of modernization was determined, defined by the lowest value of the global building energy consumption indicator. A high effectiveness of the proposed method has been shown in relation to both the selection of the modernization option and the assessment of the individual component share in each modernization solution.

Keywords: energy consumption of buildings; multi-criteria analysis; global indicator of building energy consumption

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1. Introduction

A study of the historical evolution of energy-efficient buildings that helps to provide an understanding of the changes taking place to improve thermal comfort and optimize energy consumption was discussed by Ionescu et al. in their publication [1]. In this work, it was indicated that the ancients used the thermal properties of the ground and massive walls and slabs of wood, stone, or brick. Next, the theoretical and technological foundations of modern energy-efficient construction in its initial period of development in the early years of the 20th century were described. Finally, the social acceptance of the principles of sustainable development, partially enforced by the energy crises in recent decades, has been noticed and has contributed to the definition of new principles of design strategies in construction.

Researchers consider the origins of energy-efficient construction to be as early as ancient times, as some of the principles currently used in this field of construction can be seen in the buildings of that time. It has been found that in 5500 BC houses were built partially sunk into the ground, which made it possible to achieve stable temperatures in the rooms [2].

In the 1930s, significant building heat gains from solar energy were demonstrated experimentally, which initiated the concept of the energy-efficient stream [3,4]. At the time, attention was paid to improving thermal insulation. An important part of the buildings for which energy balance measurements were carried out was the thermal design of components and equipment, such as solar collectors. Later on, the number of technical solutions increased. Improving thermal insulation became a basic principle [5].

It was not until the oil crisis of the 1970s that an intensified interest in energy-efficient construction began. It was then that the importance of the airtightness of buildings, the thermal insulation of the envelope, and the heat recovery from ventilation began to be recognized. All the technologies used at the time were focused on the use of solar thermal energy. In their publication, Brenda and Vale made descriptions and defined the building proposals of the time [6].

In 1984, a project that had already been developed in the 1950s was realized in Germany with the making of the first long-term thermal energy storage facility [7].

In the 1980s, Feist and Adamson, inspired by energy-efficient construction, developed the concept of a passive building [8].

In the followed years, further attempts were made to construct energy-efficient buildings and to develop the technologies that had been already implemented. During the energy retrofitting of the buildings, great attention began to be paid to reducing energy consumption and carbon dioxide emissions [9].

In individual countries, the general framework for the development of modern low-energy buildings is created by building traditions and the specific energy situation, as well as the climatic conditions specific to the geographical location. However, there are universal architectural, structural, material, functional, and installation solutions that can be applied everywhere [10].

Currently, there is no clear definition of energy saving; however, various methods aim to reduce the energy demand [10].

An approach to a multi-parameter description of building characteristics is presented by the current Directive 2010/31/EU of the European Parliament and of the council on the energy performance of buildings, abbreviated as EPBD (Energy Performance Buildings Directive) [11,12].

In Poland, the maximum heat transfer coefficient of the building envelope and the maximum primary energy demand are regulated. The values of both of these parameters are set out in the regulation [13].

In the buildings to be constructed, it is necessary to select the appropriate materials, technology, and installations that meet all the accepted principles of energy-efficient construction, which will reduce energy consumption. Simultaneously, when selecting the above-mentioned elements, it should be remembered that the cost of constructing an energy-efficient building is higher in comparison to that of a traditional building. This confronts the investor with the choice between a high initial cost and low energy consumption or lower initial costs and higher energy consumption.

This choice can be effectively implemented using multi-criteria optimization methods. In the literature, this discipline is also referred to as vector optimization, Pareto optimization, and polyoptimization. Many researchers consider the beginning of the discipline to be at the end of the 18th century, which is when utility theory and welfare theory were developed. Other researchers believe that it would be more reasonable to take the publication of the books by Menger in 1871 and Walras in 1874 as the beginning of the development of the multi-criteria optimization method. However, Vilfredo Federico Damaso Pareto is considered the most prominent scientist in the early history of the development of the field. His publications are considered the basis of multi-criteria optimization [14]. Multi-criteria optimization is based on the optimization of multiple, often competing or conflicting, criteria (objectives). This method helps in making a decision and in selecting the best solution. The possibility of competing (contradictory) criteria arises due to the fact that an improvement in one criterion may induce a deterioration in another one [15].

In the field of evolutionary multi-criteria optimization, two main approaches are used to solve the problem: the Pareto-based and the decomposition-based methods [16].

The publication by Dytczak [17] and Evins [18] describes selected methods for solving the multi-criteria decision-making problems in construction. The authors discussed the principles of applying the optimization methods and illustrated their usefulness with examples.

There are many studies that have investigated the impact of multiple criteria, either separately or combined, on energy consumption. For example, Zhao and Du in their publication [19] investigated the optimization of window configuration and shading with regard to energy consumption and thermal comfort for an office building. Mahdy and Nikolopoulou [20] evaluated window specifications for energy efficiency and long-term cost-effectiveness in Egypt. In turn, Zhang et al. [21] presented the results of research on the relationship between the typology of apartment blocks, the potential for obtaining solar energy, and the efficiency of energy use in buildings in the context of the city of Singapore. Neofytou et al. [22] presented research based on a model of multi-criteria decision analysis to support decision makers in developing energy-efficiency policy by selecting the most effective measures leading towards the sustainability of buildings in Greece. Roulet et al. [23] dealt with a multi-criteria analysis of the health, comfort, and energy efficiency of buildings. However, there are no publications in the biblography of the research subject that directly use the multi-criteria optimization methods to assess the cumulative impact of a set of multiple components on the energy efficiency of a building.

A review of the literature shows that the authors of the articles and studies focus on the general concept of energy efficiency, the analysis of the impact of individual materials on energy efficiency, and the improvement of the properties of these materials that affect the energy efficiency of buildings. It is worth citing a few publications describing these issues in these places. Khoukhi [24] investigated the combined effect of temperature and humidity on the change in the thermal conductivity of polystyrene foam and its impact on the energy performance of a building. Orzechowski T. and Orzechowski M. [25] addressed the determination of the optimal thickness of different insulation materials for different temperature conditions and heat sources from an economical point of view. However, in the literature it has not been possible to find articles devoted to research on the possibility of unambiguously indicating the optimal structural, building, and installation solution from the point of view of building energy efficiency. It seems that the closest are the building evaluation systems, such as BREEAM or LEED [26], which result in a single parameter. However. these are expert systems that require the action of certified auditors. Meanwhile, such a system could be based on existing parameters but could make them more accessible and clear through a final evaluation.The current practice of selecting a solution variant for the construction of an energy-efficient building is based on a direct comparison of the individual solution variants used separately in terms of final energy demand, construction cost, and investment payback period. Such a description is multi-parametrical and complicated for the user who is a non-expert but is interested in the energy assessment of the building. In the case of frequent changes in the external conditions, referring to average parameters does not always give reliable energy demand values. There is a trend towards using neural networks to predict energy demand in the near future based on historical data, Liua et al. [27], and Kathirgamanathan et al. [28]. However, all these models need the parameters of many building to be described. An energy assessment of a building may also be necessary for retrofit planning, for example, and multi-parameter systems are also proposed by Stanica et al. [29].

The aim of this study is to develop a universal method for the multi-criteria assessment of the energy consumption of buildings.

A new approach to the assessment of an energy-efficient building structure solution was proposed; it involves taking into account the weighted contribution of multiple criteria in this assessment and introducing a single, global energy consumption indicator evaluating the solution.

The method enables an unequivocal selection of the optimal combination of the components determining the energy efficiency of buildings, leading to a reduction in energy consumption over the lifetime of the building at relatively low initial construction costs.

In order to verify the proposed method, a case study analysis of the energy modernization of an adopted reference building was presented, demonstrating the high effectiveness of the modernization variant selection method.

2. Characterization of Components Influencing the Energy Efficiency of Buildings

The components influencing a building's energy efficiency can be divided into the following groups: natural components, building products, installations, and shape, function, and location of the building.

2.1. Natural Components

The natural components influencing the energy efficiency of a building include soil and the heat extracted from it by means of, for example, a ground heat exchanger, a water heat exchanger at high groundwater levels, and geothermal energy. Numerous publications on the characterization of the components of this group are known. In [30], an issue on the design aspects of a ground heat exchanger was presented. Paper [31] was devoted to the general characterization of a ground heat exchanger. In [32], the authors discussed the possibility of using soil as a heat store. In [33], the authors dealt with the influence of the ground water level on the integrity of underground structures. In [34], the damage caused by high groundwater levels was presented.

2.2. Construction Products

The components influencing the energy efficiency of buildings that can be classified as artificial are primarily the materials from which the building may be constructed.

2.2.1. Construction Materials

The material components should be divided primarily into those used for the load-bearing structure and the thermal insulation layers of the building.

Supporting Structure

The load-bearing structure of a building is responsible for carrying external loads and dead weight. The load-bearing structure includes the foundations, the load-bearing walls, the columns, the floors, and the roofs. The materials used for the load-bearing structure of a building are characterized by high strength. Usually, high strength also means high material density, which in turn impairs the insulation properties. For some structural materials, particularly reinforced concrete, methods are sought to increase thermal insulation without compromising strength. Concrete is a material with a wide spectrum of thermal conductivity; see Asadi et al. [35].

Numerous publications on the characterization of this of group components are known. Cao et al. [36] studied the properties of geopolymer concrete containing different types of thermo-regulating materials. Alqahtani et al. [37] developed a novel lightweight concrete-containing aggregate made from plastic. Rossignolo et al. [38] studied the properties of high-performance concrete with a lightweight aggregate. In their book, Satish and Berntsson [39] addressed the subject of concretes with lightweight aggregates. Xinga et al. [40] developed a technology for making a concrete perforated sandwich brick. Zukowski and Haese [41] performed a study of a perforated brick filled with perlite insulation. Millogo et al. [42] performed an experimental study on sun-dried bricks reinforced with Hibiscus cannabinus fibers. Morales et al. [43] investigated the possibility of improving the equivalent heat transfer coefficient for single layer walls. Muntohor [44] described the characteristics of brick from pressed stabilized soil. A publication by Alvaz-Ramirez et al. [45] deals with the use of sugarcane bagasse ash and lime to improve the durability and mechanical properties of compacted soil blocks.

