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Operational and energy consequences of thermomodernization of residential buildings with basements

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Abstract

Thermomodernization of buildings aims to improve their energy efficiency but should not cause deterioration of operating conditions. The article presents the consequences of different ways of insulating basements in residential buildings. The possibility of reducing heat loss when insulating external basement walls and the change in temperature values in unheated basements when insulating the ceiling above the basement are determined. The quantitative effects and consequences of using a particular thermal insulation method can be useful for investors to make appropriate decisions to avoid operating problems.

Keywords: reduction of heat losses, insulation of the ceiling above the basement, thermal modernization of basement walls, temperature value in basements, operating problems

1 INTRODUCTION

Comprehensive and deep thermomodernization of buildings can lead to a reduction in final energy consumption, and consequently in operating costs, by over 60% [1, 2]. The scope of thermomodernization and the effects that can be achieved depend on the current condition of the building, including previously performed modernization measures that affect its energy performance. In addition to comprehensive or deep thermomodernization, we can also talk about medium or light (low) thermomodernization [3].

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The term light thermomodernization should be understood as the replacement of a high-emission heat source, such as, e.g., a coal-fired boiler with an ecological heat source, which enables the improvement of air quality [4]. As part of the medium of thermomodernization, in addition to the modernization or replacement of the heat source, the replacement of window and door joinery or thermal insulation of a façade is performed. As part of the comprehensive thermomodernization, other activities that improve the energy performance of buildings are also carried out [1-3, 5]. In recent years, the issue of modernization to the nZEB standard (nearly zero energy building) [6] or ZEB (zero emission building) [7] has been increasingly discussed, which is not possible without the use of renewable energy sources [2, 8]. To reach net zero emissions by 2050 [9], all measures leading to the improvement of the energy standard of the buildings and energy savings are crucial worldwide.

According to the Joint Research Centre (JRC) report, almost 75% of the European Union's (EU) building stock is energy inefficient. It was estimated that 85% of them were built before 2001 and a large part was built without any energy performance requirements, a third of it is over 50 years old and more than 40% was built before 1960 [10]. As the EU's annual rate of energy-related building renovations is only at 1%, in October 2020 the European Commission launched a "Strategy for a renovation wave" which aims to intensify thermomodernization by renovating 35 million buildings by 2030 [11]. During this time, the EU must reduce greenhouse gas emissions from building operation by 60%, their final energy consumption by 14% and energy consumption for heating and cooling by 18%. In Poland, in February 2022, the "Long-Term Building Renovation Strategy" [12] was adopted, which specifies national actions to achieve high energy efficiency and low emission of buildings. The document plans that in the years 2020–2030, thermomodernization will be carried out in 236 thousand buildings per year. In the years 2030–2040, such plans concern 271 thousand buildings, and in the years 2040–2050, 244 thousand buildings per year. In the period 2021–2050 it is planned to carry out 7.5 million thermomodernizations, of which 4.7 million deep thermomodernizations are part of staged thermomodernization over time. The recommended action plan combines a rapid increase in the scale of light thermomodernization with a gradual dissemination of deep, more comprehensive thermomodernization in the perspective of 2030. However, it should be remembered that before taking action to improve the thermal quality of buildings, it is necessary to determine their technical condition and the possibility of their further safe use [13], also after the planned modernization procedures have been completed.

During the preparation of energy audits a certain problem was noticed related to the possible methods of basement insulation (level -1).

In most multi-family residential buildings, basements are unheated, but there are also spaces that are nominally heated (most often only in theory). In such cases, considering the actual situation, energy audits should consider insulation of the ceiling above the basements. However, this is an unfeasible undertaking in practice, considering the division of floor -1 into small storage units and their "clutter" occurring in most of these spaces. The best proof of this is the fact that during hundreds of energy audits performed by the Authors, only in a dozen or so cases did investors decide to insulate the ceiling above the basements. Sometimes the reason for the impossibility of thermal insulation of the ceiling from the basement side is its height, which should not be reduced due to requirements. In most cases, the actual situation is therefore departed from. In accordance with theoretical assumptions (project provisions), level -1 is treated as a heated space (of course, to a lower temperature value than in the entire building). The consequence of such treatment of basements is the proposal to insulate external walls both above ground and below ground level. As a result, there will be differences during the use of the building after performing this thermal modernization procedure according to the first and second variant. Sometimes the situation is different. For the reasons described above, investors do not want to insulate the ceiling above the basement, but they also do not decide to insulate the basement walls, because this measure is more complicated due to the additional work necessary in this case, such as removal and installation of the band around the building, excavation of walls or providing moisture protection [14]. Examples of the implementation of insulation of residential buildings in the basement area in various ways are presented in Fig. 1.

