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The Impact of Weather-Forecast-Based Regulation on Energy Savings for Heating in Multi-Family Buildings

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Abstract: In this study, based on 19 years of research, an analysis of thermal energy consumption for heating was carried out on a group of 22 residential multi-family buildings located in a temperate continental climate. The buildings were constructed with two different technologies based on prefabricated elements, and most of them were equipped with central heating cost allocators. A predictive control system for the central heating system was installed in the analyzed buildings, followed by a deep thermo-modernization. An evaluation was made regarding whether the use of a change in the method of central heating control, from the traditional one, which takes into account only the variable external temperature, to weather control, increases the energy efficiency of the thermo-modernized buildings. In addition, the cost-effectiveness of the modernization measures was analyzed by determining economic efficiency indicators; therefore, it was possible to identify the modernization variant that, with limited investment costs, could achieve the best energy efficiency resulting from the European energy policy.

Keywords: weather-controlled central system; energy saving; energy consumption; thermal improvement of buildings; new energy technologies; sustainable buildings

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1. Introduction

Energy efficiency means the amount of energy saved as determined by the measured or projected consumption both before and after improvements, while ensuring the normalization of external conditions affecting energy consumption [1]. This definition applies to all branches of the European economy; however, it particularly affects the construction sector, which is a huge consumer of energy—consuming more than 40% of total final energy and emitting 40% of CO_2 in the EU [2]. The residential sector accounts for about 76% of the final energy consumed in the building sector [3]. The aforementioned estimates reinforce the thesis of the great importance of the need to reduce energy consumption in buildings, particularly for heating and air conditioning, for rational energy management. Reducing energy consumption in the residential building sector is a priority action in European Union member states. The "Clean Energy for All Europeans" package sets a new target of reducing primary and final energy consumption by at least 32.5% by 2030. These measures allow efficient and sustainable use of the potential of fossil fuels and reduce emissions of gaseous and particulate pollutants produced in the process of energy fuel combustion. The ever-increasing prices of energy carriers also necessitate improvements in the energy performance of buildings. The Energy Performance of Buildings Directive (2010/31/EU) [4] was amended in 2018. The Directive (EU) 2018/844 [5], together with the Energy Efficiency Directive ((EU) 2018/2002) [6], is expected to ensure high energy efficiency and decarbonization of the building stock in each member state by 2050. It can also help achieve Europe's energy efficiency goals, such as reducing EU CO_2 emissions by 80–95% compared to 1990 [7]. It therefore becomes indispensable to look for methods to rationalize the cost of thermal energy consumption [8]. These measures are being taken not only to improve user comfort, but also to improve energy efficiency and, importantly, safety. The optimization of energy consumption and related energy efficiency have recently been studied in depth in virtually all aspects of life. These issues, in a special way, also affect buildings and their infrastructure, as they are one of the most energy-intensive zones of human functioning. In recent years, there has been noticeable progress in the technological solutions used in residential buildings, from architectural solutions to heating technology. This situation determines the need for a new approach to the design phase of planned facilities and, in the case of existing buildings, to their modernization and adaptation to modern trends and requirements [9]. Therefore, it has become an indispensable activity to conduct research on the already available climate control systems and to search for new functional climate control systems in buildings. All this is aimed at reducing electricity and heat consumption in buildings [10]. The most common form of improving energy efficiency in existing buildings is their thermal improvement—often referred to as thermo-modernization, which introduces a series of measures aimed at reducing the power and thermal energy demand of a building, thereby lowering the building's operating costs [11,12]. Moreover, the effectiveness of such measures depends on a number of factors, which include climatic conditions, age and type of building, as well as other factors that depend on building occupants. Scientific studies have shown that the habits of occupants regarding their temperature preferences have a very strong influence on the heat consumption of a building [13–15]. Hence, the energy efficiency of a building depends not only on its design, type of installation or heat source, but also on the behavior or wealth of its occupants, especially in buildings where central heating cost allocators have been installed. Very often, the impact on energy consumption in a multi-family residential building depends on the activity of the residents (working or not working) and their age (young people with or without children, or elderly people—retirees). This can be understood from evidence that similar households in similar buildings can have significant differences in energy consumption, and that a change in household population can lead to significant changes in energy consumption. According to Sun and Hong [16], relative energy savings can vary by as much as 20% due to occupant behavior. An attempt to estimate the role of occupants in shaping thermal energy consumption was made by Brom et al. [17], where their analysis indicated that about 50% of the differences in heat consumption between the same buildings can be explained by the properties of the building itself and other physical parameters that are often not taken into account in simulation models of heat transfer in buildings, and as much as 50% of the remaining may be due to the behavior of the occupants. For this, an important energy efficiency aspect that can influence occupant behavior is the introduction of modern solutions to improve heat management through operational regulation in buildings' internal heating systems using modern HVAC (heating, ventilation and air conditioning) systems managed intelligently [18–20]. The rational operation of the HVAC system to reduce energy losses and operating costs, while maintaining thermal comfort, should be based on the prediction of the heating load. The heating load is influenced by several factors, including the building's energy efficiency standard, its heating output and the location of the rooms relative to each other or to the exterior walls. Another important aspect is the location of the building in relation to the sides of the world and the density of buildings in the surrounding area [21–24]. With the use of new technologies and services in the residential sector, it is possible to accurately study the impact of dynamic changes in occupant activity on thermal energy consumption [25–27]. To estimate the amount of heat consumed in buildings, analyses usually try to find correlations between weather conditions and heat demand. Among the basic meteorological parameters, outdoor air temperature and insolation are the primary elements considered in calculating the heat demand for heating buildings [28–30]. In addition, it finds application in predicting indoor thermal comfort [31–33]. The use of Model Predictive Control (MPC) for energy management in buildings has attracted considerable interest. MPC algorithms have been applied in various forms of machine learning [34–40], making HVAC building design smarter based on historical data such as temperature, sunshine, humidity, wind power and energy consumption. In addition to the studies mentioned above, many other HVAC-related cases have been investigated [41–47].

Forecasting air temperature is one of the main topics in the field of meteorology and climatology, which explains why it is quite well studied. However, this applies to daily, monthly or annual temperature time series measured with low and medium temporal resolution (long- and medium-term forecasts) [48–52]. In many cases, the prediction of meteorological parameters is used at an early stage of heat load estimation without entering into its methodology [53]. MPC implementation in buildings is used, among other things, to reduce energy consumption and to apply demand-side management strategies [54–57]. Several approaches related to demand-side management can be found in the literature, which can be broadly divided into [58,59]:

- Regulation based on external temperature [59];
- Energy regulation using internal temperature sensors [60–62];
- Regulation based on weather forecasts [16,62–70];
- Forecast regulation using a barometer [59,60];
- Complex facility regulation models—predictive models based on data analysis using methods such as artificial neural networks [65,71–75];
- System regulation based on a multi-criteria optimization function [76–80].

Some of the above-mentioned methods of regulating the operation of the heating system are commonly used in actual residential buildings as commercial installations. These include: Egain Edge [59,68–70], EnReduce [60,62] and Kabona [60]. In situ studies in Scandinavia [60,61,67] and in Poland [69,70] have shown that, in the case of using a system based on a weather forecast (Egain Edge), measurable savings in energy consumption can be achieved in the range of 5 to 23%, whereas in the case of the other two, the savings can be up to 13% [60,67–70]. There is no precise information in the literature regarding what type of buildings (in what technology they were erected) were surveyed in Sweden, and in Poland they were buildings made with large-panel technology. This technology was dominant in residential construction from the 1960s to the 1980s. The issue of the energy efficiency of buildings that have undergone thermal modernization is addressed in many scientific papers [9,81,82]. Many authors have decided to study the effectiveness of thermal improvement measures of existing buildings on improving their energy efficiency, combined with an analysis of the economic viability of the treatments applied. Hummel et al. [83] conducted a detailed analysis on the effects and costs of thermal retrofit measures for a representative group of buildings in six European countries. They found that the costs of achieving savings of 40-60% are significantly lower than those of achieving higher savings, and the largest and cheapest savings are located in buildings that have still not been renovated. Liu et al. [84] analyzed the cost-effectiveness of retrofit measures in cold climates. They showed that the cost-effectiveness of retrofitting the building envelope increases when supported by upgrading technical installations. Chen et al. [85] and Mauro et al. [86] found similar results for Mediterranean climates, and they stressed, however, that insulation measures yield the greatest energy savings but are only cost-effective when combined with new, efficient technical installations. They showed that cost-optimal levels typically do not include envelope upgrades. These studies suggest that thermal improvement measures of the envelope are usually less cost-effective than the modernization of technical installations aimed at optimal heat management in buildings to improve their energy efficiency. Therefore, it is advisable to use other instruments to improve energy efficiency, through the modernization and improvement of heat management—operational regulation in building heating systems. One of the modern heating control systems for large-panel buildings that has found application in facilities previously subjected to thermal upgrading work is the Egain Edge system. This solution takes into account the prediction of heat demand, using a continuously updated forecast of atmospheric conditions. According to the distributor's information, in Poland, the system has found application in about 400 district heating substations installed in buildings made with prefabricated technology, hence the authors' interest in this topic. The literature analysis conducted above has identified examples of evaluating the effects of building thermal upgrades, both in terms of energy and energy–economic aspects, but there is a lack of articles covering all these aspects together, especially in the case of multi-family residential buildings.

In addition, the difference between the predicted and actual energy performance of thermally improved buildings can be significant. The authors believe that there is a need for more information, results and successful case studies, especially on a comprehensive basis, which can be taken into account when choosing a thermal upgrading option. This is because, despite the many incentives that have been carried out, the basic criterion for the application of a particular energy system is the economic calculus. In practice, energy analysis cannot be the only factor in choosing a solution to improve the energy efficiency of a building. The potential investor should evaluate both the technical and economic aspects of each of the systems under consideration and should choose the one that is the most beneficial from the perspective of the total lifetime.