Thermal Insulation Layer

Insulation materials are responsible for improving the thermal properties of the building envelopes, thus reducing energy loss for heating by reducing energy loss through the partitions and thus reducing the maintenance costs of the building. The resulting energy savings are estimated to be greater than the amount of energy used in the insulation material production. Insulation materials should be characterized primarily by the ability to fit the shape of the structure without air gaps, and they should have an unchanging shape in all three dimensions over the lifetime of the buildings. In addition, they must be resistant to moisture and biological corrosion. It is important that such materials do not emit substances in hazardous concentrations into the building. It is required that the insulation material has fire protection properties [46]. The consideration of the whole life cycle of buildings in the choice of materials is the basis of sustainable construction [47].

- *Organic Materials*

Initially, insulation was made from cheap and natural products and could therefore be called organic insulation material. Materials belonging to this group are characterized by high water absorption; simultaneously, they are more exposed to the aging process due to external environmental influences.

Many publications can be found dedicated to the characterization of the components in this group. In the publication by Gonzalez-Garcia et al. [48], eco-friendly fiberboard was evaluated. The paper by Corsadden et al. [49] describes the thermal insulation made from sheep fiber. Schmidt and Jensen [46] carried out a life cycle assessment of building insulation products made of rock wool, paper wool and flax. Siddiqui [50] wrote a textbook on cellulose insulation. Kwon and Yarbrough [51] made a comparison of cellulose insulations produced in Korea and the United States.

A publication by Ozguven and Gunduz [52] deals with the study of effective parameters for the production of expanded clay. Mounir et al. [53] described the thermal properties of a clay/granular cork composite material. Demir et al. [54] described the production of insulation and building materials from expanded perlite. Most of the authors of these publications indicate the possibilities of using organic materials to insulate buildings; simultaneously, they point out some of the limitations of their use.

- *Inorganic Materials*

Inorganic insulation materials are characterized by high temperature resistance and, unlike organic materials, do not have increased hygroscopicity.

There are many publications dedicated to the characterization of the products in this group. Karamanos et al. [55] studied the effects of temperature and moisture on the thermal properties of mineral wool.

Piotrkowski et al. [56] carried out a simulation study of the thermal resistance of walls with reflective insulation. The publication by Yarbrough [57] deals with the study of reflective insulation. The work by Kristanto et al. [58] deals with calcium silicate board as wall cladding. Ivanov [59] described the preparation and properties of foam glass. Nocentini et al. [60] describes the hygrothermal properties of silica aerogel products. All the authors point to the very good insulating performance of these materials and the possibilities of their wide application.

- *Modern Materials*

Works are progressing on the invention of new materials or technologies to provide better building insulation and thus save energy. An example may be aerogels [61], which currently have a chance of wider practical application.

In turn, reflective silica paints are used to reflect some of the thermal radiation from incident solar radiation on the partition surface. They provide a radiation barrier to minimize surface heating but do not provide an insulating layer to reduce conducted heat transfer. They are used to achieve significant cost savings by reducing energy consumption for the inside temperature control [62].

The authors of many publications have addressed the characterization of the components in this group. Zeng et al. [63] described thermally insulating lightweight cement-based composites containing glass beads and nano silica aerogels. Woltman et al. [64] conducted experimental and numerical studies of the thermal performance of insulated concrete sandwich panels with glass fiber shear connectors. A publication by O'Flaherty and Alam [65] deals with the evaluation of the thermal and acoustic insulation performance of composite vacuum insulated panels for building facades. Zhung et al. [66] described a new type of wall realization technology with heat tube implantation.

2.2.2. Installation Products

The installations which a building is equipped with are other components that influence the energy efficiency of the building. The most important of these are the heating, cooling, and ventilation installations. A parameter which proves the energy efficiency of heating and cooling installations is their high efficiency, defined in Polish and European standards as the product of the efficiency of the energy production, transmission, accumulation, and control systems. In the case of a ventilation installation, the most important parameter is the efficiency of the energy recovery from the exhaust air. All the Polish and European standards are referred to later in the text when the efficiency of heating and cooling systems is considered.

Heating

Since ancient times, people have had to deal with the problem of space heating. They have used various solutions for this purpose, starting with simple forms of hearths, fireplaces, and furnaces, as well as heat distribution systems, up to modern heating systems, which can be divided into two groups: local and central heating.

Local heating includes fireplaces, furnaces, or radiators, whose operating principle is generally based on previous designs. Due to the use of modern technology and the use of electricity or gas in addition to solid fuels for heating, they have achieved high or very high efficiencies. In addition, their operation has been greatly simplified.

The second group includes solutions with a central heat source (boiler, heat pump, or housing estate or city boiler house) from which the heat is distributed to individual houses. These systems are now automated and very often almost maintenance-free.

Numerous publications on the characterization of the components in this group are known. Broszkiewicz et al. [67] characterized central heating and ventilation systems. The publication by Mrozinski [68] describes heat pumps. The work by Rubik [69] also deals with heat pumps. Bryś et al. [70] described the heat potential of near-surface shallow ground layers for ground source heat pumps. A study by Węglarz [71] deals with different heating systems, including energy-efficient ones. A publication by Bishar et al. [72] describes an innovative wooden radiant heating system. The paper by Seyam [73] presents an experimental and numerical study of a radiant panel heating system.

Cooling

Air conditioning is involved in the formation of the microclimate by achieving and maintaining the desired temperature, humidity, air cleanliness, and air movement in a room or enclosed space [74].

Numerous publications on the characterization of the components in this group can be found in the literature. The publication by Pełech [75] describes the installation of ventilation and air conditioning. Mahammad et al. [76] described the history of cooling technology development by the evaporation of a liquid desiccant. The publication by Thosapon and Kaumar [77] describes the performance of a pre-conditioning ventilation system with a solar-regenerated liquid desiccant.

Ventilation

The most important function of a ventilation system is the exchange of air in a room. The effectiveness of the air exchange—the ventilation—is closely related to parameters such as thermal comfort, energy savings, and the minimization of pollutants, e.g., CO_2 or aerosols, which contribute to the spread of infectious diseases; see Yang et al. [78].

Electrical, Low-Current and, Automatic Installations

Important installations influencing the energy efficiency of the building are electrical and low-voltage installations and automation. These three terms cover many types of installations, e.g., alarm installation, computer network installations, and fire protection installation. The installation of lighting accounts for a large percentage of the energy used in a building. Therefore, in energy-efficient buildings, installations allowing for the control of lighting and electrical devices are used. Automatic installations allow for the remote control of the microclimate parameters of the building and enable the adjustment of the conditions of the internal environment to meet the users' requirements; see Niezabitowska [79,80].

2.3. Shape, Function, and Location of the Building

Important components influencing the energy efficiency of a building are its shape, function, and location. Energy-efficient buildings are primarily characterized by a compact form. The problem of optimizing the shape of a building for minimum energy, material, and erection costs has been addressed in studies by Marks and Owczarek [81].

There are numerous publications on the performance of the components in this group. For example the publication by Parasonis et al. [82] describes the relationship between the shape of a building and its energy performance. Moreover, Peel et al. [83] devoted a paper to the climatic classification of the world. In addition, Borucińska-Bieńkowska [84] addressed the influence of a building's location and form on its energy-saving properties.

3. Criteria for Assessing the Energy Consumption of a Building

The proposed method for assessing the energy consumption of buildings adopts four optimization criteria: final energy, cost, durability, and payback time. In addition to the durability criterion, these criteria are related to energy consumption.

The technical requirements for buildings are set at the level of primary energy, which is used to take into account the environmental impact of acquiring an energy carrier and to demonstrate the level of compliance with current requirements and energy consumption limits. However, the energy level that corresponds to the demand resulting from the energy balance and the efficiency of the installations of the reference building is final energy. Therefore, final energy has been adopted as the basic criterion for the analysis. This criterion is also linked to the cost criterion and the payback time criterion, which are accounted for according to final energy. Taking final energy as the basis of the analysis ensures the consistency of these three criteria.

All the analysis criteria must be considered in relation to the specific type of reference building, the characteristics of which define the level of the indicators determined from these criteria.

3.1. Reference Building

For the purpose of analysis, a reference building with the following characteristic parameters specified in Table 1 was adopted.

Table 1. Characteristic parameters of the reference building.

Parameters		
1. Functional and structural	1.1. General	1.1.1. Type of building (residential, public, etc.)
		1.1.2. Nature of building use (single-family, multi-family, etc.)
		1.1.3. Time of construction (new, modernized)
		1.1.4. Number of storeys
		1.1.5. Type and number of rooms
		1.1.6. Usable floor area
		1.1.7. Total cubature volume
		1.1.8. Cubature of rooms
		1.1.9. Area of floor on the ground
		1.1.10. Area of roof
		1.1.11. The building survey required to establish quantitative values for the materials of the structural layer, the insulation layer, and the installations
	1.2. Location	1.2.1. Location
		1.2.2. Location in relation to the parts of the world
	1.3. Load-bearing structure and insulation layers	1.3.1. Thicknesses of the layers: structural and insulating
		1.3.2. Thermal conductivity coefficients for all materials used
		1.3.3. Heat transfer coefficients for all building partitions
2. Equipment and Installations	2.1. Heating	2.1.1. Type of heat source
		2.1.2. Type of installation, radiators, and control
		2.1.3. Heating system parameters
		2.1.4. Thermal insulation thickness of heating pipes
		2.1.5. Type of heating system—heat transfer equipment
		2.1.6. Buffer tank location and capacity
	2.2. Domestic hot water	2.2.1. Type of heat source
		2.2.2. Domestic hot water temperature and flow type
		2.2.3. Thermal insulation thickness of water pipes
		2.2.4. Type of domestic hot water (DHW) preparation system
		2.2.5. Domestic hot water storage tank in a hot water supply system
		2.2.6. Domestic hot water storage tank location and capacity
	2.3. Cooling	2.3.1. Type of cooling system
		2.3.2. Buffer tank parameters and location
		2.3.3. Type of cooling transfer device
		2.3.4. Type of installation and its equipment
	2.4. Lighting	2.4.1. Type of lighting installation
		2.4.2. Lighting installation parameters
		2.4.3. Division of lighting zones
	2.5. Technical systems	2.5.1. Heating system (circulating pumps, boiler air blowers, mechanical window shading control devices, etc.)
		2.5.2. Domestic hot water preparation system (circulation pumps, storage tank charging pumps, etc.)
		2.5.3. Cooling system (fans pumping air in the air conditioning condenser and evaporator, etc.)