Fig. 1. *Examples of different variants of insulation of walls of residential buildings*.

The general trends of changes in energy efficiency resulting from different methods of thermomodernisation of basements are fairly easy to predict, but the quantitative effects and their consequences are not. However, the decisions for each thermomodernisation are made by the investors, often without knowledge of the consequences resulting from these decisions.

2 Selected elements of preparing the thermal modernization process

Measuring support for thermomodernization

An important element, irrespective of the degree of thermomodernization, is its correct and quite detailed planning, preferably with the help of an energy audit and then carrying out the work preferably on the basis of a project carried out in accordance with the energy audit. In the absence of reliable data on the thermal quality of the building or uncertainty on the part of the investor as to the necessary extent of thermomodernization, thermal imaging diagnostics and sometimes even the measured determination of the thermal transmittance of the partitions is useful [15].

At the stage of preparing a building for energy renovation, it is quite common for even basic technical documentation to be missing or for the existing documentation to be outdated and for there to be no reliable data on the changes made as part of the renovation and modernization carried out. In this situation, thermal imaging diagnostics can be of significant help. There have been energy audits of buildings in which the authors have also used the thermal transmittance coefficients of the building envelope determined by the measurement method (HFM). It must be noted here that the measuring approach only makes sense if we are certain of the use of thermal insulation in the envelope and at the same time there is a lack of data on its thickness and quality (unknown thermal conductivity coefficient of the material). If the partitioning consists only of structural or structural-insulating materials (concrete, brick, wood, aerated concrete, etc.), the precise determination of the thermal transmittance in the existing state is meaningless in view of the currently used thicknesses of effective thermal insulation. In other words, the initial condition of the partition has no practical effect on the resistance of the additional thermal insulation that will result from the calculations performed in the energy audit.

Fig. 2 shows a fragment of the façade of a multi-family building in which the walls of a theoretically unheated basement are the source of greater heat loss per unit area than the walls of the above-ground storey (apartments). Unfortunately, it is quite often the case that the insulation of basement walls is abandoned (Fig. 1), which will have significant consequences in terms of the deterioration of the energy performance of buildings. Such thermograms made before the energy audit may not so much improve the performance of the audit as convince the investor to perform basement wall insulation (Fig. 2) - the investor may ‘see’ the need to perform such a procedure, which is often abandoned by others for reasons described in the introduction.

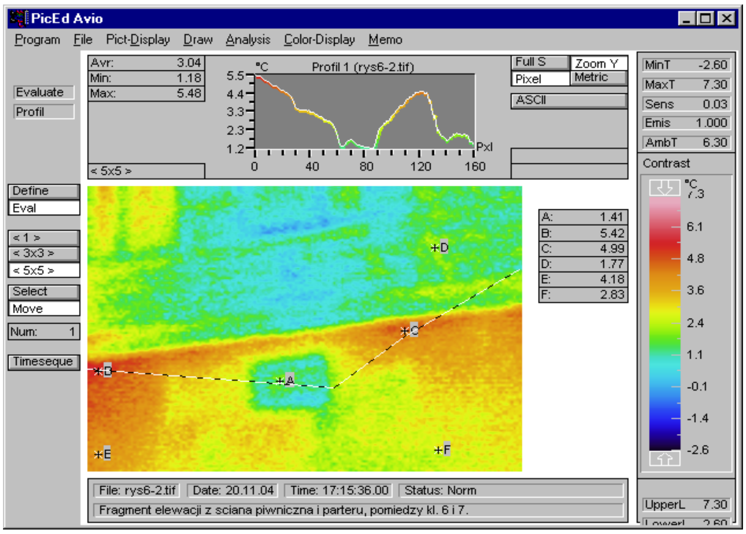

Fig. 2. *Fragment of the basement wall (case of a theoretically unheated basement).*

Another role is played by thermograms carried out after the completion of thermomodernization works. The investor can ascertain the correctness of the work carried out or ‘see’ a wrong decision (no insulation of basement walls). Such verifying thermograms are shown in Fig. 3 and Fig. 4. The difference between Fig. 3 and Fig. 4 is that the thermomodernization works for buildings whose facade fragments can be seen in Fig. 3 did not include the insulation of basement walls, while such works were included in the thermomodernization of buildings whose facade fragments can be seen in Fig. 4.