Therefore, the purpose of this study was to perform a detailed analysis of actual heating energy consumption in existing multi-family residential buildings mostly equipped with central heating cost allocators, with over 19 years of operation. It was evaluated whether the use of a change in the method of central heating control from the traditional one, which takes into account only the variable external temperature, to a control based on the weather forecast, affects the energy efficiency of buildings undergoing thermal improvements. An attempt was also made to indicate what additional factors affect the level of savings achieved. Different variants of energy efficiency improvement measures were analyzed, such as installing only the Egain Edge system in the building and then performing only thermal upgrading of the building body, or performing thermal upgrading together with the installation of Egain Edge. In addition, the cost-effectiveness of the modernization measures was analyzed by determining economic efficiency indicators; therefore, it was possible to identify the modernization variant that achieves the best energy efficiency with limited investment costs. It should be emphasized that, as shown above, the available literature lacks such a comprehensive assessment from the technical side as well as from the economic side, and it has not yet been used in the energy assessment of buildings made with prefabricated technologies, which use a control system based on the weather forecast. In addition, the buildings are equipped with cost allocators, which is the novelty of this research.

2. Materials and Methods

2.1. Description of the Research Subject

This study included 22 residential multi-family buildings constructed with two different technologies based on prefabricated elements. Buildings B1–B12 were erected with large-block technology—Żerań bricks (CŻ), whereas buildings B13–B22 were made with the large-panel system (OWT-67N). Both in terms of area and volume, only the buildings built using the large-block system are very similar to each other. In the case of properties built using large blocks, the aforementioned parameters are characterized by variation. For all analyzed buildings, the A/V aspect ratio assumes widely scattered values and ranges from 0.30 to 0.39. These are buildings with a different number of floors, including those that are three-story (B1–B3), four-story (B4–B6) and five-story (B7–B22) buildings with a full basement. There is also variation in the number of staircases, including two-staircase buildings (B1–B3; B6), three-staircase buildings (B4–B5; B11; B15; B19), four-staircase buildings (B10; B12–B14; B16–B18; B20–B22) and one each of six-staircase (B7), seven-staircase (B9) and eight-staircase (B8) buildings. The buildings built in the OWT-67N system use a cross-bearing wall system, and the large-block (CŻ) buildings were constructed in a cross-block structural system.

The multi-family residential buildings under study are located in the northeastern part of Poland, in climate zone IV, with a design temperature of -22 °C outside and a temperate continental climate.

This climate is characterized by mild summers and precipitation evenly distributed throughout the year. Importantly, in this climate, there is no month with an average temperature above +22 °C. The geographic coordinates of the location of the studied sites are: $53^{\circ}10'35''$ N longitude and $22^{\circ}04'23''$ E latitude. Both the OWT-67N and CŻ systems are among the most popular prefabricated building systems in Poland. In the first of the above-mentioned systems, the ceilings and walls form large-dimensional elements that usually correspond to interior divisions into rooms or into groups of rooms, whereas in the second, the division of building partitions that constitute walls is not related to the division of the interior into individual rooms, and the partition enclosing one room may consist of several blocks. Both technologies, however, have many shortcomings and defects, which determine and still cause the requirement for constant inspection of their technical condition, including the need for thermo-modernization due to their low thermal insulation. In this region of Poland, which is the location of the buildings included in the study, the standard heating season lasts 222 days. In turn, the average annual outdoor temperature is +7.7 °C, and the number of degree days in a standard heating season ($HDD(t_b)_0$), based on multi-year outdoor temperatures (1991–2020), is 3413.1 K·day/year [87]. In particular, in line with the trend recorded globally, recent years have been characterized by very mild winters with respect to the statistical multi-year period describing climatic conditions. This was certainly directly reflected in the recorded amount of thermal energy consumed for property heating.

A view of an example of the studied building, made with OWT-67N technology, is shown in Figure 1, and one erected with CŻ technology is shown in Figure 2.

Figure 1. View of a typical building (B19) accepted for the study, made with OWT -67N large-panel prefabricated technology, 5-story, 3-cage [photo taken by authors].

Figure 2. View of a typical building (B3) adopted for the study, made with large-block prefabricated CŻ technology, 3-story, 2-cage [photo taken by authors].

Table 1 shows the basic technical parameters of the 22 buildings analyzed, which are labeled B1–B22.

Table 1. Basic technical parameters of the surveyed buildings.

Object	Buildings B1–B12 Prefabricated Technology Type CŻ Buildings B13–B22 Prefabricated Technology Type OWT-67N							
	Year of the Construction of the Building	Building Area		Heated Volume of the Building [m^3]	A/V	Number of Staircases	Year of Thermal Modernization	
		Usable A_F [m^2]	Housing [m^2]				Gable Walls	Longitudinal Walls
B1	1992	1031	656.1	5395	0.39	2	2016	2016
B2	1992	1029	656.1	5395	0.38	2	- *	- *
B3	1992	1017	619.95	5417.7	0.37	2	2017	2017
B4	1992	1489	953	7935.8	0.38	3	2013	2013
B5	1991	1688	1115.8	8677.4	0.36	3	2019	2019
B6	1991	1199	774.6	6251.1	0.38	2	2010	2010
B7	1994	3603	2235.2	18,376	0.33	6	2014	2014
B8	1994	4670	2409.5	23,955	0.34	8	2010	2010
B9	1995	4317	2499.1	25,178	0.31	7	- *	- *
B10	1996	2397	1389.06	11,988	0.33	4	- *	- *
B11	1993	1866	1237.75	9640	0.34	3	2019	2019
B12	1993	2896	1827.75	14,748	0.30	4	2009	2009
B13	1983	2292	1657	9197	0.38	4	2003	2007
B14	1984	2292	1657	9232.6	0.37	4	2003	2007
B15	1984	1868	1292.6	7558.9	0.38	3	2003	2007
B16	1984	2408	1575.6	9877.8	0.38	4	2002	2007
B17	1983	2423	1608.2	9983.6	0.38	4	2001	2005
B18	1983	2426	1685	9991.8	0.38	4	2001	2005
B19	1988	1993	1918.6	8459.6	0.35	3	2001	2011
B20	1988	2413	1686	10,404	0.38	4	2002	2011
B21	1986	2426	17,589.7	10,295.7	0.38	4	2003	2009
B22	1986	2665	1961	11,151.2	0.38	4	2003	2009

*—buildings that have not been thermo-modernized.

The buildings are supplied with thermal energy by system heat, produced by a district heating plant operating in the city. In all buildings, since 2014, the heat sources have been individual, dual-function heat substations operating for central heating and hot water. Prior to the installation of a control system, based on the prediction of climatic conditions, in the heat substations, tracking weather control was used. The study of thermal energy consumption for heating buildings was carried out in the years from 2002 to 2020 (inclusive). A significant part of the buildings erected with prefabricated large-block technology of the Żerań CŻ brick type (except for B2, B9, B10) and all buildings made with prefabricated large-block technology of the OWT-67N type underwent deep thermo-modernization (Table 1). The CŻ-type buildings were thermally improved between 2010 and 2019. The thermal modernization work consisted of insulating the longitudinal and gable walls with a layer of 12 cm-thick polystyrene foam, λ = 0.04 W/m·K, with thermal resistance of R = 3.0 m^2·K/W. In parallel with the thermal insulation work of the above-ground walls, the thermal insulation of the basement walls with 10 cm-thick extruded polystyrene foam with λ = 0.036 W/m·K was carried out, as well as the replacement of windows and door frames in the stairwells and basement rooms. The ventilated flat roofs were not thermally upgraded due to a sufficient layer of the existing insulation that met the technical requirements.

In the case of large-panel buildings, thermo-modernization was carried out in two stages. In the first stage, in 2001–2003, the insulation of gable walls was performed. These partitions were insulated with polystyrene foam that was 10 cm thick, λ = 0.04 W/m·K, with a layer of thermal insulation with thermal resistance of R = 2.5 m^2·K/W. The second stage of the thermo-modernization works included in its scope the insulation of longitudinal walls and basement walls, as well as the insulation of flat roofs with mineral wool granules with a thickness of 14 cm, λ = 0.04 W/m·K, with a layer of thermal insulation with thermal resistance of R = 3.5 m^2·K/W. It also included the replacement of window frames in basements U = 1.3 W/m^2·K and in staircases U = 1.1 W/m^2·K and installing aluminum entrance doors in buildings U = 1.5 W/m^2·K. These works were carried out in 2005–2011.

The heat transfer coefficients U of the building envelope after thermal upgrading in buildings B1–B22, calculated in accordance with PN-EN ISO 6946:2017-10 [88], are shown in Table 2.

Table 2. Heat transfer coefficients U of building partitions after thermal improvement.

Type of Partition	Heat Transfer Coefficients U [W/(m^2·K)] after Thermal Improvement	
	Prefabricated Technology	
	Large-Block CŻ	Large-Plate OWT-67N
gable walls	0.19	0.26
longitudinal walls	0.19	0.24
ventilated flat roofs	0.18	0.18
entrance doors	1.50	1.50
windows in staircases	1.10	1.10
windows in basements	1.10	1.30

In all buildings after thermal modernization, except B16, the hydraulic regulation of the central heating system was carried out in order to adjust the distribution of the flow of the heating medium to individual radiators, after reducing the heat demand in the rooms. In the buildings included in the analysis, the heating system is a two-pipe system, with bottom distribution with the operating parameters of the internal system of 80/60 °C. The living quarters and common rooms (laundry rooms, dryers) are equipped with cast iron and panel radiators. In 1995–1999, all radiators were equipped with thermostatic valves with thermostatic heads. The use of thermostatic heads allows users to rationally manage heat energy by using a mechanism to automatically close the valve when the temperature near the head reaches a value higher than that set on the dial by the resident. In addition, this solution makes it possible to take advantage of gains from insolation, gains from appliances or domestic gains.

In 1995–1999, the first evaporative central heating cost allocators were installed in all apartments (except apartments in building B10), and then, in 2010, they were replaced by electronic cost allocators equipped with a radio module. This allows for the remote reading of these devices without the need for visits to the apartments.

Buildings B1–B22 were equipped with the Egain-Edge-type predictive control system. Chronologically, this system was installed in buildings B7 and B10 in September 2012; in buildings B13–B16 in September 2013; in building B8, B9, B11, B12, B17 and B18 in September 2014; and in buildings B1–B6 and B19–B22 in January 2015.