3.2. Relative Annual Final Energy Demand

According to the provisions of the Regulation [85], the relative annual final energy demand factor is the energy supplied to the building in relation to the building area. It is therefore the energy that takes into account both the needs of the building resulting from its heat balance and the efficiency of the heating systems.

In order to calculate the final energy demand supplied to the building, it is necessary to know the parameters of the devices for each system, including in particular: the type of device, the number of devices, and the technical parameters such as efficiency, power consumption, etc.

The methodology for calculating the energy demand for a building [85] defines three levels of energy: usable, final, and primary. Usable energy is the energy resulting directly from the energy balance of the building. In determining the value of this energy, the heat losses and gains of the building are taken into account, as is the demand for domestic hot water. The level of final energy takes into account the efficiency of the energy installations in the building. This is the amount of energy to be supplied in fuel or from an external heating system. The primary energy level which is the most general takes into account the environmental load of non-renewable energy or the use of renewable sources. Each of these three energy levels is assigned an indicator per unit of floor area of the building. The levels are related to each other, but the useful energy demand is calculated first. The relative annual final energy demand E_i (kWh/m^2/year) of the applied component $\{i\}$ from the set of components of the material, construction, or installation solution influencing the energy consumption of the building is determined in the reference building as follows:

$$E_i = Q_i / A_u, \tag{1}$$

where Q_i (kWh/year) is the annual final energy demand supplied to the reference building extracted for each component $\{i\}$ used, assuming fixed annual final energy demand parameters for the other technical systems (material, construction, and installation) Q_k; A_u (m^2) is the useful floor area of the building [85].

The annual final energy demand supplied to the building for each applied component $\{i\}$ is defined as the sum of the final energy demand for the heating system ($Q_{H,i}$), the domestic hot water system ($Q_{W,i}$), the built-in lighting system $(Q_{L,i})$, and, optionally, for the cooling system ($Q_{C,i}$) and technical systems ($E_{TS,i}$) [85]:

$$Q_i = Q_{H,i} + Q_{W,i} + Q_{L,i} + \langle Q_{C,i} \rangle + \langle E_{TS,i} \rangle. \tag{2}$$

The annual final energy demand supplied to the building for the heating system is calculated as follows:

$$Q_{H,i} = \frac{Q_{uH}}{\eta_{Htot}}|_{,i}, \tag{3}$$

where Q_{uH} is the annual useful energy demand, and a η_{Htot} is the overall efficiency of the heating system.

The overall heating system efficiency η_{Htot} is defined as the product of four kinds of efficiencies: generation η_{Hg}, regulation η_{He}, transmission η_{Hd}, and accumulation η_{Hs}:

$$\eta_{Htot} = \eta_{Hg}\eta_{He}\eta_{Hd}\eta_{Hs}. \tag{4}$$

The annual energy need for heating Q_{uH} (kWh/year) is calculated from the energy balance of the building collated on a monthly basis, assuming that the calculation of the heating demand does not take into account the summer months, e.g., in Poland in June, July, and August, $6 \le m \le 8$:

$$Q_{uH} = \sum_{\substack{1 \le m \le 5 \\ 9 \le m \le 12}} Q_{uH,m}. \tag{5}$$

The monthly useful energy demand for heating $Q_{uH,m}$ (kWh/month) is calculated as follows:

$$Q_{uH,m} = Q_{tr} + Q_{ve} - \eta(Q_{sol} + Q_{int}), \tag{6}$$

where Q_{tr} is the heat exchanged by transfer through the building envelope, Q_{ve} is the heat exchanged through ventilation, Q_{sol} is the solar heat gain, Q_{int} is the internal heat gain, and η is the utilization factor for the heat gains.

The amount of heat exchanged by transfer Q_{tr} (kWh/month) [85], according to Paraschiv et al. [86], over a period of t hours each month depends on the surface area of the building envelope A_p, the heat transfer coefficient of the building envelope U_p, and the difference between the indoor T_{int} and outdoor T_{ext} environment temperatures; it is determined as follows:

$$Q_{tr} = \frac{U_p A_p (T_{int} - T_{ext})}{1000} t. \tag{7}$$

The internal temperature T_{int} is assumed to be constant throughout the year and equal to 20 °C for most rooms. The outdoor temperature T_{ext} is determined on the basis of meteorological data. For example, in Poland, for Warsaw the outdoor temperatures in the following months can be found in the Meteorological Yearbook 2020 on the website of the Institute of Meteorology and Water Management [87].

The heat transfer coefficient U_p (W/m^2/K) [88] is the inverse of the thermal resistance coefficient of the building envelope material R_p (m^{2}K/W):

$$U_p = {R_p}^{-1}. \tag{8}$$

The thermal resistance coefficient of a building envelope material R_p is calculated in different ways depending on the type of partition. In the case of a sandwich wall comprising n_p layers, the thermal resistance is:

$$R_p = R_{si} + \sum_{i=1}^{n_p} \frac{d_i}{\lambda_i} + R_{se}, \tag{9}$$

where d_i is the layer thickness, λ_i (W/m/K) are the thermal conductivity coefficients of the layer material taken from building material manufacturers' data, and R_{si} i R_{se} are the heat transfer coefficients of the external and internal side, respectively; they are determined, for example, according to the standard in [89], as well as the standard in [88].

The heat exchanged by ventilation Q_{ve} (kWh/month), according to the publications by Kurtz et al. [90] and Żarski [91], over a period of t hours each month is calculated using the formula:

$$Q_{ve} = \frac{\rho c_p (q_{v,1} + q_{v,2})(T_{int} - T_{ext})}{1000} t, \tag{10}$$

where ρc_p is the heat capacity of the air and $q_{v,1}$ i $q_{v,2}$ are the basic and infiltrating fluxes exchanged by the ventilation. If the ventilation flows are expressed in units (m^3/h), then the air heat capacity ρc_p = 0.34, while if we express the heat flux units (m^3/s), then ρc_p = 1200.

The basic ventilation flow rate $q_{v,1}$ (m^3/h) is the design volume for the building and can be determined from the ventilation standards. It can also be calculated as a function of the air change rate per hour n_v (1/h) and the volume of the building V (m^3) [88]:

$$q_{v,1} = n_v V. \tag{11}$$

For residential and office buildings, the air change rates can be assumed to be in the range of $n_v = (0.3,\ 0.5)$.

The infiltration flux flows into the building through leaks in the building envelope. In the absence of an accurate building leakage test, it can be calculated as a fraction of the building volume [85]:

$$q_{v,2} = 0.2V. \tag{12}$$

On the other hand, if the air tightness coefficient of the building n_{50} is known then the infiltration flux is calculated as [84]:

$$q_{v,2} = 0.05 n_{50} V. \tag{13}$$

The solar heat gains Q_{sol} (kWh/month), according to Levison et al. [92–94], are generated during the period of each month by solar radiation through transparent partitions and can be described by the equation:

$$Q_{sol} = IA_{tp}Cg, \tag{14}$$

where I is the solar radiation energy per month according to the climatic data (kWh/m^2/month), A_{tp} is the area of transparent partitions, C is the share of glazing area in the total window/door area, and g is the transmittance of solar radiation through the transparent partitions [95].

The internal heat gains Q_{int} (kWh/month) [96] are generated over a period of t hours each month by all the objects that are not part of the heating system and by the occupants of the building. These gains can be calculated based on the actual output of devices, such as those in kitchens and washing machines, and occupants or in a lump sum based on standard q-factors determining the power of the internal heat gains per unit of floor area A_u:

$$Q_{int} = qA_u t, \tag{15}$$

where q is the specific internal heat gain depending on the type of building, for example: q = 6.8 W/m^2 for a single-family building or q = 12 W/m^2 for an educational building [97].

We calculate the heat gain utilization factor η for each month based on the ratio of gains to losses of heat:

$$\gamma_h = \frac{Q_{sol} + Q_{int}}{Q_{tr} + Q_{ve}}, \tag{16}$$

as follows:

$$\eta = \begin{cases} \frac{1-\gamma_h{}^{a_h}}{1-\gamma_h{}^{1+a_h}} & if \quad \gamma_h \neq 1 \\ \frac{a_h}{1+a_h} & if \quad \gamma_h = 1 \end{cases},$$

where $a_h = a_{h,0} + \frac{\tau}{\tau_{H,0}}$, $a_{h,0} = 1$, $\tau_{H,0} = 15$ h, $\tau = \frac{\frac{C_m}{3600}}{Q_{tr}+Q_{ve}}$, and C_m is the thermal capacity of the building, taken as the thermal capacity of the internal layer, which is 0.10 m thick, of the external wall of the building.

The annual final energy demand supplied for the DHW preparation system is calculated as follows:

$$Q_{W,i} = \frac{Q_{uW}}{\eta_{Wtot}}|_{,i}, \tag{17}$$

where Q_{uW} is the annual useful energy demand of the DHW preparation system and a η_{Wtot} is the total efficiency of the DHW preparation system.