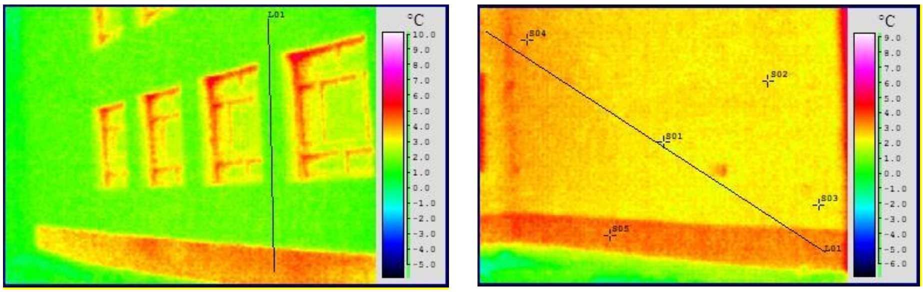

Fig. 3. *School buildings after thermomodernization - basement walls were not insulated.*

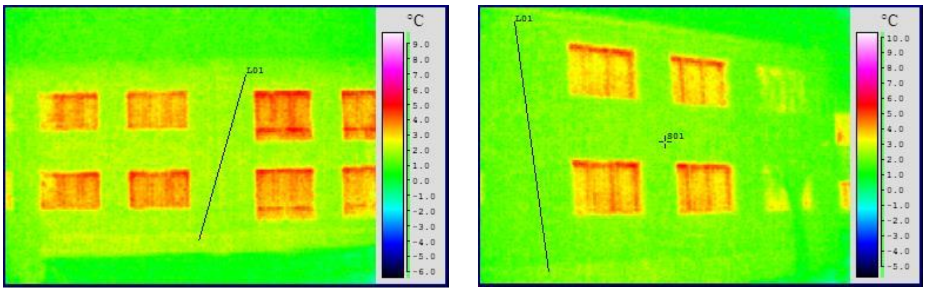

Fig. 4. *School buildings after thermomodernization - basement walls were insulated.*

In Fig. 3, the effect of increased heat loss through the basement wall surfaces is very evident. The difference in the temperature values of the insulated (walls of the first and second storey) and non-insulated (walls of storey -1) surfaces is about 2.5÷3 K. Fig. 4 shows fragments of the façades of buildings after thermomodernisation works have been carried out, but with all external walls (including basement walls) insulated. The entire surfaces visible in the thermograms are practically one colour; which means one temperature value regardless of the storey. This is obviously an improvement on the situation shown in Fig. 3.

The achievement of the expected results of thermal modernisation can be influenced not only by the assessment of the existing state, the adopted design solution [16] and the correctness of its implementation, but also by the way the building is used and the behaviour of the users [17]. Also of importance are the assemblies adopted at the stage of estimating the planned savings [18].

Including thermal bridges and basements in thermal calculations

When predicting the possible effects and consequences of thermomodernization, the adopted calculation method is an important issue. Failure to adapt the calculation model of the building to its actual condition may lead to misleading results and expectations, but also bring about unforeseen operational problems.

In the Polish methodology for determining the energy performance of a building or part of a building and energy performance certificates (EPCs), the monthly balance method was adopted [19]. The demand for usable energy for heating and ventilation of a building QH,nd is treated as the sum of the heat demand in individual heated zones in the subsequent months of the year (values higher than 0 kWh are taken into account). The monthly demand is obtained by subtracting the total heat gains in the zone (QH,gn,s,n) from the total amount of heat transferred from the heated zone (QH,ht,s,n), taking into account the heat gain utilization factor (ηH,gn,s,n) determined according to the Polish Standard on energy performance of buildings - calculation of energy consumption for heating and cooling [20]. An unheated space is defined in the EPCs as a room or a group of rooms in a building or part of a building for which no internal temperature value has been specified. The heat transfer coefficient from the heated zone through adjacent unheated spaces is to be determined in accordance with the basic method according to the Polish Standard concerning heating installations in buildings – method of calculating the design heat load [21]. This standard introduced a completely different method of determining heat losses in the case of an unheated space adjacent to a heated space. Previously, the boundary of these spaces was the boundary of the analyzed system, and calculations were performed analogously to the case of direct penetration to the outside, assuming the design temperature in the adjacent space according to the PN-82/B-02403 standard [22]. The values of the design air temperature in basement rooms for individual climate zones in Poland are presented in Table 1.