Table 3 presents data on the thermal parameters that characterize each building.

Table 3. Energy performance of surveyed buildings before and after thermal improvements [89].

Buildings Under Study	Calculated Thermal Power of the Heating System [MW]	
	Before Thermal Improvement	After Thermal Improvement
B1	0.0600	0.0570
B2	0.0584	- *
B3	0.0600	0.0600
B4	0.0900	0.0810
B5	0.1003	0.0990
B6	0.0730	0.0721
B7	0.2070	0.1842
B8	0.3110	0.2700
B9	0.2425	- *
B10	0.1250	- *
B11	0.1180	0.1049
B12	0.1599	0.1396
B13	0.2848	0.1081
B14	0.2480	0.1133
B15	0.2305	0.1161
B16	0.3029	0.0937
B17	0.3123	0.1180
B18	0.2895	0.1187
B19	0.2176	0.0980
B20	0.2765	0.1243
B21	0.2526	0.0919
B22	0.2581	0.1280

*—non-insulated buildings.

2.2. Forecast-Based Regulation System

The control system installed in the surveyed buildings, which uses predictions of climatic conditions, consists of several devices that interact in real time with both the thermal node fittings and the software located on the operator's servers [68–70]. These devices include: Egain Hub acting as a weather forecast receiver; eGain 905 climate loggers installed in residential units; and eGain 902 signal transmitters installed in the thermal node, whose task is to provide information about the equivalent temperature value to the controller. Unlike traditional control systems, in the forecasting system, the external temperature sensor is replaced by a receiver receiving local weather forecasts. The continuously updated weather forecast, correlated with the relevant data about the building (glazed area, ventilation system, type of windows, location in relation to the world) is treated as input data for calculating the equivalent temperature. The algorithm used to determine the equivalent temperature, in addition to the above-mentioned information, is fed with a whole range of data, completely ignored in the case of control in conventional systems. Figure 3 shows the parameters taken into account by the predictive control system.

Equivalent temperature is a key parameter in this system, on which the amount of heat consumed by the building depends. The Egain Hub weather forecast receiver measures the current outdoor temperature in real time, but it also receives a signal from the operator in the form of data from weather stations. This signal includes information on other climate parameters such as sunshine, wind direction and speed, and precipitation. These data are continuously recorded and related to their values obtained from weather forecasts. As a result of the registration and ongoing analysis of the weather conditions prevailing at a given moment in relation to the forecast, it is possible to open or close the control valves in the thermal node well in advance, and thus to adjust the temperature of the energy carrier to changing weather conditions. What is extremely important here is the issue of leveling the influence of the hydraulic and thermal inertia of the building on the mechanism of achieving the expected thermal comfort in dwellings.

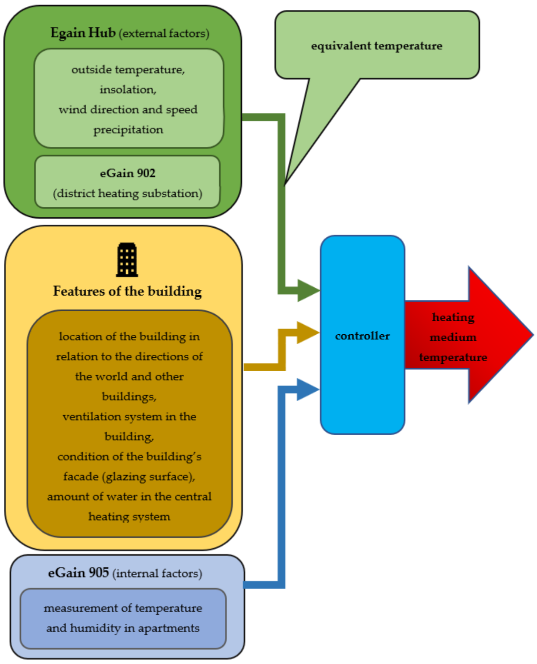

Figure 3. Compilation and comparison of elements included in heating regulation systems [own study].

Figure 4 shows an Egain Hub weather forecast receiver mounted on the exterior wall of one of the buildings surveyed, along with a signal transmitter mounted in the heating substation.

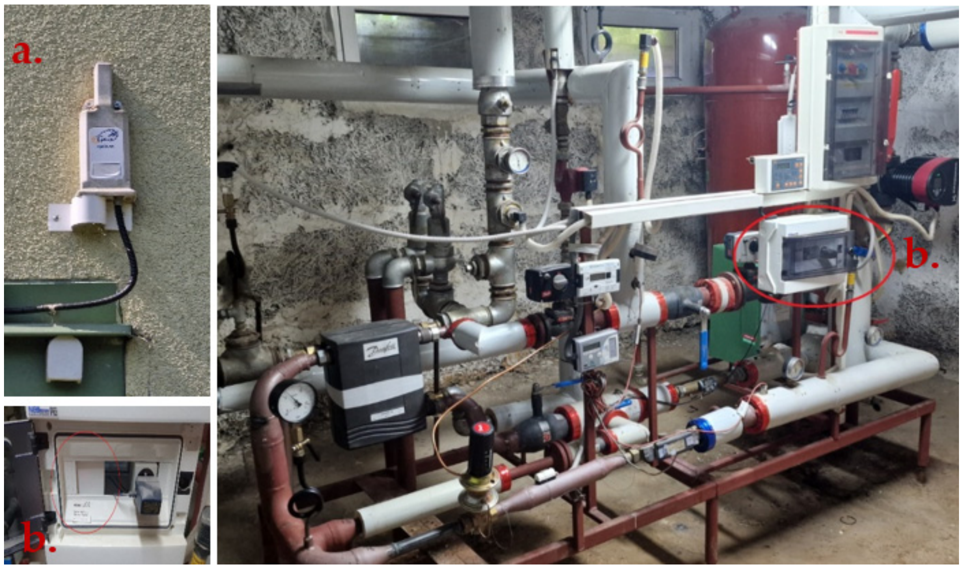

Figure 4. Egain Hub weather forecast receiver (**a**) mounted on the outside wall of the building and the signal transmitter (**b**) mounted on the heating substation [photo taken by authors].

The operator's servers exchange data with a weather forecast receiver installed on the outside wall of the building, using the GSM network. The purpose is to generate and deliver equivalent temperature values to the controller in the thermal node (via a signal transmitter). Both the equivalent temperature values and the data related to the post-weather forecast are downloaded for the next 5 days. Once the information is downloaded, the equivalent temperature, as a control parameter, replaces the outdoor temperature. The Egain Hub receiver (Figure 4) can also act as a temperature sensor used in traditional control systems. This is because it is equipped with a device that measures the outside temperature in real time.

This measurement can be made with an accuracy of ± 0.5 K, in the range of −50 to +50 °C. Egain Hub automatically switches to the conventional mode in the event of a system failure or an unexpected interruption in the reception of the equivalent temperature.

It is worth mentioning that the Egain Hub weather forecast receiver is not only responsible for transmitting the equivalent temperature and measuring the outside temperature. Its tasks also include increasing energy efficiency, enlisting data from M-bus sensors, calibrating the forecast for current conditions and remotely controlling heating systems [68].

Egain Edge 905 climate recorders, which are installed in apartments selected by the property manager, have the ability to measure temperatures with an accuracy of ±0.5 K, ranging from −40 to +50 °C. They also measure air humidity with an accuracy of ±3%. These recorders guarantee proper control of thermal comfort in dwellings. Building administrators, as a result of the online platform, have a direct opportunity to control the situation related to thermal conditions in apartments, and in the event of a malfunction, they can efficiently take action to remove it. It is important that climate recorders can also play a key role, as priority data, in calculating the equivalent temperature given to the controller. In this case, however, it is important that these devices are installed in apartments whose users manage heat in a rational manner, not overcooling, but also not overheating.

2.3. Measurement Methodology

In buildings B1–B22 located in northeastern Poland, in a temperate continental climate–Dfb [90], measurements were made of heat consumption for central heating in the years 2002–2020. The analyzed buildings, except for building B10, were equipped with radiator-based central heating cost allocators. The study was carried out using ultrasonic heat meters located in the district heating substations in each building. The measured heating energy consumption was converted to a standard heating season according to Relation (1). Calculations were made to eliminate temperature fluctuations in different years of the heating season. To calculate the value of the number of heating season degree days, the outdoor temperatures in 2002–2020 were assumed on the basis of data provided by MPEC Łomża.

Figure 5 shows the number of degree days (the number of HDDs) characterizing the 2002–2020 heating season in the study region.

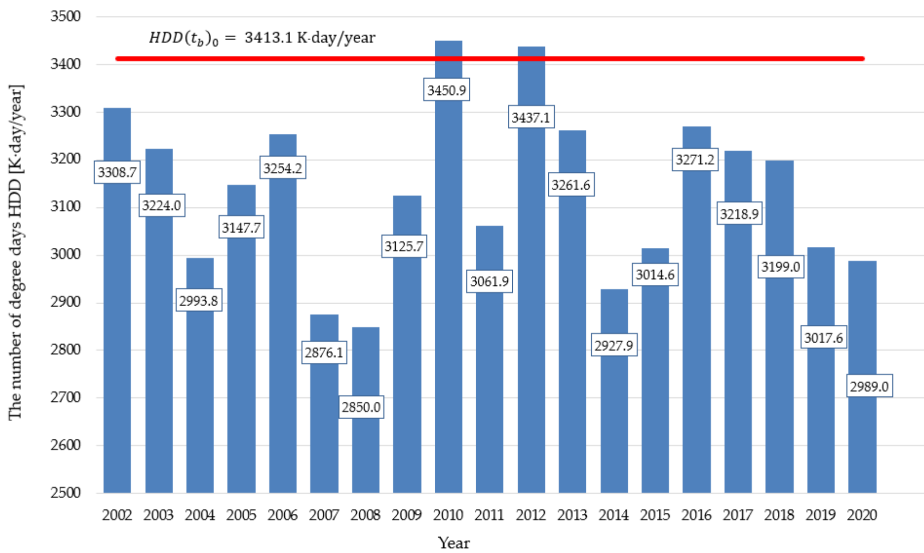

Figure 5. Number of heating season degree days determined for 2002–2020 based on temperature data of MPEC Łomża Heat Plant and typical heating season (1991–2020) [87].