The overall efficiency η_{Wtot} is defined as the product of four efficiencies: the generation η_{Wg}, regulation η_{We}, transmission η_{Wd}, and accumulation η_{Ws} of heat:

$$\eta_{Wtot} = \eta_{Wg}\eta_{We}\eta_{Wd}\eta_{Ws}. \tag{18}$$

The annual heat demand for the DHW heating system Q_{uw} (kWh/year) is calculated as follows [85]:

$$Q_{uW} = \frac{V_{wi}A_u\rho_w c_w(T_w - T_0)k_r t_r}{3600}, \tag{19}$$

where V_{wi} is the unit daily DHW demand dm^3/m^2/day; ρ_w = 1 kg/dm^3—density i; c_w = 4.19 kJ/kg/K—specific heat of water; T_w = 55 °C—hot water temperature; $T_0 = 10$ °C—cold water temperature; k_r is the correction factor due to interruptions in DHW use; and t_r = 365 days—number of days in a year [85].

The annual final energy demand supplied for the lighting system is calculated as follows:

$$Q_{L,i} = \frac{Q_{uL}}{\eta_{Ltot}}|_{,i}, \tag{20}$$

where Q_{uL} is the annual useful energy demand for the lighting system, and a η_{Ltot} = 1 is the overall efficiency of the lighting system, adopted on the basis of [85].

The annual useful energy demand supplied to the lighting system Q_{uL} (kWh/year) is calculated by taking into account the zoning of the lighting; it is calculated as follows [98]:

$$Q_{uL} = \sum_{n=1}^{N} Q_{uL,n} A_n, \tag{21}$$

where N is the number of lighting zones with area A_n with the diversified performance parameters, and $Q_{uL,n}$ is the coefficient of annual useful energy demand per unit area for the lighting system in each zone (kWh/m^2/year):

$$Q_{uL,n} = F_{cn}\left(\frac{P_n}{1000}\right) F_{0n}[(t_{Dn}F_{Dn}) + t_{0n}] + Q_{min,1} + Q_{min,2}, \tag{22}$$

where F_{cn} is the illuminance factor; P_n is the illumination power density (W/m^2); F_{0n} is the area utilization factor; F_{Dn} is the daylight factor; t_{Dn} is the total annual daylight duration (h); t_{0n} is the total annual lack of daylight duration (h); $Q_{min,1}$ = 1.0 kWh/m^2/year—default standby energy value for battery charging; $Q_{min,2}$ = 1.5 kWh/m^2/year—default standby energy value for control.

In this paper, it was assumed that the reference building types considered will not apply to industrial buildings with installed cooling and technical systems. Therefore, the study does not present detailed considerations for the calculation of the final energy demand for cooling systems $Q_{C,i}$ and technical systems $E_{elpom,i}$. The calculation assumptions for determining the final energy demand for these systems can be found in Kurtz et al. [90] and Żarski [91].

3.3. Cost

The main issue for the cost estimation is the selection of the sub-costs, which represent the total cost C_i [PLN—the symbol of the Polish currency, with current average exchange rates as of 17 October 2022: USD 1 = PLN 4.9573, EUR 1 = PLN 4.8342] of each component $\{i\}$ from the set of components influencing the energy consumption of the building, as incurred during the design lifetime of the construction works T_{blc}. This calculation period may also be referred to as the life cycle of the building.

Sub-costs include initial (investment) costs, utility operating costs, maintenance costs, and possible demolition and disposal costs [99].

Therefore, the total cost of each component should be considered to be the initial costs $C_{st,i}$ and the long-term costs $C_{lt,i}$:

$$C_i = C_{st,i} + C_{lt,i}. \tag{23}$$

The initial costs (referred to as the acquisition costs) consist of the purchase costs, including the cost of delivery to the site, $C_{p,i}$, and the assembly costs with the possible costs of the building project, $C_{b,i}$:

$$C_{st,i} = C_{p,i} + C_{b,i}. \tag{24}$$

In this work, all the initial costs of the applied component $\{i\}$ are calculated as the product of the average market unit price of the material, the construction or installation solution c_i (PLN/unit of measurement), and the unit of measurement $n_{k,i}$ (e.g., pieces, m^2, m^3) of this solution:

$$C_i = c_i n_{k,i}. \tag{25}$$

In the local market, the manufacturers quote unit prices for a given material, construction, or installation solution as the sum of the direct costs, indirect costs, and profit. The cost estimates were made on the basis of an analysis of the market data.

The long-term costs consist of operating cost $C_{e,i}$ and net maintenance cost $C_{m,i}$ and possible demolition and disposal costs $C_{d,i}$, once the cost-effectiveness of the further operation and modernization has been established:

$$C_{lt,i} = C_{e,i} + C_{m,i} + C_{d,i}. \tag{26}$$

The operating costs $C_{e,i}$ over the calculation period T_{blc} are determined on the basis of the relationship:

$$C_{e,i} = T_{blc} E_{k,i} C_E, \tag{27}$$

where $E_{k,i}$ is the final energy determined for a given component in the reference building (kWh/m^2/year), and C_E is the energy unit cost (PLN/kWh).

The cost per unit C_E of energy is taken from the average price quoted by the suppliers of different types of energy and converted per unit of energy into kWh. In the second quarter of year 2022, the market price of energy was C_E = 471,96 PLN/MWh (according to the Energy Regulatory Office [100]). However, the cost of energy for consumers consists of the market price of energy and the transmission fee, which, per 1 kWh, gives a cost of PLN 0.68, including the PLN 0.48 market price of energy and the PLN 0.20 cost of the energy transmission fee.

The net maintenance costs $C_{m,i}$ are calculated on the basis of the following relationship:

$$C_{m,i} = C_{mg,i} - C_{mw,i}, \tag{28}$$

where $C_{mg,i}$ is the gross maintenance cost of component {i} during the calculation period, and $C_{mw,i}$ is the value of the contractor's guarantee for component $\{i\}$.

The gross cost of maintenance over the calculation period is calculated using the formula:

$$C_{mg,i} = C_{mr,i} N_{c,i}, \tag{29}$$

where $C_{mr,i}$ is the replacement cost, and $N_{c,i}$ is the design number of duty cycles of the design period.

The value of the contractor's guarantee is calculated according to the formula:

$$C_{mw,i} = C_{mg,i} \frac{T_{w,i}}{T_{blc}}, \tag{30}$$

where $T_{w,i}$ is the warranty period (year).

The exact methodology for calculating the initial costs is described in the Regulation [101].

The proposed method for determining the costs corresponds to the cost classification set out in the Regulation [102].

3.4. Durability

Durability D_i (year) is the period in which the material, structural, or installation solution from the set of $\{i\}$ components affecting the energy consumption of a building maintains its performance properties [103].

The durability should be considered over the design lifetime of the building object T_{blc}, in which the necessity of the designed number of periods of maintenance or modernization of the adopted solutions should be foreseen [104]. Thus, in principle, the durability period of the component used will not be considered longer than the service life of the building:

$$D_i < T_{blc}. \tag{31}$$

The design service life for different categories of buildings is specified in the standards, e.g., EN 1990:2002 [105], ISO 15686-1:2000 [106], or CSA S478:1995 [107]. For example, it is 10 years for temporary buildings and 100 years for monumental buildings.

Durability can be defined not only as an intrinsic characteristic of a given solution but above all as durability associated with the place of incorporation in the building structure.

In this paper, only the associated durability will be taken as a criterion for assessing a given component influencing the energy consumption of a building.

In the present study, the durability was determined on the basis of the normative test results adopted from various publications. For example, in the studies carried out by the Forschungs Institut für Wärmeschutz e.V. in Munich (FIW), at the request of the Eurima Association [108], the durability of mineral wool was determined to be 50 years. The EN 206 standard [109] indicates a concrete durability of 50 years.

The durability of individual building elements is also determined by various insurance and construction companies. For example, in the instruction [110], the durability of a brick wall is assumed to be 130–150 years.

The durability estimation of building materials and products can also be found in the publication [111].

For the purposes of the work, databases of the durability of the components $\{i\}$ influencing the energy efficiency of the building were prepared.

3.5. Payback Time

Payback time P_i is the period necessary for the costs incurred for a given material, construction, or installation solution from the set $\{i\}$ of components influencing the energy consumption of a building, to be fully balanced by the value of the savings in the relative annual final energy demand resulting from the application of the solution [112].

The payback time is closely related to the cost of implementing a given solution and the relative annual final energy demand for that solution. It is calculated on the basis of the parameters of a reference building and the unit kWh price on the local market. It can be calculated statically, using the so-called simple payback time (SPBT) [113]. Then, the payback time is the quotient of the investment cost and the savings in a relative annual final energy demand due to this investment:

$$P_i = \frac{C_i}{C_E \cdot \Delta E_{R,i} \cdot A_u}, \text{ (year)}, \tag{32}$$

where $C_i = C_{st,i}$ is the initial cost of applying the component (PLN), $\Delta E_{R,i} = E_R - E_i > 0$ is the saving in the relative annual final energy demand resulting from the application of a given solution in a reference building (kWh/m^2/year), and E_R is the relative annual final energy need of the reference building.

The payback time can also be calculated dynamically using, for example, the NPV (net present value) method. In this method, the changes in the price of fuel or repair services over the lifetime of the building, according to Hanafizadeha et al. [114] and Adamowicz et al. [115], and the change in the time value of money [116] can be taken into account.

In this study, the current dynamic payback time was determined based on the formula:

$$P_i(t) = \frac{C_i(t)}{C_E(t) \cdot \Delta E_{R,i}(t) \cdot A_u}, \tag{33}$$

where $C_i(t)$ is the total cost of application of the component (PLN) (excluding the cost of demolition); $C_E(t)$ is the unit cost of energy (PLN/kWh), including the projected change in energy costs; $\Delta E_{R,i}(t) = E_R(t) - E_i(t) > 0$ is the current saving of the relative annual final energy demand resulting from the application of the given solution in the reference building; $E_i(t)$ is the relative annual final energy need determined for a given component in a reference building, taking into account the projected aging—the loss of properties of the given component in the reference building; and $E_R(t)$ is the current relative annual final energy need in the reference building.

