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A New Approach to the Economic Evaluation of Thermomodernization: Annual Assessment Based on the Example of Production Space

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Abstract: Energy and economic assessments are of great relevance in the context of decision processes for the most optimal solutions for building renovations. Following the method recommended by UNIDO, economic analyses of thermal modernization options are carried out based on the Simple Payback Time (SPBT), Net Present Value Ratio (NPVR) and Internal Rate of Return (IRR) indices. Incorporating these indicators and a new approach that involves aggregating thermomodernization activities not only in the cold and warm seasons separately, but throughout the whole year, an economic evaluation of the thermomodernization of a production space was carried out. In this case study, the renovation options included wall insulation, window replacement, the installation of infrared heater, a two-flow air diffuser (TFAD) and variable air volume. The economic effect indicated by the highest NPVR over a normative period of 15 years was obtained for the installation of an infrared heater and a TFAD with a variable mode ventilation system. The SPBT for this case was also the lowest.

Keywords: UNIDO; electric radiant heater; two-flow air diffuser (TFAD); variable air volume (VAV)

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1. Introduction

A significant policy priority of European countries is saving energy [1–8]. In order to effectively save energy, technical innovations must be applied in a rational economic way. However, in order to provide sufficient indoor conditions in industrial premises, a large amount of energy is consumed for heating and cooling in the cold and warm seasons, respectively [9–13].

Today, reducing energy consumption and moving away from fossil fuels is a priority. This can be addressed through the widespread use of renewable and waste energy [14]. However, in certain European countries, like Ukraine and Poland, gas is still one of the main sources of energy. This raises questions about the diversification of the gas supply and pricing policies. Therefore, in these countries, policies to reduce the need for thermal energy consumption and its economic justification have been widely implemented. Energy saving problems in all European countries include topics such as heat supply, internal HVAC systems in buildings, heating and ventilation in the cold season [13,15], ventilation and air conditioning in the warm season [16,17], and hot water supply throughout the year [18,19]. Other considerations include building envelope, indoor environment and building operation. In order to effectively reduce energy consumption, the thermal modernization of buildings primary involves lowering the coefficients of heat transfer of walls and windows [20]. A reduction in heating and cooling demand is achieved by the modernization of existing systems, thus maximizing the effect of both thermal and economic savings. The heat transfer coefficient of envelopes and windows in new buildings must not exceed the maximum values given in the standards and regulations defined in particular countries [21,22].

An analysis of the literature clearly indicates that thermal modernization activities bring economic benefits, social benefits, environmental benefits and benefits for the energy system. There is even evidence for modernizing a building to a passive and nearly zero energy building standard [23–25].

The thermal diagnostics of a building can reveal factors influencing its heat consumption. By integrating various partial diagnoses, one can determine the overall heat consumption of the entire structure and gather data for devising improved solutions. When evaluating energy consumption, it is important to consider the indoor environment's quality, ensuring that energy-saving measures do not compromise it. The diagnostic procedure involves two phases: inspections and diagnostic measurements. Inspections aim to assess the technical conditions of systems and compare their performances with the designer's specifications. Diagnostic measurements are conducted in order to evaluate system operation under real conditions. A comprehensive method for assessing the physical envelope, HVAC systems and indoor environment was proposed in the literature [26,27].

When making decisions, including those related to improving the energy efficiency of a building, the decision-maker, consciously or unconsciously, most often uses the single-criterion method, looking for a solution that best meets one selected criterion. The single-criterion method gives a clear result, which decision should be made, knowing that many important parameters of the analyzed solutions will not be taken into account at all [28].

The basic single-criterion analytical methods include Cost–Benefit Analysis (CBA) and Cost-Effectiveness Analysis (CEA) [29]. The CBA analysis is carried out in three stages. In the first stage, after defining which variants of solutions should be compared, all costs and benefits of each variant are given a monetary value. During the second stage, costs and benefits are compared for all analyzed variants. The comparison is made using different measures of economic efficiency [28].

The economic criterion can be described using many indicators known from the literature [30]. The most frequently used are investment and operating costs related to energy consumption. Importantly, the operating costs index may combine many elements: energy consumption for heating, hot water preparation and cooling, electricity for lighting, operation of equipment, machines, technologies, water consumption and sewage disposal. They can be analyzed together or individually. The most popular indicators of economic efficiency include Net Present Value (NPV), Simple Payback Time (SPBT) and Internal Rate of Return (IRR) of an investment. Additionally, the economic uncertainty and service life of the installation are assessed. However, a tool based on the assumptions of life cycle costing (LCC) can be used to compare the economic effectiveness of alternative investment solutions and the profitability of a product over the entire life cycle. Depending on the detail and purpose of the analysis, there are three types of life cycle costing: conventional LCC (also called traditional or business LCC), environmental LCC and social LCC. This tool requires a large amount of data and complements the multi-criteria analysis, which eliminates unacceptable solutions that are not subject to detailed analyses, e.g., LCC.