The index of annual final energy demand FE_H for central heating adjusted to the standard conditions of the heating season [kWh/(m^2·year)], including the period before and after thermal modernization and the period taking into account the installation of predictive control, was calculated using Relation (1):

$$FE_H = \frac{Q_{K,H} \cdot HDD(t_b)_0}{HDD(t_b)_j \cdot A_F}, \quad (1)$$

where

FE_H is the index of annual final energy demand for heating corrected to standard conditions, [kWh/(m^2·year)];
$Q_{K,H}$ is the measured energy consumption for heating purposes, [kWh/year];
$HDD(t_b)_0$ is the number of degree days calculated in a standard year, [K·day/year];
$HDD(t_b)_0$ = 3413.1 K·day/year [87];
$HDD(t_b)_j$ is the number of degree days calculated for each year, [K·day/year];
A_F is the heated area of the usable part of the building, [m^2], according to Table 1.

The energy savings after applying the Egain Edge system in buildings that have not yet been thermally improved were determined using Relation (2):

$$ES_1(\%) = \left(\frac{FE_{H,R} - FE_{H,E}}{FE_{H,R}}\right) \cdot 100\%, \quad (2)$$

where

$ES_1(\%)$ is the percentage savings in energy used to heat the building after using the Egain Edge system prior to thermal improvement, [%];
$FE_{H,R}$ is the index of annual final energy consumption for heating purposes before thermal improvement when using weather control in the building, [kWh/(m^2·year)];
$FE_{H,E}$ is the index of annual final energy consumption for heating before thermal improvement after using the Egain Edge system in the building, [kWh/(m^2·year)].

On the other hand, the energy savings after thermal improvement with weather control (without the installation of Egain Edge system) in the buildings were determined using Relation (3):

$$ES_2(\%) = \left(\frac{FE_{H,R} - FE_{H,TM}}{FE_{H,R}}\right) \cdot 100\%, \quad (3)$$

where

$ES_2(\%)$ is thepercentage of savings of energy used to heat the building after the thermal improvement is made, but without the installation of the Egain Edge system, [%];
$FE_{H,TM}$ is the index of the annual final energy consumption for heating with the use of weather control in the building after thermal improvements, [kWh/(m^2·year)].

The total energy effect taking into account both thermal improvements and the installation of a central heating system control system based on Egain Edge weather prediction was determined using the Relation (4):

$$ES_3(\%) = \left(\frac{FE_{H,R} - FE_{H,TME}}{FE_{H,R}}\right) \cdot 100\%, \quad (4)$$

where

$ES_3(\%)$ is the percentage of savings of energy used to heat the building after thermal improvement and the installation of a central heating control system based on weather prediction, [%];
$FE_{H,TME}$ is the index of annual energy consumption after thermal improvement and the installation of the Egain Edge system, [kWh/(m^2·year)].

The study also determined the savings that resulted from replacing weather control with forecast control of the Egain Edge system in buildings previously subjected to thermal improvement. The savings were determined based on Relation (5):

$$ES_4(\%) = \left(\frac{FE_{H,TM} - FE_{H,TME}}{FE_{H,TM}}\right) \cdot 100\%, \quad (5)$$

where

$ES_4(\%)$ is the percentage of savings achieved by replacing weather control with weather-prediction-based control after thermal improvement, [%].

In addition, the energy savings from thermal improvement in buildings where Egain Edge was previously installed was determined using Relation (6):

$$ES_5(\%) = \left(\frac{FE_{H,E} - FE_{H,TME}}{FE_{H,E}}\right) \cdot 100\%, \quad (6)$$

where

$ES_5(\%)$ is the percentage of savings achieved as a result of thermal improvement in buildings where the Egain Edge system was already installed, [%].

2.4. Methodology for Assessing the Economic Viability of Investments

In this article, two indicators were used to evaluate the economic viability of an investment involving the thermal improvement and installation of a forecast control system for the Egain Edge central heating system in buildings B1–B22. These were the Life Cycle Cost (LCC) and Cost of Energy Saving (CCE) indicators. These indicators are used most often when evaluating the profitability of investments made in energy-saving projects in Poland.

The economic analysis was performed for the following variants:

Variant 0 is the period before thermal improvement;

Variant 1 is the installation of the Egain Edge system;

Variant 2 is the execution of thermal improvement;

Variant 3 is the execution of thermal improvement and the installation of the Egain Edge system.

The life cycle cost index LCC_i allows one to determine the total investment and operating costs of the system for the *i*-th variant in the considered life cycle based on Relation (7):

$$LCC_i = Ic + \sum_{n=0}^{T} \frac{C_{e,o} \cdot (1 + r_e)^n}{(1 + i)^n} \quad (7)$$

where

LCC_i is the life cycle cost for the i-th variant, [EUR/m^2];

Ic is the initial cost incurred in the base year n = 0 (unit purchase and commissioning costs of the installation, unit investment outlays for thermal improvement), [EUR/m^2];

$C_{e,o}$ is the annual cost of using the system (fixed fees, etc.), [EUR/m^2];

T is the assumed number of years of the installation's life cycle (T = 25);

n is the years of operation ($n = 1, 2, 3, 4 \ldots 25$), [year];

i is the discount rate, [%], i = 8%;

r_e is the energy price growth rate, [%], (assuming an average r_e value of 15% per year).

On the other hand, the cost index of saved energy CCE_i allows one to determine the amount of money spent to save a unit of thermal energy for the *i*-th modernization variant. The CCE_i index was calculated based on Relation (8):

$$CCE_i = \frac{I_c \cdot \frac{i}{1-(1+i)^{-n}}}{\Delta FE_{Hi}} \quad (8)$$

where

CCE_i is the cost index of saved thermal energy for the i-th modernization variant, [EUR/kWh];
Ic is the initial cost (unit purchase and commissioning costs of the installation, unit investment outlays for thermal improvement), [EUR/m^2];
ΔFE_{Hi} is the annual thermal energy savings (reduced to standard season conditions) obtained as a result of the i-th modernization variant, [kWh/m^2·year].

The CCE index was determined under the assumption of carrying out the investment during the year and trouble-free operation during n = 25 years of the accrual of energy effects. Calculated as the ratio of the expenditures incurred for the implemented thermal modernization project (insulation of the building body, installation of the Egain Edge predictive control system) to the annual heat energy savings obtained as a result of the implemented investment. The value of CCE should be compared to the unit cost of heat energy supplied to the building (fixed and variable costs), which, in the case under review, averaged 0.056 EUR/kWh.

A profitable investment is an investment in which CCE is within the limits of $0 < CCE$ < the unit cost of the purchase of thermal energy.

Investment outlays I_c and exploitation costs C_e, o were adopted in the form of unit indicators related to 1 m^2 of heated usable area per year. The average value of the installation of the Egain Edge system was 0.68 EUR/m^2, and the cost of the thermal improvement was 109 EUR/m^2. The operating costs for a given year of building use were as follows: the Egain Edge system operation was 0.26 EUR/m^2, the charge for contracted power was 1.49 EUR/m^2 and the cost of thermal energy was 0.043 EUR/m^2.

The details of costs for individual buildings are summarized in Table 14.

3. Results and Discussion

3.1. Technical Analysis

The research conducted on the actual thermal energy consumption includes a total of 22 multi-family residential buildings made with prefabricated technology of the Żerań Brick (CŻ) type and OWT-67N type. The research was carried out from 2002 to 2020. Measurements of thermal energy consumption were carried out using ultrasonic heat meters. During the course of the study, the buildings were subjected to thermo-modernization measures (external walls, ceilings were insulated and windows and doors were replaced), and there was a change in the weather regulation of the central heating system to forecast regulation, which influenced the real change in the measured thermal energy during the measurements.

Table 4 highlights the three periods of thermal energy measurements: before thermal improvement, after thermal improvement (green) and the third period, when the Egain Edge central heating predictive control system was installed in the buildings (yellow), which replaced the weather regulation of the central heating substation (Figure 1).

Only buildings B2, B9 and B10 did not undergo thermal improvement. In these buildings, only a predictive control system for the central heating system was introduced, consisting of continuous predictions of weather conditions, such as outdoor temperature, sunshine, wind and humidity. In all buildings, except building B10, cost allocators for the central heating system were installed. Building B10 had the highest annual average final energy demand index of 126 kWh/(m^2·year). The remaining buildings had an average FEH index ranging from 75 kWh/(m^2·year) to 102 kWh/(m^2·year).

Table 4 shows the index of the annual final energy demand in buildings B1–B22 calculated on the basis of measurements obtained from ultrasonic heat meters according to Relation (1), after taking into account the heated area of each building, which is included in Table 1.

Table 4. Index of annual final energy demand FE_H in the studied facilities B1–B22 from 2002 to 2020 [kWh/(m^2·year)].