In the analysis of the initial operating state of the reference building, the payback time for the components used in the reference building is assumed to be equal to the design lifetime of the building $P_i(t_0) = T_{blc}$.

4. Method of Analysis

A three-stage multi-criteria optimization method is proposed and aims to: (1) order a finite set of components influencing the energy efficiency of buildings; (2) objectively select a set of the best components influencing the energy efficiency of buildings; and (3) determine the optimal design solution for an energy-efficient building.

In the multi-criteria optimization analysis of the components influencing the energy efficiency of buildings, the following criteria have been adopted: the relative annual final energy demand, cost, durability, and outlays investment payback time. These criteria are the normalized components of the meta-criteria function, which is subjected to minimization. The values of these criteria will be calculated with reference to the design of the reference building structure, and the values of the weights assigned to each criterion will be adopted on the basis of an expert assessment of user preferences.

Stage 1. Preparation of the dataset

1.1. Listing of components affecting the energy consumption of the building.
1.2. Selection and description of the material, construction, and installation solution of the reference building.
1.3. Development of the energy performance of a reference building.
1.4. Selection of criteria for assessing the components affecting the energy consumption of a building: relative annual final energy demand, cost, durability, outlays investment payback time.
1.5. Assigning of assessment criteria to components affecting the energy consumption of the building.

Stage 2. Determination of energy consumption partial indicators of components influencing the energy efficiency of the reference building

2.1. Determination of the normalized values of the optimization criteria for each component $\{i\}$ from the set of components affecting the energy consumption of the building (the first-order indicators, called criteria indicators):

(a) the relative annual final energy demand indicator

$$\delta_{E,i} = \frac{E_i - E_{min}}{E_{max} - E_{min}},\ 0 \le \delta_{E,i} \le 1\ , \tag{34}$$

where E_i is the relative annual final energy demand of the reference building (kWh/m^2/year), in the range $E_{min} \le E_i \le E_{max}$.

(b) cost indicator

$$\delta_{C,i} = \frac{C_i - C_{min}}{C_{max} - C_{min}},\ 0 \le \delta_{C,i} \le 1, \tag{35}$$

where C_i is the cost of the component used (PLN), in the range $C_{min} \le C_i \le C_{max}$.

(c) durability indicator

$$\delta_{D,i} = 1 - \frac{D_i - D_{min}}{D_{max} - D_{min}} = \frac{D_{max} - D_i}{D_{max} - D_{min}},\ 0 \le \delta_{D,i} \le 1, \tag{36}$$

where D_i is the lifetime of the component used (year), in the range $D_{max} \ge D_i \ge D_{min}$.

(d) the outlays investment payback time indicator

$$\delta_{P,i} = \frac{P_i - P_{min}}{P_{max} - P_{min}},\ 0 \le \delta_{P,i} \le 1, \tag{37}$$

where P_i is the payback time of the component (year), in the range $P_{min} \le P_i \le P_{max}$.

2.2. Determination of the normalized values of the optimization meta-criteria for each component $\{\boldsymbol{i}\}$ from the set of components affecting the energy consumption of the building (the second-order indicators, called components energy consumption indicators):

$$\delta_{ec,i} = w_1\delta_{E,i} + w_2\delta_{C,i} + w_3\delta_{D,i} + w_4\delta_{P,i},\, 0 \leq \delta_{ec,i} \leq 1\;, \tag{38}$$

where w_j is the weight to the criterion assigned $j = \{1,\, 2,\, 3,\, 4\} \equiv \{E,\, C,\, D,\, P\}$, on condition that $\sum_{j=1}^{j=J} w_j = 1.0$, $J = 4$ is the number of the criteria adopted.

2.3. Arranging the set of energy consumption indicators of components influencing the energy consumption of a building.

The selection of the most advantageous energy consumption indicator values, which are the smallest values for the set of $\{i\}$ components influencing the energy consumption of the building, is carried out according to the formula

$$\delta_{ec,1} = \delta_{ec,min} < \;..< \delta_{ec,i} < \;..< \delta_{ec,I} = \delta_{ec,max},\; i = \{1, \ldots\,, I\}, \tag{39}$$

where I is the number of all the considered components influencing the energy consumption of the building.

The values of the energy consumption indicators are the weighted sums of the individual criteria indicators and are contained in the range $0 \leq \delta_{ec,i} \leq 1$.

Stage 3. Determination of the global energy consumption indicator of the reference building

3.1. Determination of the set of the solution variants $\{v\}$ using the selected components from the set of components $\{i\}$ influencing the energy consumption of the building. The set of acceptable variants $\{v\}$ of the solution is the set that satisfies both the limiting conditions $c_{v,req}$ for the solution variant v and the limiting conditions $c_{r,\,req}$ for the components r of the solution variant:

$$\{v\} = \left\{ \begin{array}{l} v(r)\big|c_v \leq c_{v,req} \\ v(r)\big|c_r \leq c_{r,req} \end{array} \right\}. \tag{40}$$

3.2. Determination of the energy consumption indicator of the reference building for each solution variant (the third-order indicators, called solution variants indicators).

The value of the solution variant indicator is the average value of the component energy consumption indicators for each variant of the structural, building, installation solution:

$$\Delta_{ec,v} = \frac{1}{N_v}\sum_{i=1}^{N_v} \delta_{ec,i}, \tag{41}$$

where N_v is the number of components in the set of each solution variant $\{v = 1, \ldots, V\}$, and V is the number of solution variants applied to the reference building.

3.3. Determination of the global building energy consumption indicator of the reference building (the fourth-order indicator).

The global building energy consumption indicator of the reference building is determined as the smallest value of the solution variant indicators (41) used in the reference building, according to the formula:

$$\Delta_{ec} = \min\{\Delta_{ec,v}\}. \tag{42}$$

The proposed method of analysis allows the obtaining of the answer as to whether the solution adopted in the building is the most advantageous and whether, by changing at least one variable, one can optimize the achieved results. The proposed method can allow the verification of the adopted design concepts, as well as the selection of the most beneficial solution variants. Smaller values of each order of indicators (i.e., criteria indicators, component energy consumption indicators, solution variant indicators, and the global energy consumption indicator) indicate more advantageous solutions.

5. Computational Algorithm of the Method

To perform the calculations, a proprietary computer program was developed, the algorithm of which contains all the equations describing the proposed method for multi-criteria assessment of the energy consumption of buildings.

In Figure 1, the block diagram of the computational algorithm is shown. The essence of this algorithm is the content regarding the following elements:

1. Databases including the set of components influencing the energy efficiency of buildings with the characteristics of their properties, costs, and durability periods;
2. Definition of the assessment criteria of the energy consumption of buildings;
3. Procedure for determining the global building energy consumption indicator.

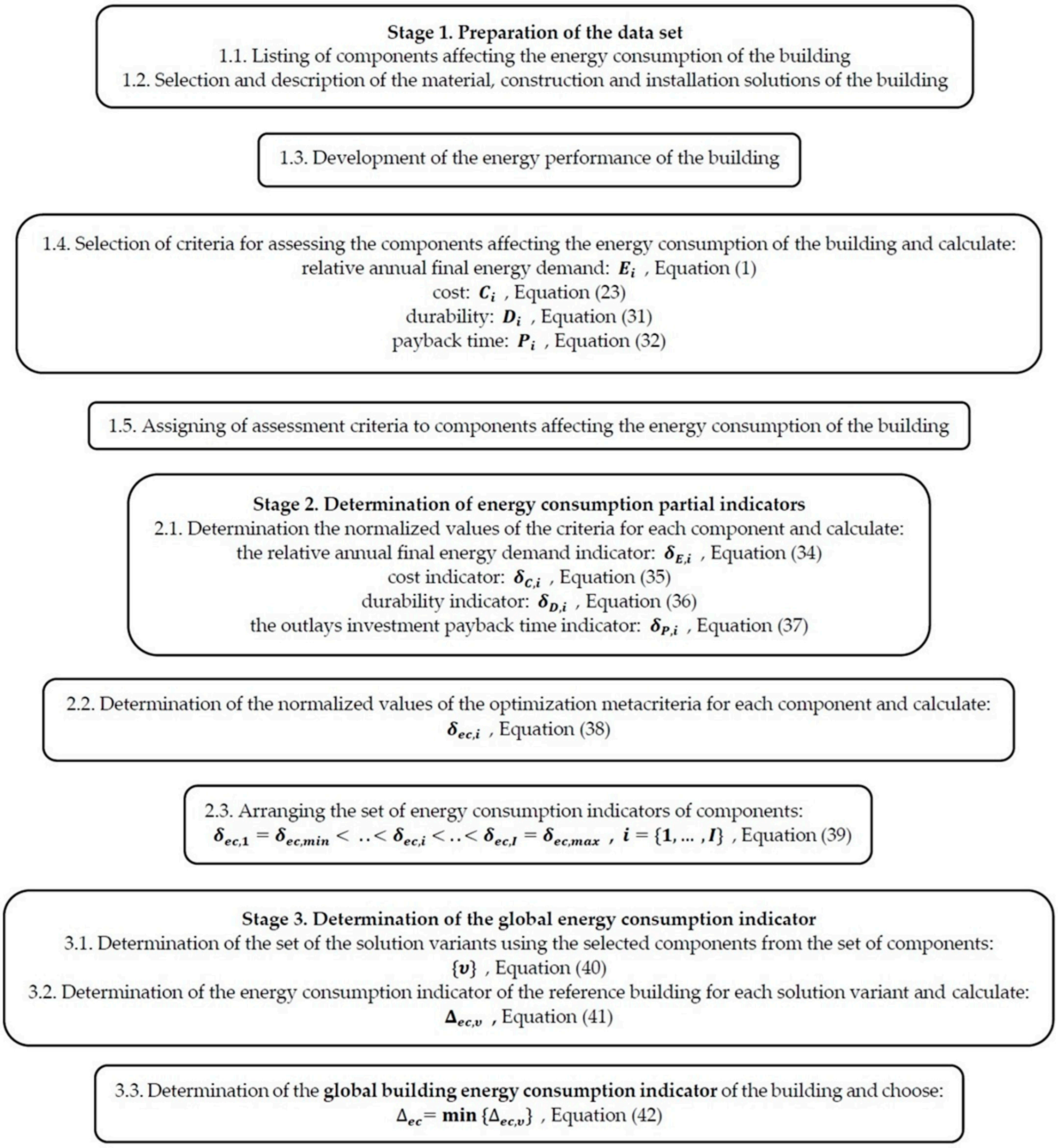
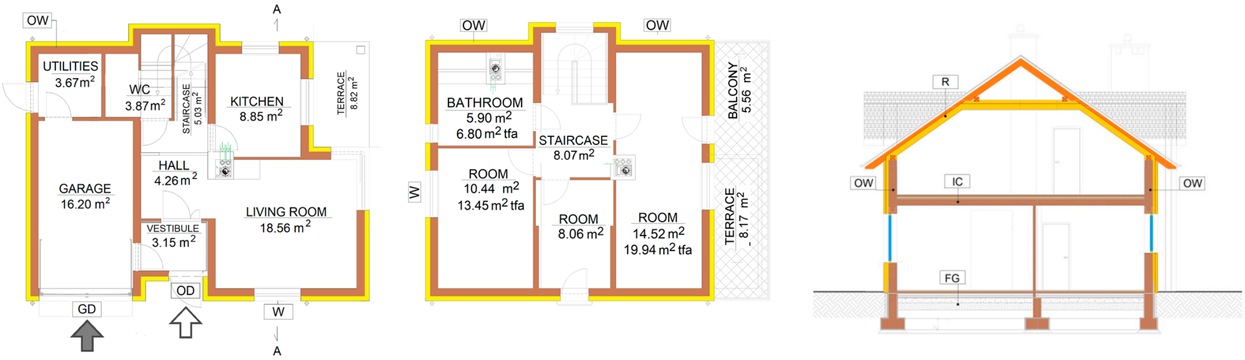