A type of underground space	Climate zone in Poland				
	I	II	III	IV	V
	t_i [°C]				
boiler and heating plant room	20	20	20	20	20
without windows, but with central heating pipes	12	10	8	6	4
without windows and without central heating pipes	8	6	4	2	0
with windows and central heating pipes	4	2	0	-1	-2
with windows and without central heating pipes	0	-2	-4	-5	-6

Table 1. *Design air temperature in selected unheated spaces for individual climatic zones of Poland [22].*

The model adopted in the new standard [21] considers the heat exchange between the heated space and the environment through the unheated space Qstr, and the design heat loss coefficient is calculated using the temperature reduction coefficient btr, which considers the difference between the temperature of the unheated space and the external design temperature. The temperature reduction coefficient can be calculated both when the temperature of the unheated space is known and when it is not known and then it can be calculated by means of a heat balance [23] based on the PN-EN ISO 13789 standard [24]. However, most often, as permitted by the EPCs, tabulated values of the temperature reduction coefficient are used in calculations, which in the case of underground spaces are 0.5 (when there are no windows or external doors) or 0.8 (when there are windows or external doors). The article [25] presents the variability of the temperature reduction coefficient of ceilings above unheated basements, depending on the thermal insulation of the partitions closing the heated and unheated space and the external environmental conditions. It has been shown that the use of a constant value of the temperature reduction coefficient for calculating the thermal needs of a building is associated with an overestimation of heat losses from the surface of the ceiling above unheated basements. The temperature reduction coefficient determined in detail, and consequently the estimated heat losses, allow for demonstrating energy savings related to the insulation of unheated basement walls. It has been proven that the detailed calculations also allow for a more accurate estimation of the energy demand in the building before and after the planned thermal modernization than in the case of using constant temperature reduction coefficients, often determining compliance with the requirements of financial support programs for improving energy efficiency.

Another simplification, permitted in the EPCs, but which may result in the calculation model of the building not being adjusted to its actual condition, is the possibility of adopting tabulated values of linear thermal bridges according to the PN-EN ISO 14683 standard [26]. The accuracy of such a method is only from 0 to 50% due to the poor list of possible details to choose from and the assumptions adopted in the standard for their determination. Additionally, the occurrence of thermal bridges is often overlooked by designers, architects or constructors, which is probably why the simplified method is most often used in practice. Meanwhile, this is a phenomenon that significantly affects the thermal parameters of the building, and thus its energy characteristics [27]. Therefore, it is worth using thermal bridge catalogues, which allow for greater accuracy (up to 20%) or performing your own numerical calculations, in which case the accuracy is even 0-5%.

In terms of possible building materials:

- basement walls in contact with the ground should be insulated with a material resistant to water and significantly resistant to freezing and thawing cycles, e.g. XPS extruded polystyrene foam boards (the thermal conductivity coefficient of such boards available on the market is from 0.032 to 0.036 W/(m·K)),
- ceiling above the basement: the most beneficial way to reduce heat losses in the case of modernized buildings is to install insulation boards, mainly polystyrene boards, to the ceiling from the side of the unheated space by gluing or suspending them; the insulation layer is attached using hooks or steel mesh, and the insulation from the side of the unheated space can be uncovered or covered, e.g. with aluminum foil, plaster, etc. [28]. In recent years, other materials have also become fashionable, such as thermal insulation plasters [29, 30] which can be used both outside and inside, or innovative spray insulation systems.

The insulation thickness required to meet the current thermal protection requirements in Poland, specified in Regulation [31], depends on the initial condition of the partition and the thermal conductivity coefficient of the selected material.

3 Materials and methods

The research problem undertaken in the article concerns the quantitative energy and operational consequences of various methods of basement insulation of residential buildings.