Year	Heating Final Energy Index FE_H [kWh/(m^2·year)]																					
	B1	**B2**	**B3**	**B4**	**B5**	**B6**	**B7**	**B8**	**B9**	**B10**	**B11**	**B12**	**B13**	**B14**	**B15**	**B16**	**B17**	**B18**	**B19**	**B20**	**B21**	**B22**
2002	106	107	107	115	115	115	108	108	111	121	93	93	110	124	114	117	104	118	98	86	115	95
2003	113	113	113	129	129	129	114	119	120	127	97	97	101	130	121	119	107	124	101	94	123	101
2004	109	109	109	122	122	122	111	111	117	137	93	93	105	115	115	111	98	114	88	96	107	87
2005	98	97	98	113	113	113	102	110	96	124	86	86	103	106	102	99	85	93	87	92	96	81
2006	108	108	108	111	110	111	104	108	73	127	87	87	107	109	116	99	71	76	95	90	92	81
2007	105	105	105	116	116	116	107	100	82	132	89	89	99	100	107	95	75	81	98	97	93	79
2008	113	113	113	120	120	120	112	111	95	140	92	92	80	84	97	90	80	81	94	102	98	82
2009	106	106	107	115	115	115	107	110	103	132	83	83	80	78	92	90	75	82	86	99	82	75
2010	106	106	106	116	116	116	111	104	102	123	89	89	78	74	78	88	72	85	87	100	68	64
2011	96	95	96	97	97	97	92	80	91	117	84	84	69	73	70	83	70	80	77	86	65	61
2012	103	103	103	100	100	100	95	82	87	127	81	74	68	78	72	76	68	74	55	63	64	54
2013	108	108	108	97	97	97	91	82	92	121	90	76	71	75	76	78	72	73	55	62	70	48
2014	101	102	103	85	83	81	82	84	90	120	84	73	64	68	65	72	70	68	55	62	64	52
2015	89	84	91	78	80	67	65	74	81	118	81	65	61	67	68	62	63	62	53	54	55	52
2016	83	94	96	82	86	73	68	78	89	130	85	69	69	73	67	62	66	67	59	59	60	59
2017	73	96	92	84	92	75	68	82	90	138	87	68	71	78	71	69	67	71	60	61	63	64
2018	67	92	73	84	88	73	68	79	88	122	83	69	74	77	65	62	66	77	57	60	62	61
2019	70	93	70	86	79	72	63	79	86	118	79	71	71	73	62	60	64	70	59	62	61	64
2020	69	85	64	79	63	70	68	81	81	110	73	64	69	65	60	58	62	63	56	61	60	63
Average value	96	101	98	102	101	98	91	94	93	126	86	80	82	87	85	84	76	82	75	78	79	70

Designations: green—building energy consumption one year after thermal improvement; yellow—installation of weather control system Egain Edge.

As can be seen in Table 4, in individual years as a result of the work, whether after modernization or after the introduction of the Egain Edge system, the rate of the annual final energy demand during building use varied from 140 kWh/(m^2·year) (B10) to 52 kWh/(m^2·year) (B22).

Before thermal improvement in buildings B1–B22, but without including building B10, the measured seasonal final energy demand ratio varied from 129 kWh/(m^2·year) (B4,B5) to 79 kWh/(m^2·year) (B22) in different years.

In buildings B1–B22, which did not undergo thermal improvement, the average energy consumption value (median) was 106 kWh/(m^2·year), with the lower limit of the confidence interval being 82 kWh/(m^2·year), building B22, and the upper limit being 127 kWh/(m^2·year), building B10, as shown in Table 5 and Figure 6.

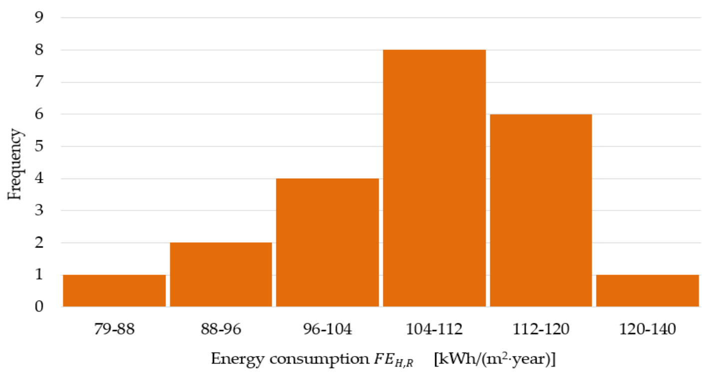

Figure 6. Structure of buildings by size of heating energy demand index before thermal improvement $FE_{H,R}$ [kWh/(m^2·year)].

Figure 7 shows the structure of buildings by the magnitude of the energy demand index for heating before thermal improvement, where weather control is still implemented in the heat source. Among the analyzed buildings, the largest number of buildings had an energy consumption index in the range of 104–112 kWh/(m^2·year), and the smallest number of buildings had energy consumption indexes in the range of 120–127 kWh/(m^2·year) and 82–88 kWh/(m^2·year).

Table 5. Energy consumption in buildings B1–B22 before thermal improvement; weather control is implemented in the heat source FE_{HR} in [kWh/(m^2·year)].

Building	Energy Consumption Before Thermal Improvement (Weather Control System) $FE_{H,R}$ [kWh/(m^2·year)]		
	Median (Me)	Confidence Interval	
		Lower Limit	Upper Limit
B1	106	104.2	107.8
B2	106	104	108
B3	107	105.3	108.7
B4	115	111.5	118.5
B5	115	111.5	118.5
B6	116	111.8	120.2
B7	107.5	105	110
B8	110	104.4	115.6
B9	95.5	90.4	100.6
B10	127	123.3	130.7
B11	89	87.2	90.8
B12	92	90.2	93.8
B13	104	102	106
B14	112	106.2	117.8
B15	114.5	111	118
B16	105	99.7	110.3
B17	101	94.9	107.1
B18	116	107.5	124.5
B19	94	91.6	96.4
B20	96	93.9	98.1
B21	98	92.4	103.6
B22	82	78	86
Average Value	106	104.1	108.4

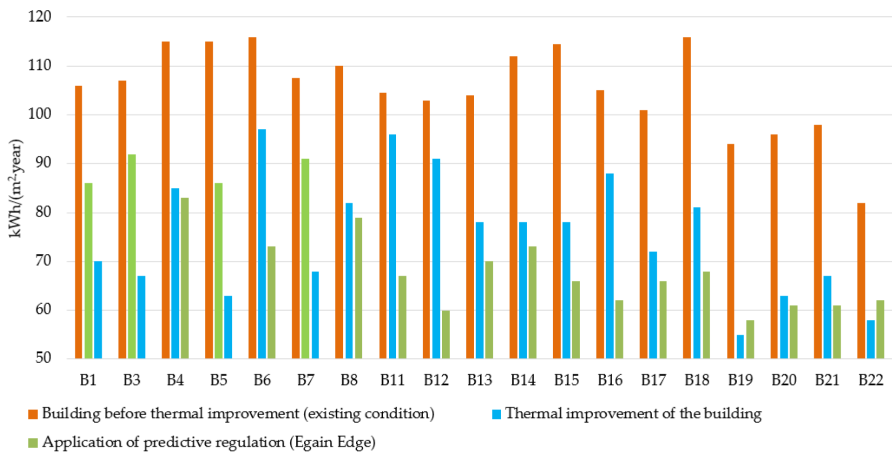

Figure 7. Change in energy consumption for heating purposes after the introduction of the individual variants.

The surveyed buildings were put into use between 1986 and 1994 (Table 1), in accordance with the regulations then in force in Poland. The value of the energy demand index for heating for buildings constructed between 1970 and 1984 was 180–250 kWh/(m^2·year). For buildings constructed after 1984, it was 140–180 kWh/(m^2·year), and for buildings erected after 1993, it was in the range of 70–140 kWh/(m^2·year) [91].

Based on the comparison of the magnitude of the energy demand index for heating before thermal improvement $FE_{H,R}$ in Table 5 and presented graphically in Figure 6, it can be seen that the energy consumption of buildings was not very high. The buildings consumed much less thermal energy than the Technical Conditions that were in force in Poland [91]. Szul and Kokoszka [9] performed a study in 109 buildings made with the same technologies. These buildings had an energy consumption of 164–245 kWh/(m^2·year) before thermal improvement, and thus it was nearly 50% higher compared to the energy consumption of the studied group of buildings. Most likely, this was influenced by the introduction in 1995–1997 (except for building B10) of the individual billing of residents by means of cost allocators, the installation of which always greatly affects the reduction in thermal energy consumption in a building. Individual billing, the essence of which is to directly link the number of fees to the registered heat consumption, generally provides an effective financial mechanism to motivate users to rationally manage thermal energy. In the case of the studied group of buildings, this goal was achieved.

Based on the measured thermal energy consumption, this article analyzes various variants of measures to improve energy efficiency. The following were considered: variant 1, involving only the installation of the Egain Edge predictive control system in the buildings (Table 6); variant 2, performing only the thermal improvement of the building body (Table 7); and variant 3, performing thermal improvement together with the installation of the Egain Edge system (Table 8).

The use of an innovative predictive control system, as the first modernization project before the thermal improvement of the building envelope, was performed in the facilities designated as: B1, B2, B3, B5, B7, B9, B10 and B12. After applying the Egain Edge system, the average value (Me) of energy consumption was 90 kWh/(m^2·year) and varied from 85.9 kWh/(m^2·year), the lower range of the confidence interval, to 92.8 kWh/(m^2·year), the upper range. Table 6 shows the average values of energy consumption (median) after the introduction of the predictive regulation of the central heating system, involving continuous predictions of weather conditions in individual buildings.

Table 6. Annual heating energy consumption index after introduction of Egain Edge system $FE_{H,E}$ (building in existing condition and before thermal improvement) in [kWh/(m^2·year)].

Building		Unit Energy Consumption after the Introduction of the Weather Forecasting System $FE_{H,R}$ [kWh/(m^2·year)] B1	B2	B3	B5	B7	B9	B10	B11	Average Value
Median (Me)		86	93	92	86	91	88	121	85	90
Confidence Interval	Lower Limit	82.3	90.4	85.6	82.9	86.1	86.1	117.6	83.4	85.9
	Upper Limit	89.7	95.6	98.4	89.1	95.9	89.9	124.4	86.6	92.8

Another variant that was studied in detail was a variant that included a group of buildings where only thermal improvement was carried out; here, those buildings are marked as: B4, B6, B8, B12–B22. Thermo-modernization was carried out in these buildings, where gable walls, curtain walls, the ceilings, basement windows and exterior entrance doors were insulated, and residents individually replaced windows in their apartments. As part of the thermal improvement, plumbing adjustments of the central heating systems were also carried out. The work was carried out due to available funds in two stages, as shown in Table 1. The completion dates of the work are shown in Table 4.

Table 7 shows energy consumption after carrying out only thermal modernization work on buildings and using weather control at the heat source.