Figure 1. Block diagram of the computational algorithm.

6. Case Study of the Modernized Building

6.1. Reference Building—Data

In order to carry out of the case study analysis, the actual building intended for modernization was adopted as the reference building. Figure 2 shows the diagrams of the horizontal sections and the vertical section of the building.



(**a**) (**b**) (**c**)

Figure 2. Diagram of the building: (**a**) ground plan; (**b**) first floor plan; (**c**) vertical A-A section. OW—outer wall; R—roof; FG—floor on the ground; IC—internal celling; W—window; OD—outer door; GD—garage door.

In turn, the characteristic parameters of building are summarized in Table 2, in accordance with the description specified in Table 1.

Table 2. Characteristic parameters of the modernized building.

Parameters According to Description in Table 1			Reference Building	
1.	1.1.	1.1.1.	Residential	
		1.1.2.	Single-family	
		1.1.3.	Modernized, about 20 years ago	
		1.1.4.	2	
		1.1.5.	Garage	1
			Vestibule	1
			Technical room	1
			Rooms	4
			Kitchen	1
			Bathrooms	2
			Staircase/hall	3
		1.1.6.	120 m^2	
		1.1.7.	280 m^3	
		1.1.8.	Windbreak/vestibule	8.19 m^3
			Garage	47.32 m^3
			Technical room	9.54 m^3
			Hall	11.08 m^3
			Staircase	34.06 m^3
			Toilet	10.06 m^3
			Room 1	37.89 m^3
			Room 2	20.96 m^3
			Room 3	25.56 m^3
			Bathroom	12.92 m^3

Table 2. *Cont.*

Parameters According to Description in Table 1			Reference Building		
		1.1.9.	69 m^2		
		1.1.10.	108.4 m^2		
		1.1.11.	External wall surfaces	125 m^2	
			Volume of 25 cm thick external wall construction layer	31.25 m^3	
			Volume of 10 cm thick external wall insulation layer	12.5 m^3	
	1.2.	1.2.1.	Kielce City, Poland		
		1.2.2.	North-west		
	1.3.	1.3.1.	Construction layer	25 cm	
			Insulation layer	10 cm	
		1.3.2.	Outer wall	Porous ceramic brick Porotherm 25 Profi—25 cm	0.283 W/m/K
				Expanded polystyrene EPS 75—10 cm	0.042 W/m/K
				Quartz plaster 1 cm	1.0 W/m/K
				Silicate plaster 2 mm	1.0 W/m/K
			Roof	Cement roof tile 1.1 cm	1.0 W/m/K
				Bitumen membrane 2 mm	0.18 W/m/K
				OSB board 1 cm	0.13 W/m/K
				Rock wool 22 cm	0.034 W/m/K
				Vapor barrier foil 2 mm	0.18 W/m/K
				Drywall on a wooden grate—2.5 cm	0.23 W/m/K
				Thin-layer plaster 2 mm	1.0 W/m/K
			Floor on the ground	Parquet 2.2 cm	0.2 W/m/K
				Cement screed 5 cm	1.0 W/m/K
				Thermal insulation foil 2 mm	0.045 W/m/K
				Reinforced concrete foundation slab 25 cm	1.7 W/m/K
				Foamed polystyrene board PERIPOR 25 cm	0.034 W/m/K
				Bituminous roofing felt 3 mm	0.18 W/m/K
				Lean concrete 10 cm	1.7 W/m/K
				Cement stabilized sand 20 cm	0.4 W/m/K
				Sand foundation 10 cm	0.4 W/m/K
		1.3.3.	Outer walls	0.285 $W/m^{2/}K$	
			Roof	0.148 $W/m^{2/}K$	
			Floor on the ground	0.115 $W/m^{2/}K$	
			Exterior doors	1.5 $W/m^{2/}K$	
			Windows	1.1 $W/m^{2/}K$	
2.	2.1.	2.1.1.	Combined gas condensing boiler 24.6 kW		
		2.1.2.	55/45 °C		
		2.1.3.	20 mm (according to technical conditions)		
		2.1.4.	Central water heating		
		2.1.5.	200 dm^3		
		2.1.6.	In the heated zone of the building		
	2.2.	2.2.1.	Combined gas condensing boiler 24.6 kW		
		2.2.2.	Adjustable front heaters		
		2.2.3.	55/45 °C		
		2.2.4.	20 mm (according to technical conditions)		
		2.2.5.	Water central heating from a local heat source located in the heated building		
		2.2.6.	Did not occur		

Table 2. *Cont.*

Parameters According to Description in Table 1		Reference Building
2.5.	2.5.1.	Auxiliary drive and boiler control for heating a building with an area of up to 250 m^2
	2.5.2.	Auxiliary drive and boiler control for hot water heating in a building with an area of up to 250 m^2
	2.5.3.	Not applicable

All the location parameters, as well as those concerning the shape and form of the building, were taken into account in the final energy calculations. However, it was assumed that the lighting installation and the cooling system would not be included in the calculations.

Table 3 presents the selected parameters of the reference building that do not meet the current technical conditions contained in the Regulation [13].

Table 3. Parameters of the reference building that do not meet current technical conditions.

	Material/Device	Thickness	Parameter Values	Technical Conditions [13]	Meets/Does Not Meet
Outer wall	Porous ceramic brick	25 cm	U = 0.285 $W/m^2/K$	U = 0.20 $W/m^2/K$	Does not meet
	Expanded polystyrene (1)	10 cm			
Roof			U = 0.148 $W/m^2/K$	U = 0.15 $W/m^2/K$	Meets
Exterior doors			U = 1.5 $W/m^2/K$	U = 1.30 $W/m^2/K$	Does not meet
Windows			U = 1.1 $W/m^2/K$	U = 0.90 W/m^2K	Does not meet
Primary energy demand indicator			EP = 193.29 $kWh/m^2/year$	EP = 70 $kWh/m^2/year$	Does not meet

The analysis of the parameters of the reference building showed that it does not meet the current requirements specified in the technical conditions (Regulation [13]) for the primary energy demand indicator *EP* and the heat transfer coefficient *U* for the walls, windows, and doors. An energy modernization of the building is therefore necessary based on the principles of the proposed multi-criteria method for assessing the energy consumption of buildings.

6.2. Assumptions for the Modernization of the Reference Building to Meet the Requirements of the Technical Conditions

The aim of the energy modernization is to adjust the parameters of the individual building elements to values that meet the requirements of the technical conditions [13].

This will be achieved by replacing windows and doors and insulating the external walls with an additional 8 cm thick insulation layer made of materials with different physical parameters and possibly changing the type of heat source for the central heating system.

A preliminary analysis of a set of potentially usable materials was carried out to meet the current technical requirements.

The value of the relative annual final energy demand for each component was calculated based of the baseline assumptions of the reference building, taking into account only the change of the given component, while the other components remained unchanged. For all the components, the relative annual final energy demand value was calculated assuming the replacement of the windows and doors with those meeting the requirements of the technical conditions [13].

6.3. Calculation of the Energy Consumption Indicator of a Building

Step 1. Preparation of the dataset

According to the analysis method developed, eight components were selected from the three groups described in Section 2:

(a) One component from the material products group—supporting structure: porous ceramic brick (maintained as in the reference building);

(b) Four components from the material products group—thermal insulation layer: expanded polystyrene (1) (maintained as in the reference building), expanded polystyrene (2) (thickness of 8 cm, with thermal conductivity coefficient λ = 0.042 W/m/K), extruded polystyrene (thickness of 8 cm, λ = 0.03 W/m/K), rock wool (thickness 8 cm, λ = 0.032 W/m/K), and polyurethane foam (thickness 8 cm, λ = 0.025 W/m/K);

(c) Three components from the installation products—heating group: combined gas condensing boiler (maintained as in the reference building), ground heat pump—ground/water with the ground as the lower heat source (power input 6 kW, 180 hot water tank of 180 dm^3), water heat pump—water/water with the water reservoir as the lower heat source (power input 6 kW, hot water tank of 180 dm^3).