Description of the selected building and calculation variants

A multi-family residential building was chosen as a case study. It was built in 1970, using traditional technology. It is a five-storey, single-staircase building with a basement containing a boiler room, a common room and 15 storage units for residents. All rooms designed as unheated constitute 71.7% of the basements, and the basement walls are sunk into the ground by 1 m. The length of the building is 11.6 m, width 15.1 m and height 16 m. The building area is 176 m2, and the usable area is 695 m2. The balcony elevation, oriented to the south-west, is shown in Fig. 5.

Fig. 5. *South-west elevation of the analyzed building*

Basement walls made of 38 cm thick concrete; gable walls made of hollow brick, longitudinal walls made of cellular concrete; ceilings: 24 cm thick hollow core slabs (1 layer of fibreboard is used in the ceiling above the basement); ventilated ceiling; PVC windows and external doors. It was assumed that all the building envelope (apart from the ones currently analyzed: the ceiling above the unheated basement and the basement walls: the ceiling over the unheated basement and the basement walls) had previously been thermally upgraded and meets current Polish requirements (WT2021). The thickness the insulation of the ceiling above the basement and basement walls analyzed in this article is 10 cm and 15 cm respectively (at λ=0.033 W/(m·K)). The influence of the thermal bridge at the connection of the walls with the ceiling above the unheated basement was minimized by placing the insulation layer of the above-ground storey walls below the ceiling level. The values of the thermal transmittance coefficients of the individual building partitions of individual building partitions, calculated on the basis of the PN-EN ISO 6946 [32] standard, are shown in Table 2.

Building envelope element	**Area**	**Calculated/Assumed Value**	**Value required in Poland, according to WT 2021** [31]
	A [m^2]	U [W/(m^{2}K)]	
External walls	614.50	0.20	0.20
Basement walls	86.78	0.95; 2.06→0.18; 0.20	–
Basement walls in the ground	50.73	0.73; 1.22→0.17; 0.19	–
Ceiling above the basement	175.46	1.02→0.25	0.25
Flat roof	175.46	0.15	0.15
Floor on the ground	175.46	0.90	–
Windows in apartments	124.32	0.90	0.90
Windows in the unheated basement	4.55	2.60→0.90	–

Windows in stairwell	12.02	0.90	1.40
Doors		1.30	1.30

Table 2. *The values of thermal transmittance coefficient of individual partitions of the analyzed building*

Two different schemes of thermomodernization of the building in the basement area were considered: insulation of external walls of level -1 (W1) without replacing windows (W1a) and with replacing basement windows (W1b) and insulation of the ceiling above the basements without replacing basement windows (W2). In variant W2, replacing basement windows was not considered, because according to the Polish "Act on supporting thermal modernization and renovations" [33], the undertakings are to concern only the temperature-regulated zone. In W1, insulation of basement walls was analyzed as an alternative to insulation of the ceiling in the event of its technical and operational impracticability. The change in the values of the thermal transmittance coefficients of partitions of partitions intended for thermomodernization is shown in Table 2.

Calculation method

The calculations were carried out according to the scheme presented in Fig. 6, using the methods, standards and regulations described above.