After the thermal modernization work, the average value of energy consumption (median) was 78 kWh/(m^2·year) and varied from 75.1 kWh/(m^2·year), the lower range of the confidence interval, to 82.2 kWh/(m^2·year), the upper range.

Table 7. Index of annual energy consumption after thermal improvement of buildings, but with the use of weather control in the heat source $FE_{H,TM}$ [kWh/(m^2·year)].

Building	**Unit Energy Consumption after Thermal Improvement (Weather Control), $FE_{H,TM}$ [kWh/(m^2·year)]**		
	Median (Me)	**Confidence Interval**	
		Lower Limit	**Upper Limit**
B4	85	85.0	85.0
B6	97	91.6	102.4
B8	82	81.1	82.9
B12	84	80.1	87.9
B13	78	74.6	81.4
B14	78	75.6	80.4
B15	78	71.2	84.8
B16	88	84.6	91.4
B17	72	70.3	73.7
B18	81	79.0	83.0
B19	55	48.1	61.9
B20	63	55.6	70.4
B21	67	63.5	70.5
B22	58	53.0	63.0
Average Value	78	75.1	82.2

Table 8. Index of annual energy consumption in buildings after thermal improvement and introduction of Egain Edge system $FE_{H,TM}$ [kWh/(m^2·year)].

Building	**Unit Energy Consumption after Introducing Egain Edge System and Performing Thermal Improvement $FE_{H,TM}$ [kWh/(m^2·year)]**		
	Median (Me)	**Confidence Interval**	
		Lower Limit	**Upper Limit**
B1	70	68.4	71.6
B3	67	63.3	70.7
B4	83	81.3	84.7
B5	63	63	63
B6	73	71.6	74.4
B7	68	66.9	69.1
B8	79	77.5	80.5
B11	76	72.3	79.7
B12	69	67.2	70.8
B13	70	68.1	71.9
B14	73	70.9	75.1
B15	66	63.7	68.3
B16	62	58.9	65.1
B17	66	64.7	67.3
B18	68	65.6	70.4
B19	58	57.1	58.9
B20	61	60.6	61.4
B21	61	60.3	61.7
B22	62	61.3	62.7
Average Value	68	65.6	70.4

The last study of changes in energy consumption in buildings was a variant in which buildings underwent deep thermal improvement and had the Egain Edge weather prediction system installed. A group of buildings was evaluated, labeled as: B1, B3–B8 and B11–B22. Buildings B2, B9 and B10 were not included in the scope because these buildings did not undergo thermal improvement, but they had a predictive control system installed.

Table 8 shows the measured thermal energy consumption of the above-mentioned buildings after thermal improvement and the introduction of the Egain Edge system. The energy consumption is given as an indicator in relation to the heated floor area.

After thermal improvement and the application of the Egain Edge system, the average value of energy consumption was 68 kWh/(m^2·year) and varied from 65.6 kWh/(m^2·year), the lower limit (of the confidence interval), to 70.4 kWh/(m^2·year), the upper limit.

Figure 7 shows in which ranges the heating energy consumption rate changed after the introduction of the three variants discussed above. The chart also illustrates the order in which the projects were carried out in the buildings, where the orange color indicates the initial state before thermal improvement, the green color indicates the installation of the Egain Edge predictive control system and the blue color indicates the implementation of thermal improvement.

As shown in Figure 7, the use of the Egain Edge system resulted in a reduction in heating energy consumption, except for two buildings: B19 and B22.

Based on the thermal energy measured in the buildings with ultrasonic heat meters before and after the application of the Egain Edge system and based on Relation (2), the savings were calculated, which are included in Table 9. According to Table 9, the energy effects obtained after the introduction of predictive regulation in the facilities ranged from 4.5% (building B11) to 25.2% (building B5). The average value of the savings that were achieved was 13.2%. The introduction of predictive regulation made it possible to adjust the parameters of the central heating system to the needs of the residents while maintaining thermal comfort in the premises.

Table 9. Energy savings after using Egain Edge predictive control system in buildings before thermal improvement, ES_1 (%), [%].

Installation of a Predictive Control System Prior to Thermal Improvement ES_1 (%), [%]									
Building	**B1**	**B2**	**B3**	**B5**	**B7**	**B9**	**B10**	**B11**	**Average Value**
Median (Me)	18.9	12.3	14.0	25.2	15.3	7.9	4.7	4.5	13.2

Figure 8 shows the reduction in final energy consumption for central heating after using only the predictive control system (Egain Edge) without thermal improvement of the building.

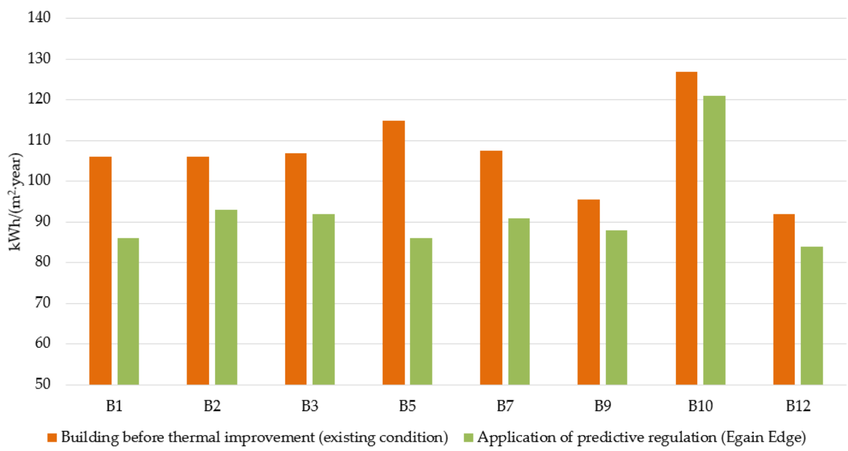

Figure 8. Reduction in energy consumption for central heating after using predictive control system (Egain Edge) without thermal improvement of the building.

In contrast, according to Relation (3), the thermal energy savings in buildings where only thermal improvement was performed and weather control was left in the thermal node (without installation of the Egain Edge system) were calculated, which are shown in Table 10. The study included a group of buildings designated as: B4, B6, B8 and B12–B22.

Table 10. Energy savings after thermal improvement only (weather control) ES_2 (%), %.

Building	Building Thermal Improvement (Weather Control) ES_2 (%), [%]														Average Value
	B4	B6	B8	B12	B13	B14	B15	B16	B17	B18	B19	B20	B21	B22	
Median (Me)	26.1	16.4	25.5	8.7	25.0	30.4	31.9	16.2	28.7	30.2	41.5	34.4	31.6	29.3	29.0

Carrying out thermal improvement in the buildings allowed for saving final energy for heating purposes in the range of 16.45% (building B6) to 41.5% (building B19), and the average value of the achieved savings was 29%.

Table 11 shows the total energy effect taking into account both thermal improvement and the installation of the Egain Edge weather-predictive central heating control system, which was calculated based on Relation (4).

Table 11. Energy savings after thermal improvement and introduction of Egain Edge system ES3 (%), [%].

Building	Building Thermal Improvement and the Installation of Predictive Control ES_3 (%), [%]										Average Value B1–B22
	B1	B3	B4	B5	B6	B7	B8	B11	B12	B13	
Median (Me)	34.0	37.4	27.8	45.2	37.1	36.7	28.2	14.6	25.0	32.7	36.5
Building	B14	B15	B16	B17	B18	B19	B20	B21	B22		
Median (Me)	34.8	42.4	41.0	34.7	41.4	38.3	36.5	37.8	24.4		

The percentage of savings of the thermal energy consumed for the heating of buildings after deep thermal improvement and after the introduction of forecast regulation in the surveyed buildings ranged from 14.6% (B11) to 45.2% (B15), and the average value of the savings that were obtained was 36.5%. This article also determines the savings that were achieved by replacing weather regulation with forecast regulation of the Egain Edge system in buildings previously subjected to thermal improvement. The savings were determined based on Relation (5), and the results are presented in Table 12. This study included buildings designated as: B4,B6, B8 and B12–B22.

Table 12. Energy savings as a result of replacing weather control with Egain Edge predictive control (after thermal improvement) ES_4 (%), [%].

Replacing Weather Regulation with Predictive Regulation ES_4 (%), [%]															
Building	**B4**	**B6**	**B8**	**B12**	**B13**	**B14**	**B15**	**B16**	**B17**	**B18**	**B19**	**B20**	**B21**	**B22**	**Average Value**
Median (Me)	2.4	24.7	3.7	17.9	10.3	6.4	15.4	29.5	8.3	16	−5.5	3.2	9	−6.9	8.7

Based on Table 12, except for buildings B19 and B22, replacing weather control with predictive control of the central heating system parameters saved between 2.4% (B4) and 29.5% (B16). The average value of the achieved savings was 8.7%. In two buildings, B19 and B22, the introduction of a system of regulation of the central heating system based on weather prediction (Egain Edge) did not bring the expected results. In these buildings, after the introduction of predictive regulation, energy consumption increased by 5.5% (B19) and 6.9% (B22). This was associated with very low final energy consumption (on average 74–83 kWh/(m^2·year) Table 4) already before the introduction of the forecast regulation. In the buildings, the installation of cost allocators resulted in the lowering of indoor temperatures by the residents themselves, at the expense of thermal comfort. In contrast, the predictive control system tried to ensure higher indoor temperatures in the rooms in order to improve the thermal comfort of the residents.

The thermal energy savings after thermal improvement in buildings with a previously installed Egain Edge system were determined from Relation (6) and are shown in Table 13. The study included buildings, designated as: B1, B3, B5, B7 and B11.

Table 13. Energy savings after thermal improvement in buildings equipped with Egain Edge systems, ES_5 (%), [%].

Thermal Improvement of a Building Equipped with a Predictive Control System, ES_5 (%), [%]						
Building	**B1**	**B3**	**B5**	**B7**	**B11**	**Average value**
Median (Me)	18.6	27.2	26.7	25.3	10.6	25.3

The energy efficiency gains from performing this project ranged from 10.6% (B11) to 27.2 (B3), with an average value of 25.3%.