Then, for the selected components, the evaluation criteria E_i Equation (1), C_i Equation (23), D_i Equation (31), and P_i Equation (32) were assigned, and their values were determined and are summarized in Table 4.

Table 4. Assigned evaluation criteria for selected components.

Component No. $\{i\}$	Components	E_i (kWh/m^2/Year)	C_i (PLN) *	D_i (Year) **	P_i (Year)
1	Porous ceramic brick	172.70	30,000	50	50.0000
2	Expanded polystyrene (1)	172.70	6500	50	50.0000
3	Expanded polystyrene (2)	156.38	5000	50	3.7546
4	Extruded polystyrene	145.57	10,500	50	4.7430
5	Rock wool	153.85	4500	50	2.9256
6	Polyurethane foam	151.37	9500	25	5.4581
7	Combined gas condensing boiler	172.70	20,000	20	50.0000
8	Ground heat pump	79.84	50,000	25	6.5986
9	Water heat pump	79.22	45,000	25	5.8993

* The cost of individual components was determined on the basis of unit prices as of 1 May 2022. ** Durability period was assumed as the minimum service life of the component.

Step 2. Determination of energy consumption indicators for components influencing the energy efficiency of the reference building

For each component $\{i = 1, 9\}$ from the set of components influencing the energy consumption of the building, the normalized values for the optimization criteria (indicators) are defined as $\delta_{E,i}$ Equation (34), $\delta_{C,i}$ Equation (35), $\delta_{D,i}$ Equation (36), and $\delta_{P,i}$ Equation (37). Then, the normalized values of the optimization meta-criteria, i.e., the component energy consumption indicator $\delta_{ec,i}$ (38), were calculated, assuming that the weights of the individual criteria are the same and equal to $w_j = 0.25$, $j = \{E, C, D, P\}$. The results of these calculations are summarized in Table 5.

Table 5. Normalized values of optimization criteria as energy consumption indicators for selected components.

Component No. $\{i\}$	**Components**	$\delta_{E,i}$	$\delta_{C,i}$	$\delta_{D,i}$	$\delta_{P,i}$	$\delta_{ec,i}$
1	Porous ceramic brick	1.000	0.5604	0.0000	1.0000	0.6401
2	Expanded polystyrene (1)	1.000	0.0440	0.0000	1.0000	0.5110
3	Expanded polystyrene (2)	0.825	0.0110	0.0000	0.0176	0.2135
4	Extruded polystyrene	0.710	0.1319	0.0000	0.0386	0.2201
5	Rock wool	0.798	0.0000	0.0000	0.0000	0.1996
6	Polyurethane foam	0.772	0.1099	0.8333	0.0538	0.4422
7	Gas boiler	1.000	0.3407	1.0000	1.0000	0.8352
8	Ground heat pump	0.007	1.0000	0.8333	0.0780	0.4795
9	Water heat pump	0.000	0.8901	0.8333	0.0632	0.4467

Step 3. Determination of the global energy consumption indicator of the reference building

On the basis of the adopted components $\{i\}$, the value of the energy consumption indicator was calculated as $\Delta_{ec,v}$ (41) for the possible solution variants $\{v\}$, taking into account the limiting conditions (40). The limiting conditions concerning the parameters of the building partitions, the windows and doors ($c_{r,req} = U$), and the reference building ($c_{v,req} = EP$) were adopted on the basis of the technical conditions [13], and their values are presented in Table 3.

The results of the energy consumption indicators calculation are presented in Table 6. The solution for variant $v = 0$ determines the indicator value $\Delta_{ec,v=0}$ for the reference building before modernization.

The possible solution variants were selected in accordance with the developed method and were calculated using the proprietary calculation program based on the principle of selecting one component from each group of components, assuming that the components from the same group cannot be repeated in a given solution variant. All the selected components should be used for the analysis, together with those that were used in the reference building and will be retained in the modernized building.

Based on the calculations carried out, $V = 8$ possible variants of component combinations were obtained, all of which have lower global energy consumption indicators than for the variant $v = 0$ used in the reference building.

The analysis of the results obtained indicates that the most advantageous global energy consumption indicator was determined according to Formula (41):

$$\Delta_{ec} = \min\{\Delta_{ec,v}\} = \Delta_{ec,v=7} = 0.4493.$$

for the solution variant $v = 7$ with the combination of components: $i = 1$ porous ceramic brick/$i = 2$ expanded polystyrene (1)/$i = 5$ rock wool/$i = 7$ water heat pump.

6.4. A summary of the Case Study Results

A case study analysis based on the developed method, assuming the same degree of validity ($w_j = 0.25$, $j = \{E, C, D, P\}$) for the individual criteria, enables the identification of the following facts.

1. The highest value of the global energy consumption indicator for variant $v = 0$ of the solution used in the reference building $\Delta_{ec,v=0} = 0.6621$, indicating that keeping this solution in use is unprofitable, but first of all, it indicates the need for the energy modernization of the building in order to meet the current requirements specified in the technical conditions [13].
2. All the solutions including additional wall insulation made from one of the following groups of materials: expanded polystyrene, extruded polystyrene, rock wool, and

polyurethane foam, and the replacement of the heat source (variants 1–8), guarantee the fulfillment of the technical conditions [13].

3. The proposed method also makes it possible to determine the detailed values of the individual criteria for each solution variant. For example, the solution variant $v = 7$ is characterized by the lowest value of the global energy consumption indicator. Table 7 presents a summary of the criteria values of the individual components included in this solution, and Table 8 presents the values of the individual criteria for the component combination of this solution variant.

Table 6. Normalized values of energy consumption indicators for variants of selected components.

Solution Variant No. $\{v\}$	Component No. $\{i\}$	Options for Solutions	$\delta_{ec,i}$	$\Delta_{ec,v}$
0	1	Porous ceramic brick	0.6401	0.6621
	2	Expanded polystyrene (1)	0.5110	
	7	Gas boiler	0.8352	
1	1	Porous ceramic brick	0.6401	0.4610
	2	Expanded polystyrene (1)	0.5110	
	3	**Expanded polystyrene (2)**	0.2140	
	8	**Ground heat pump**	0.4795	
2	1	Porous ceramic brick	0.6401	0.4627
	2	Expanded polystyrene (1)	0.5110	
	4	**Extruded polystyrene**	0.2211	
	8	**Ground heat pump**	0.4816	
3	1	Porous ceramic brick	0.6401	0.4575
	2	Expanded polystyrene (1)	0.5110	
	5	**Rock wool**	0.1996	
	8	**Ground heat pump**	0.4795	
4	1	Porous ceramic brick	0.6401	0.5182
	2	Expanded polystyrene (1)	0.5110	
	6	**Polyurethane foam**	0.4437	
	8	**Ground heat pump**	0.4795	
5	1	Porous ceramic brick	0.6401	0.4528
	2	Expanded polystyrene (1)	0.5110	
	3	**Expanded polystyrene (2)**	0.2140	
	9	**Water heat pump**	0.4467	
6	1	Porous ceramic brick	0.6401	0.4545
	2	Expanded polystyrene (1)	0.5110	
	4	**Extruded polystyrene**	0.2211	
	9	**Water heat pump**	0.4467	
7	1	Porous ceramic brick	0.6401	0.4493
	2	Expanded polystyrene (1)	0.5110	
	5	**Rock wool**	0.1996	
	9	**Water heat pump**	0.4467	
8	1	Porous ceramic brick	0.6401	0.5100
	2	Expanded polystyrene (1)	0.5110	
	6	**Polyurethane foam**	0.4437	
	9	**Water heat pump**	0.4467	

Table 7. Criteria values for the individual components included in the $v = 7$ solution variant.

Solution Variant No. $\{v\}$	Component No. $\{i\}$	Components of the Solution	E_i (kWh/m^2/Year)	C_i (PLN) *	D_i (Year) **	P_i (Year)
7	1	Porous ceramic brick	172.70	30,000	50	50.0000
	2	Expanded polystyrene (1)	172.70	6500	50	50.0000
	5	Rock wool	153.85	4500	50	2.9256
	7	Water heat pump	79.22	45,000	25	5.8993

* and ** Description as in Table 4.

Table 8. Values of individual criteria for the component combination in the $v = 7$ solution variant.

Solution Variant No. $\{v\}$	E_v (kWh/m^2/Year)	C_v (PLN)	D_v (Year)	P_v (Year)
7	73.27	49,500	25	6.101

The relative annual final energy demand E_v (kWh/m^2/year) of the most advantageous solution $v = 7$ was calculated according to the formula in Equation (1) and was properly associated with formulas in Equations (2)–(22).

The cost of the porous ceramic brick is not included in the cost of the C_v of the solution $v = 7$ due to its presence in the reference building.

The durability D_v of the solution variant $v = 7$ was taken as the smallest durability period among the components used in this variant.

The payback time P_v in Equation (32) was calculated on the basis of the relative annual final energy demand E_v, the costs C_v incurred for the implementation of this solution, and the adopted minimum durability period D_v.

This solution variant is characterized by the following parameter values: relative annual final energy demand—E_v = 73.27 kWh/m^2/year; cost—C_v = PLN 49,500; durability—D_v = 25 years; and payback time for investment outlays— P_v = 6.101 years, which is equal to 6 years, 1 month, and 6 days.