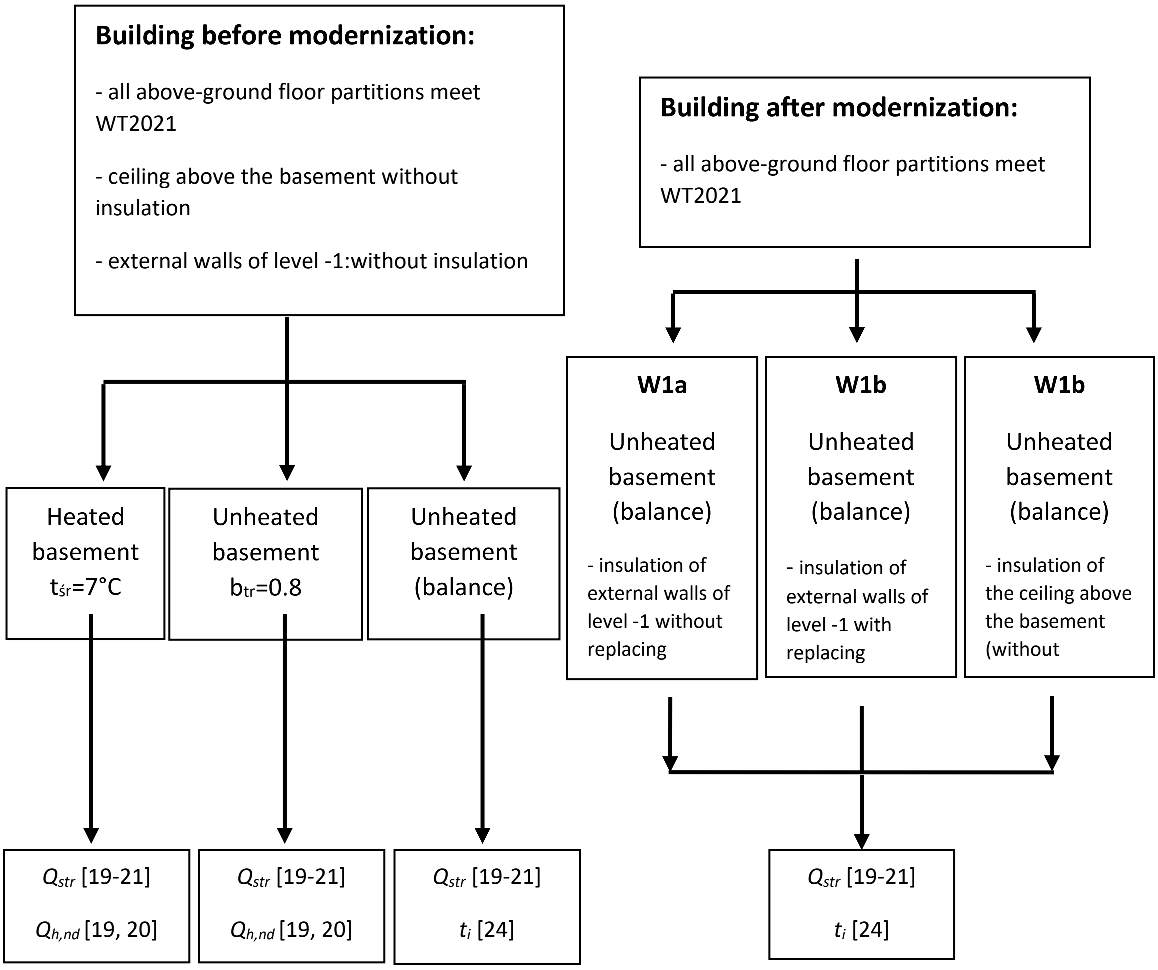

Fig. 6. *Block diagram of the calculation method*

4 Results and discussion

The calculation results for the existing condition of the building (before the modernization of the basement ceiling and walls of level -1) and for the condition of the building in the individual variants of thermal modernization of the basements are presented in Fig. 7.

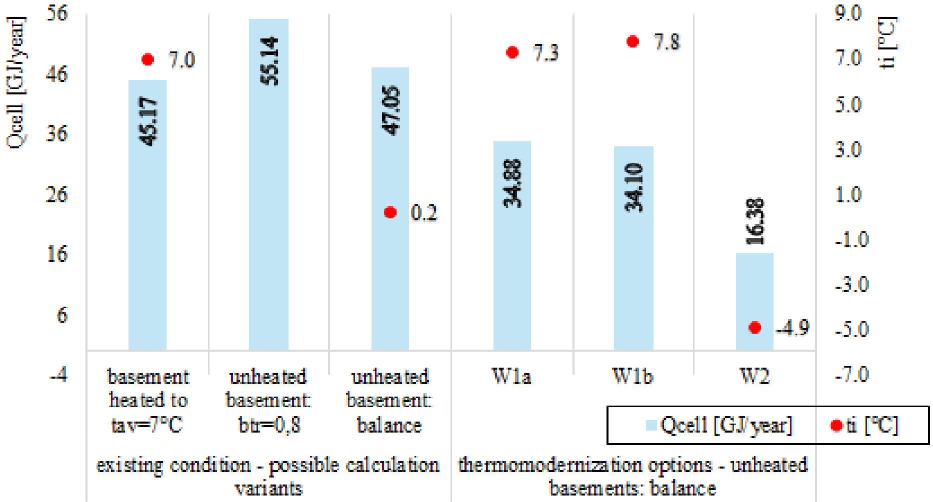

Fig. 7. *The effects of thermal modernization of the basement of the analyzed building in the individual analyzed variants.*