3.2. Economic Analysis

A detailed analysis of the economic viability of the implementation options for projects aimed at improving energy efficiency was carried out, including, in particular, the types of investment costs, the adopted current and forecast prices of thermal energy as well as the expected payback period and the cost of the investment life cycle. In the case of multi-family residential buildings, energy renovations to improve energy efficiency belonged to the group of cost-intensive investments. It was estimated that the average investment costs of energy renovation for 1 m^2 of heated usable space per year in residential buildings in EU countries are, on average, 111 EUR/m^2 (from 49 EUR/m^2 in Latvia to 183 EUR/m^2 in Sweden [92]). In Poland, the cost of deep thermal improvement averaged 105 EUR/m^2 [18]. According to the data obtained from the housing cooperative to which the buildings subjected to economic evaluation belonged, the average cost of the thermo-modernization works carried out in this group of buildings, subjected to energy efficiency improvements (in 2017–2022), in relation to 1 m^2 of heated usable area, was in the range of 90.6 to 124 EUR/m^2. The average value for the analyzed group was 109 EUR/m^2, which is close to the European average. A reliably performed economic analysis of a particular solution should be based on objective criteria. It is commonly believed that such a criterion is the excess of effects over inputs. Hence, the economic analysis was made on the basis of methods of evaluating physical investments, based on the interest (discount) rate, taking into account the change in the value of money over time. Such a criterion can include life cycle costs (LCC) and the cost of saved energy (CCE). Capital expenditures (Ic) and operating costs (Ce, o) for the different variants were assumed in the form of unit rates related to 1 m^2 of heated usable area per year.

Table 14 shows the actual investment and operating costs for individual buildings, as well as the amount of power ordered for heating buildings.

Capital expenditures for the installation of the Egain Edge predictive control system ranged from 0.28 to 1.29 EUR/m^2. The average value for the study group was 0.68 EUR/m^2. The operating costs associated with the use and maintenance of the Egain system averaged 0.26 EUR/m^2. The costs for heating buildings were divided into fixed and variable costs, the size of which was determined by the heat supplier serving the area. The fixed costs depended on the amount of power ordered and ranged from 1.08 (B21) to 1.82 EUR/(m^2·year) (B11).

Table 14. A statement of the adopted costs for conducting the economic analysis.

Building	Power Ordered [MW]	Egain Edge System		Heating Fee Costs	
		Installation [EUR/m^2]	Operation [EUR/m^2]	Fixed [EUR/m^2·year]	Variable [EUR/kWh]
B1	0.0570	1.28	0.28	1.58	0.043
B2	0.0584	1.28	0.28	1.62	0.043
B3	0.0600	1.29	0.28	1.68	0.043
B4	0.0810	0.88	0.27	1.55	0.043
B5	0.0990	0.78	0.26	1.67	0.043
B6	0.0721	1.10	0.27	1.72	0.043
B7	0.1842	0.37	0.25	1.46	0.043
B8	0.2700	0.28	0.25	1.65	0.043
B9	0.2514	0.30	0.25	1.66	0.043
B10	0.1250	0.55	0.26	1.49	0.043
B11	0.1049	0.80	0.27	1.82	0.043
B12	0.1396	0.37	0.25	1.12	0.043
B13	0.1081	0.57	0.26	1.35	0.043
B14	0.1133	0.57	0.26	1.41	0.043
B15	0.1161	0.70	0.26	1.78	0.043
B16	0.0937	0.55	0.26	1.11	0.043
B17	0.1180	0.54	0.26	1.39	0.043
B18	0.1187	0.54	0.26	1.40	0.043
B19	0.0980	0.66	0.26	1.40	0.043
B20	0.1243	0.54	0.26	1.47	0.043
B21	0.0919	0.54	0.26	1.08	0.043
B22	0.1280	0.49	0.26	1.37	0.043

The average value of the fee for ordered power was 1.49 EUR/(m^2·year). Variable costs refer to the amount of thermal energy consumed for heating and amount to 0.043 EUR/kWh. The adopted investment and operating expenditures were first used to calculate the life cycle costs for the adopted modernization variants. For the exemplary B7 building, which was characterized by energy consumption before thermal improvement at the level of 107.5 kWh/(m^2·year), life cycle cost indicators were calculated before the modernization LCC_0 and after the modernization projects LCC_1, the application of forecast regulation (Egain Edge), and LCC_3, the implementation of the improvement, for the thermal efficiency of building with the use of forecast regulation. The calculations were made from the 1st to the 25th year of using the building, in accordance with the Relation (7), and the results of the calculations are shown in Figure 9.

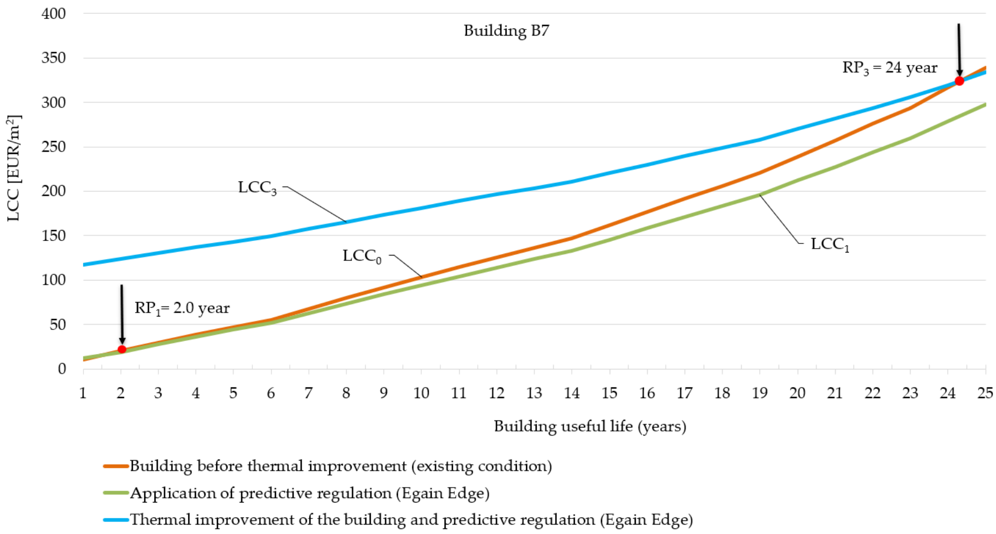

Figure 9. Life cycle costs LCC_0, LCC_1 and LCC_3 using building B7 as an example.

If the status quo (LCC_0 variant) was maintained, the life cycle costs over the assumed 25-year lifetime would be 338.8 EUR per m^2 of heated usable area of the building, as shown in Figure 9 and Table 15. The introduction of the Egain Edge system would bring the value of the index down to 297.7 EUR/m^2. The thermal improvement of the building (with the Egain Edge system), which resulted in a 40% reduction in energy compared to the baseline due to the high investment costs associated with the thermal improvement (amounting to 109 EUR/m^2), resulted in a reduction in the value of the LCC_3 index to 334.0 EUR/m^2. The calculation of the LCC indexes for each year of assumed operation made it possible to determine the payback period of the investment (RP_1 and RP_3). The payback periods are illustrated in the graph at the intersection of the LCC_0 life cycle cost line with the LCC_1 and LCC_3 indicator lines. As can be seen in the graph (Figure 9), the expenses incurred for the installation and related maintenance and operating costs are paid back after just two heating seasons. In the case of applying thermal improvement consisting of the implementation of deep thermal modernization, the period of return on investment expenditures at the current energy prices, are extended to 24 years.

The calculations of life cost ratios, according to Relation (7), and the payback time for the other buildings were performed in a similar manner, and the results are shown in Table 15.

Based on an analysis of the results shown in Table 15, it can be seen that the value of the LCC_0 life cycle cost index before building retrofit projects ranged from 253.9 (B22) to 368.8 (B8) EUR/m^2. The average value was 309 EUR/m^2. Buildings with a final energy demand rate for heating higher than 100 kWh/(m^2·year) had an LCC_0 value of 325 EUR/m^2. Buildings with consumption lower than 100 kWh/(m^2·year) were characterized by lower index values, which averaged 275 EUR/m^2. The introduction of the Egain Edge system allowed for reductions in the value of the LCC_1 index to the average value of 276.8 EUR/m^2. The level of cost reduction was not significantly influenced by the energy consumption of heating in buildings before the introduction of the weather forecast control system. Depending on the building, the investment returned in the period from 1 to 7 years, most often after 3–4 heating seasons. The performance of thermal improvement did not reduce the value of the LCC_2 index, which, in the assumed 25-year service life, is higher than before the improvement, and for buildings subjected to thermal modernization, it amounted to an average of 337 EUR/m^2. This state of affairs resulted from high investment costs and relatively small savings (an average of 29%) obtained as a result of the undergoing thermal improvement. The data analysis shows that the least favorable financial effects expressed by the LCC_2 indicator were obtained in buildings that were characterized by a relatively low energy consumption before thermo-modernization, oscillating around the value of the final energy demand indicator for heating of 100 kWh/(m^2·year) and below this value (buildings B8, B12, B13, B16, B17, B20, B21 and B22). The value of the LCC_2 ratios directly translate into the payback period, which, for 12 of the 14 buildings undergoing thermal improvements, exceeds 25 years and can reach 30 to 40 years. The longest payback period for thermal improvement is in buildings with low energy consumption (before thermo-modernization) of 80 to 100 kWh/(m^2·year). For example, in building B12, which had a final energy consumption for heating before the thermal improvement of 92 kWh/(m^2·year), the investment costs incurred for thermal improvement are recouped only after about 44 years. Similar results can be observed in buildings where thermal improvement was introduced in conjunction with the use of the Egain Edge system. In addition, in this case, it was observed that, as the energy demand became lower, the investment returns became longer (B11, B12 and B22). In the case of Variant 3 (LCC_3), in two cases (B19 and B22) the use of Egain Edge negatively affected the values of the indicators, which were higher compared to Variant 2 (LCC_2).

Table 15. Life cycle cost index before retrofit LCC_0 [EUR/m^2] and after retrofit projects LCC_1–LCC_3 [EUR/m^2] and payback time on investment RP_1–RP_3 [years].