7. Disscusion

The main purpose of the proposed method is not only energy consumption calculation but also the optimization of the building parameters in terms of energy. One of the pillars of the proposed method is a reliable algorithm for calculating energy demand. It is part of the method itself and provides data for its application. Therefore, the proposed method is in line with the trend of good practice in analyzing the energy consumption of buildings. For example, Manfren et al. [117] organized the analysis along three levels, from building energy modeling at multiple scales, through to the selection of energy performance analysis methods, to the detailed analyses of user-focused flexible modeling of energy consumption. Detailed building energy consumption assessment requires energy values on an hourly basis. It can be achieved by simulations, but it requires an excessive amount of data and computing time. Fumo et al. [118] proposed the method for the obtaining of hourly energy data from monthly results applying a series of predetermined coefficients from electrical energy bills. These coefficients were calculated for a particular type of building using EnergyPlus software for simulating a benchmark object. Lamagna et al. [119] presented a similar approach, but instead of the EnergyPlus program, they used a piecewise function, described in three non-connected intervals based on the Italian tariff subdivision, to distribute and normalize the monthly data obtained by utility bills on an hourly load curve. The standard monthly method was used in an article but an hourly one can also be adopted if the particular building requires a more detailed calculation or the monthly method does not give a distinct answer on the selection of the optimal combination of components. The process of optimization can be sped up when working with buildings on similar energy profiles. For assessing the groups of buildings with similar load profiles, clustering techniques may be useful. A general framework for the extraction of typical energy load profiles is presented by Capozzolia et al. [120]. An algorithm for the characterization of building performance data for use in a clustering process was given by Miller et al. [121]. Hourly energy load profile can be estimated, according to Granderson et al. [122], using the time of the week technique, in which predicted energy consumption is a combination of two terms that relate the energy consumption to the time of the week and the piecewise continuous effect of the temperature. This method has proven effective in demand response analysis in the case of electricity load events, according to Mathieu et al. [123].

The basic feature of the proposed method is the introduction of a single, global building energy consumption indicator resulting from a multi-criteria analysis of energy, durability, cost, and investment payback time parameters. This feature distinguishes the proposed method in comparison to other methods of estimating the energy consumption of buildings. Carrying out comparative analyses according to the other methods known from the bibliography would require the appropriate calculations and would be beyond the scope of this paper but may be the subject of separate considerations.

The method is of universal character because it does not assume any limitations regarding the type of building and the possibility of its use in other climatic regions. It is an open method in which it is possible to take into account specific requirements regarding the region of the building's location. In addition, the method enables analysis from the point of view of other criteria, e.g., the criterion of comfort (thermal, acoustic, electromagnetic, gas emissivity from building materials or ground foundation, etc.) in the building.

The limiting assumptions adopted in the case study analysis of a modernized building regarding the omission of calculations related to the lighting installation and the cooling system were caused only by the need to focus the considerations. In turn, the assumption of minimum durability, which was adopted as a value not exceeding the designed service life of the structure, is a conservative assumption and therefore does not result in an overly optimistic assessment of the energy consumption of the building.

The proposed method can be further developed in the direction of changing the number and types of analysis criteria, e.g., the comfort criterion, and by investigating the impact of changes in the importance of the degree of individual analysis criteria, or it can be developed with regard to the use of different types of reference buildings and to those located in different climatic regions. Moreover, the method makes it possible to study the correlation between the proposed global building energy consumption indicator and the carbon footprint or the qualification level of the building's energy consumption class.

8. Conclusions

The paper presents a proposal for a universal method for the unequivocal selection of the optimal combination of components determining the energy efficiency of buildings with the use of the introduced global building energy consumption indicator.

The basis of this method is the multi-criteria optimization of the components influencing the energy efficiency of buildings. The criteria, which included relative annual final energy demand, cost, durability, and payback time of the investment outlays, were adopted in the analysis. The values of these criteria are calculated in relation to the construction of the reference building, and the weight values assigned to the individual criteria are adopted on the basis of an expert assessment of user preferences.

The set of components influencing the energy efficiency of buildings, including the characteristics of their properties, is an open database set and can be updated and supplemented. Similarly, the cost set of these components needs to be updated in relation to the local market situation. The analysis of the durability of these components also depends on the results of the research on maintaining their functional properties over a long period of operation.

As a result of a detailed analysis of the case study of the modernized building, the most advantageous variant of modernization was determined, defined by the lowest value of the global building energy consumption indicator. Moreover, the detailed criteria values were determined for this solution variant both for the individual components and for the component combination. These results indicate the high efficiency of the proposed method. In general, the method allows for an unambiguous indication of the most advantageous solution, with, however, the reservation that the final decision on the choice of the modernization variant remains with the investor.

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Nomenclature

The following symbols are used in the paper.

A_u	usable floor area of the building
A_p	area of the building envelope
A_{tp}	areas of transparent partitions
A_n	area of lighting zone
C	share of glazing area in total window/door area
$C_{b,i}$	assembly costs with the possible costs of the building project
$C_{d,i}$	possible demolition and disposal costs once the cost-effectiveness of further operation and modernization has been established
C_E	energy unit cost
$C_{e,i}$	the operating costs
C_i	the total cost
$C_i(t)$	total cost of application of the component (excluding the cost of demolition)
$C_E(t)$	unit cost of energy including the projected change in energy costs
$C_{lt,i}$	long-term costs
C_m	the thermal capacity of the building
C_{max}	maximum cost of the component used
$C_{m,i}$	net maintenance costs
$C_{mg,i}$	gross maintenance cost of component $\{i\}$ during the calculation period
C_{min}	minimum cost of the component used
$C_{mr,i}$	replacement cost
$C_{mw,i}$	value of the contractor's guarantee for component
$C_{p,i}$	the cost of delivery to site
$C_{st,i}$	the initial costs
c_i	price of the material, construction, or installation solution
$c_{r,req}$	the components r of the solution variant
$c_{v,req}$	the limiting conditions for the solution variant v
c_w	specific heat of water
D_i	the durability
D_{max}	the maximum lifetime of the component used
D_{min}	the minimum lifetime of the component used
d_i	layer thickness
E_R	the relative annual final energy need of the reference building
$E_R(t)$	the current relative annual final energy need in the reference building
$E_{TS,i}$	the final energy demand for technical systems
$E_{elpom,i}$	the final energy demand for technical systems
E_i	the final energy demand

$E_i(t)$	the relative annual final energy need determined for a given component in a reference building
$E_{k,\,i}$	the final energy determined for a given component in the reference building
E_{min}	minimum of annual final energy of the reference building
E_{max}	maximum of annual final energy of the reference building
F_{cn}	illuminance factor
F_{0n}	area utilization factor
F_{Dn}	daylight factor
g	transmittance of solar radiation through transparent partitions
I	the number of all considered components influencing the energy consumption of the building
I	solar radiation energy per month according to climatic data
k_r	correction factor due to interruptions in DHW use
N	number of lighting zones
$N_{c,i}$	design number of duty cycles of the design period
N_v	number of components in the set of each solution variant $\{v = 1, \ldots, V\}$
$n_{k,i}$	unit of measurement
n_v	air change rate
n_{50}	air tightness coefficient of the building
P_n	illumination power density
P_i	payback time
P_{min}	the minimum payback time of the applied component
P_{max}	the maximum payback time of the applied component
$Q_{C,i}$	final energy demand for the cooling system
$Q_{H,i}$	final energy demand for the heating system
$Q_{L,i}$	the annual final energy demand supplied for the lighting system
$Q_{W,i}$	final energy demand for the domestic hot water system
Q_i	the annual final energy demand supplied to the reference building extracted for each component used
Q_{int}	internal heat gains
Q_k	the annual final energy demand parameters for the other technical systems (material, construction, installation)
$Q_{min,1}$	default standby energy value for battery charging
$Q_{min,2}$	default standby energy value for control
Q_{tr}	the amount of heat exchanged by transfer
Q_{sol}	solar heat gains
Q_{uH}	the annual useful energy demand
$Q_{uH,m}$	the monthly useful energy demand for heating
Q_{uL}	the annual useful energy demand for the lighting system
$Q_{uL,n}$	coefficient of annual useful energy demand per unit area for the lighting system in each zone
Q_{uW}	the annual useful energy demand of the DHW preparation system
Q_{ve}	heat exchanged through ventilation
q	specific internal heat gain depending on the type of building
$q_{v,1}$; $q_{v,2}$	basic and infiltrating fluxes exchanged by the ventilation
R_p	the thermal resistance coefficient of the building envelope material
R_{si}	heat transfer coefficients of the internal side
R_{se}	heat transfer coefficients of the external side
T_0	cold water temperature
T_{int}	indoor environments temperatures
T_{ext}	outdoor environments temperatures
T_w	hot water temperature
$T_{w,i}$	warranty period
t	time
t_r	number of days in a year
t_{Dn}	total annual daylight duration
t_{0n}	total annual of lack of daylight duration

U_p	the heat transfer coefficient of the building envelope
V	the total cubature volume
V_{wi}	unit daily DHW demand
w_j	the weight to the criterion assigned
$\Delta E_{R,i}$	the saving in relative annual final energy demand resulting from the application of a given solution in a reference building
$\Delta E_{R,i}(t)$	the current saving of the relative annual final energy demand resulting from the application of the given solution in the reference building
Δ_{ec}	the fourth-order indicator
$\Delta_{ec,v}$	the third-order indicators, called solution variants indicators
$\delta_{C,i}$	cost indicator
$\delta_{D,i}$	durability indicator
$\delta_{E,i}$	the relative annual final energy demand indicator
$\delta_{ec,i}$	the second-order indicators, called component energy consumption indicators
$\delta_{P,i}$	the outlays investment payback time indicator
η	the heat gain utilization factor for each month
η_{Hd}	efficiencies transmission
η_{He}	efficiencies regulation
η_{Hg}	efficiencies generation
η_{Hs}	efficiencies accumulation
η_{Htot}	the overall efficiency of the heating system
η_{Ltot}	the overall efficiency of the lighting system
η_{Wd}	transmission of heat
η_{We}	regulation of heat
η_{Wg}	generation of heat
η_{Ws}	accumulation of heat
λ_i	thermal conductivity coefficients of the layer material taken from building material manufacturers' data
ρc_p	heat capacity of the air
ρ_w	density of water

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