In the first step, the results obtained for the building before the basement modernization were assessed using different methods and assumptions. The temperature value in the unheated basements of the building calculated using the balance method before their modernization was t_i=0.2°C, which is significantly lower than in the case of treating the basements as heated to an average temperature ($t_{śr}$=7°C) calculated for individual rooms. At the same time, this temperature is higher than assumed in the standard [22] – the temperature value of basement rooms with windows with central heating ducts in climate zone IV was assumed as t_i=-1°C (Table 1). The use of a constant value of the temperature reduction coefficient b_{tr} for the calculation of the building's thermal needs is associated with an overestimation of heat losses from apartments to the basement in the case of treating them with the temperature reduction coefficient b_{tr}. These losses (Q_{str} = 55.14 GJ/year) are almost 15% lower than when the balance method is used. The results obtained are consistent with the conclusions presented in the article [25]. Therefore, the balance method was selected for further analysis, which allows for demonstrating energy savings related to the insulation of unheated basement walls; the results are presented in Table 3.

Insulation of unheated basement walls (with thermally poor - uninsulated ceilings above the basement and good thermal quality of the remaining parts of the building envelope) causes the temperature in the basement to increase from t_i =0.2°C to t_i =7.3°C without simultaneous replacement of windows (variant W1a) and to t_i =7.8°C with simultaneous replacement of basement windows (variant W1b). When the ceiling above the unheated basement was insulated, the temperature dropped to -4.9°C (variant W2), which is a much lower value than it would result from the standard [22].

Calculation variant	Demand for usable energy for heating $Q_{h,nd}$	Total amount of heat transferred from apartments to the basement Q_{str}	Total amount of heat transferred from the heated zone $Q_{H,ht,s,n}$
	[GJ/rok]		
existing state	112,01	47,05	295,21
W1a	101,39	34,88	283,24
W1b	100,61	34,10	282,47
W2	92,95	16,38	263,25

Table 3. *Heat losses and demand for usable energy for heating the analyzed building*

The greatest reduction in heat losses from ground floor apartments (around 65.2%) was achieved by insulating the ceiling above the unheated basement (variant W2). The overall reduction in losses was as much as 10.8%. Insulating the basement walls gave smaller results: without simultaneous replacement of windows (variant W1a), heat losses dropped by 25.9% and 4.1%, respectively, and with simultaneous replacement of basement windows (variant W1b), by 27.5% and 4.3%, respectively.

In the case of multi-family buildings meeting the requirements specified in the "Regulation of the Minister of Infrastructure of 6 November 2008 amending the regulation on technical conditions to be met by buildings and their location" (WT2008), the share of heat losses through ceilings above unheated basements and garages is 3.8% - 14.3% [34]. In the analyzed building with above-ground storey partitions meeting the requirements of WT2021 [31], the share of heat losses transferred from apartments to basements before their thermomodernization was 15.9%, after insulation of basement walls without replacing windows: 12.3%, with replacing windows: 12.1% and after insulation of the ceiling: 6.2%.

5 Conclusions

Insulation of the ceiling above the unheated basement in the analyzed building (variant W2) reduces heat losses from the apartments on the ground floor by 65.2%. and in the scale of the entire building by 10.8%. while insulation of basement walls without simultaneous replacement of windows (variant W1a) by 25.9% and 27.5%. respectively. With simultaneous replacement of basement windows (variant W1b). the reduction is 4.1% and 4.3%. respectively. From the point of view of the residents. it is more beneficial to insulate the ceiling. not the walls. This results in lower heating costs but is sometimes not possible to implement in practice (cluttered storage rooms in the basement).

Insulation of unheated basement walls (with thermally poor uninsulated ceilings above the basement) also causes an increase in the temperature in the basement from 0.2°C to 7.3°C without simultaneous replacement of windows (variant W1a) and to 7.8°C with simultaneous replacement of basement windows (variant W1b). Sometimes such an increase in temperature in rooms intended for storing e.g. food products may be undesirable.

After insulating the ceiling above the unheated basement (in addition to lower heat losses than when insulating the walls of unheated basements). there may be a risk of a negative temperature value in the basements. In the analyzed building. the temperature value will drop to -4.9°C (variant W2).

The results of the analyses carried out show the complexity of the issue and the need to consider each case individually. The pursuit of maximum energy savings should not worsen the operating conditions of the premises. There is also a need to investigate this issue in depth for other shapes and types of buildings and other locations than the one presented (north-east of Poland). Material solutions for architectural details and the depth of the walls in the ground are also important.

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