Building	Life Cycle Cost Index [EUR/m^2]				Payback Time on Investment [years]		
	LCC_0	LCC_1	LCC_2	LCC_3	RP_1	RP_2	RP_3
	Variant 0	Variant 1	Variant 2	Variant 3	Variant 1	Variant 2	Variant 3
B1	300.3	250.2	-	315.7	3	-	26
B2	300.3	268.8	-	-	4	-	-
B3	302.7	266.1	-	308.6	4	-	27
B4	316.0	-	349.0	345.0	-	30	28
B5	319.36	247.1	-	298.2	1	-	23
B6	313.0	-	374.2	316.4	-	35	26
B7	338.8	297.7	-	334.0	2	-	24
B8	368.8	-	395.6	391.2	-	27	26
B9	335.3	293.0	-	-	3	-	-
B10	355.5	340.9	-	-	6	-	-
B11	259.8	250.7	-	331.0	7	-	39
B12	279.1	-	362.1	324.7	-	44	34
B13	300.5	-	355.2	315.6	-	32	27
B14	323.6	-	338.2	326.3	-	26	25
B15	329.9	-	338.2	308.6	-	26	23
B16	294.2	-	357.4	292.5	-	36	24
B17	313.6	-	326.0	311.4	-	27	25
B18	354.4	-	348.7	316.5	-	24	21
B19	281.2	-	277.2	285.5	-	24	26
B20	289.2	-	303.3	298.9	-	27	26
B21	288.3	-	304.5	290.1	-	28	26
B22	253.9	-	290.7	301.5	-	31	34

Description: Variant 0 is the period before thermal improvement; Variant 1 is the installation of the Egain Edge system; Variant 2 is the execution of thermal improvement; and Variant 3 is the execution of thermal improvement and the installation of the Egain Edge system.

Another criterion for evaluating the energy efficiency of the introduced energy-saving solutions was the calculation of the cost of saved energy CCE_i. If the value of this indicator was less than or equal to the price paid for energy, there were indications that the investment was profitable. Calculations were made for three retrofit variants, according to Relation (8). The first of these was variant CCE_1, the installation of the Egain Edge system, for which the results of the calculations are summarized in Table 16.

Table 16. Value of cost index of saved thermal energy after installation of Egain Edge system in buildings before thermal improvement CCE_1 [EUR/kWh].

Cost Index of Saved Heat Energy CCE_1, [EUR/kWh] Installation of Egain Edge System (Variant 1)								
Building	B1	B2	B3	B5	B7	B9	B10	B11
CCE_1	0.024	0.036	0.031	0.013	0.018	0.037	0.057	0.097

Analyzing the results of Table 16, it can be concluded that the installation of the Egain Edge system in buildings not subjected to thermal improvements is a cost-effective investment, as evidenced by the values of indicators for most buildings. The exceptions may be two buildings, B10 and B11, for which the indicators were higher than the price of purchased energy. The high values of these indices were due to the fact that, in the case of these buildings, the achieved thermal energy savings were about 4.5–4.7%. In the remaining buildings, the value of the CCE_1 indices fluctuated in the range of 0.013–0.037 EUR/kWh. The average value was 0.026 EUR/kWh and thus was about 50% lower than the cost of purchasing energy.

Other variants for which calculations of the cost of saved energy were performed were thermo-modernization activities consisting of the thermal improvement of CCE_2 external partitions. The values of the indicators for this variant are presented in Table 17.

Table 17. Value of cost index of saved energy for heating after thermal improvement only (weather control) CCE_2, [EUR/kWh].

Cost Index of Saved Heat Energy CCE_2, [EUR/kWh] Implementation of Thermal Improvement (Variant 2)														
Building	B4	B6	B8	B12	B13	B14	B15	B16	B17	B18	B19	B20	B21	B22
CCE_2	0.37	0.59	0.40	1.39	0.43	0.33	0.30	0.65	0.38	0.32	0.29	0.34	0.36	0.46

Table 18 shows the results of CCE_3 calculations for Variant 3, where comprehensive thermal modernization measures were applied along with the installation of a predictive control system (Egain Edge).

Table 18. Value of cost index of saved energy for heating after thermal improvement with installation of Egain Edge predictive control system CCE_3, [EUR/kWh].

Cost Index of Saved Heat Energy CCE_3, [EUR/kWh] Execution of Thermal Improvement and the Installation of the Egain Edge System (Variant 3)										
Building	**B1**	**B3**	**B4**	**B5**	**B6**	**B7**	**B8**	**B11**	**B12**	**B13**
CCE_3	0.32	0.29	0.36	0.22	0.27	0.29	0.37	0.88	0.50	0.34
Building	**B14**	**B15**	**B16**	**B17**	**B18**	**B19**	**B20**	**B21**	**B22**	
CCE_3	0.29	0.23	0.27	0.33	0.24	0.32	0.33	0.31	0.57	

None of the values shown in Tables 17 and 18 meet the economic efficiency condition: $0 < CCE_i < 0.056$ EUR/kWh.

The values of the indices for the analyzed Variants 2 and 3, with actual investment, operating costs and achieved savings, ranged for CCE_2 from 0.29 to 1.39 EUR/kWh and for CCE_3 from 0.22 to 0.88 EUR/kWh. The average value of the CCE_2 index exceeded the upper value of the economic efficiency condition by seven times. In the case of Variant 3, the CCE_3 index was five times higher than the limit value. Particularly unfavorable indicator values were recorded for buildings B12 (in Variant 2) and B11 (in Variant 3), where energy consumption before thermal improvements was about 90 kWh/(m^2·year). Equally unfavorable indicator values were recorded for buildings that had energy consumption below 100 kWh/(m^2·year). This clearly shows that this type of investment, which is necessary due to energy policies as well as environmental considerations, should be able to receive financial support in order to be profitable and be undertaken by the investor.

4. Conclusions and Perspectives

On the basis of 19 years of research conducted on a group of 22 residential multi-family buildings located in a temperate continental climate, made with two different technologies based on prefabricated elements (Żerań brick (CŻ) and OWT-67N), in which a predictive control system for the central heating system was installed and deep thermo-modernization was carried out, the following conclusions can be drawn:

In buildings where radiator cost allocators were installed, the measured thermal energy consumption before thermal modernization was much lower than in buildings that were made with similar technologies and that were put into use in 1986–1994. The average value of thermal energy consumption was 106 kWh/(m^2·year), with a confidence interval of 104–108 kWh/(m^2·year). This was influenced by the introduction of individual billing for residents, where the amount of central heating charges incurred was linked to thermal energy management.

The introduction of a system of predictive control (Egain Edge) of the central heating system based on continuous prediction of weather conditions, even before deep thermo-modernization was carried out, resulted in a reduction in thermal energy by an average of 13.2%, with energy effects varying from 4.5% to 25.2%. The average energy consumption was 90 kWh/(m^2·year) and varied from 85.9 kWh/(m^2·year) to 92.8 kWh/(m^2·year).

The introduction of predictive control made it possible to adjust the parameters of the central heating system to the needs of the residents while maintaining thermal comfort in rooms where, due to excessive and exaggerated conservation of thermal energy, it was not always maintained (B19, B22).

The performance in buildings with cost allocators, with only deep thermo-modernization without installing the Egain Edge system, saved final energy for heating by an average of 29%, with energy effects ranging from 16.45% to 41.5%. The average energy consumption was 78 kWh/(m^2·year) and varied in the range of 75.1–82.2 kWh/(m^2·year).

The performance of thermal improvements in the buildings, together with the installation of the Egain Edge system in the heat substation, allowed for energy savings of 36.5% on average. Energy savings in the surveyed facilities ranged from 14.6% to 45.2%. The average energy consumption was 68 kWh/(m^2·year) and varied from 65.6 kWh/(m^2·year) to 70.4 kWh/(m^2·year).

In buildings previously subjected to thermal upgrading, where the next stage of modernization work replaced traditional weather control at the district heating substation with predictive control, by installing the Egain Edge system, an average of 8.7% savings was achieved. Energy effects ranged from 2.4% to 29.5%. In two buildings, energy consumption increased by 5.5% (B19) and 6.9% (B22) after the forecast adjustment. This was likely due to very low final energy consumption, averaging 74–83 kWh/(m^2·year) before the introduction of the predictive regulation, compared to other buildings.

The average cost of the thermal improvement work that was carried out in this group of buildings averaged 109 EUR/m^2, ranging from 90.6 to 124 EUR/m^2.

Based on the economic analysis, it can be seen that a large share of the cost of heating buildings is accounted for by fixed costs, which depend on the amount of power ordered and the prices set by the heat supplier. The average value of the fee for ordered power was 1.49 EUR/(m^2·year), and the variable fee, which depended on the amount of heat consumed, was 0.043 EUR/kWh. Hence, it is very important to reduce the power ordered from the heat supplier after carrying out thermal upgrading work. Very often, heat suppliers compensate for the lower consumption of heat energy by users by raising the fixed costs for the connection power.

The value of the life cycle cost index translates into the payback period of the investment. The least favorable financial effects expressed by the LCC indicator are obtained in buildings that had relatively low energy consumption before thermo-modernization, with about 100 kWh/(m^2·year) and below this value. For such buildings, the payback period is above 25 years.

The installation of the Egain Edge system in non-thermally upgraded buildings is a cost-effective investment. It allows for a reduction in the value of the LCC_1 index to an average value of 276.8 EUR/m^2. The venture pays for itself in 1 to 7 years, depending on the building, on average after 3–4 years. The average value of the CCE_1 index is 0.026 EUR/kWh and is, on average, about 50% lower than the cost of purchasing thermal energy.

The cost ratios of the saved energy CCE_3 after deep thermal modernization with the installation of the Egain Edge system in any building did not meet the condition of economic efficiency: $0 < CCE_i < 0.056$ EUR/kWh.

Actual measurement results from 19 years can be used to test mathematical models using rough set theory to perform simulations of thermal energy consumption in buildings equipped with predictive control systems.

In further research, the authors plan to test the usefulness of the predictive control system in other types of buildings, such as public buildings, e.g., schools, kindergartens and others.

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