However, the literature review shows that the most popular methods include net present value or internal rate of return of an investment. The third stage of the decision-making process is the selection of the best solution, i.e., the one that best meets the adopted objective function. This evaluation mechanism has also been recommended by the United Nations Industrial Development Organization (UNIDO).

The motivation for scientific research and studies in this area is the search for optimal solutions that not only yield results in reducing energy consumption, but are also economically justified. As indicated by numerous articles [20,29,31–33], the renovation of buildings, despite unquestionable benefits in reducing energy consumption, is an undertaking requiring significant investment. The authors took the initiative to identify the optimal solution for another case and thus contributed to research towards cost optimization using a new approach in the selection of thermal modernization options and measures, because in many studies on lowering energy demand in buildings, thermal modernization measures are considered seasonally (Table 1). In the cold season, thermal modernization of the buildings focuses mainly on the building envelope [20,34–36], the heating systems [21,22] and the heat sources, for example, gas supply [37]. In the aforementioned publications, the technical merits and the economic efficiency were investigated.

Table 1. Thermal modernization measures undertaken in case of thermal modernization activities.

Authors, Year	Title; Journal	Thermal Modernization Measure	Season
Krawczyk D.A., 2004 [38]	The optimum variants of warming up walls, roof, windows change and a heating system modernization in the typical school according to its localization (in Polish); Instal.	Reducing heat losses through building partitions, improving the efficiency of the heating system.	1
Przesmycka N. et al., 2023 [39]	Modernisation of hospital buildings built in the 20th century in the context of architectural, functional and operational problems; Architectus.	Modernization of installation, thermomodernization, replacement of window and door joinery.	1
Krawczyk D.A., 2014 [40]	Theoretical and real effect of the school's thermal modernization—A case study; Energy and Buildings.	Reducing heat losses through building partitions, improving the efficiency of the heating system.	1
Gładyszewska-Fiedoruk K. et al., 2014, [41]	The possibilities of energy consumption reduction and a maintenance of indoor air quality in doctor's offices located in north-eastern Poland; Energy and Buildings.	Replace radiators and pipes; pipe insulation; wall insulation; window replacements.	1
Ołtarzewska A. et al., 2022 [20]	Analysis of the influence of selected factors on heating costs and pollutant emissions in a cold climate on the example of a service building located in Bialystok; Enegies.	Thermal insulation of the building partitions, heat source replacement.	1
Lis A., 2020 [8]	Renewable Energy Sources and Rationalisation of Energy Consumption in Buildings as a Way to Reduce Environmental Pollution; Renewable Energy	Thermal insulation of building envelope; renewable energy sources; replacement of the windows and doors; modernize the central heating system; hot water heating; installation of heating elements with low thermal inertia and thermostatic valves; installation lagging on the central heating pipes; ineffective electric heaters with a centralized heating from their own boiler room replacement.	1
Lis A. et al., 2019 [42]	The quality of the microclimate in educational buildings subjected to thermal modernization	Insulation of building envelope and modernization of the heating system and hot water preparation.	1
Bøhm B., 2013 [43]	Production and distribution of domestic hot water in selected Danish apartment buildings and institutions. Analysis of consumption, energy efficiency and the significance for energy design requirements of buildings; Energy Conversion and Management Journal	Improving the DHW system.	1/2
Hałacz J. et al., 2020 [44]	Assessment of Reducing Pollutant Emissions in Selected Heating and Ventilation Systems in Single-Family Houses; Energies	Heat sources, mechanical ventilation with ground-coupled heat exchanger.	1/2

Table 1. *Cont.*

Authors, Year	Title; Journal	Thermal Modernization Measure	Season
Ferdyn-Grygierek J. et al., 2019 [45]	HVAC control methods for drastically improved hygrothermal museum microclimates in warm season; Building and Environment	HVAC control.	2
Ratajczak, K et al., 2020 [46]	Assessment of the air streams mixing in wall-type heat recovery units for ventilation of existing and refurbishing buildings toward low energy buildings; Energy and Buildings	Mechanical ventilation systems with heat recovery.	2
Zender-Świercz E. et al., 2013 [47]	Thermomodernization a building and its impact on the indoor microclimate; Structure and Environment	Sealing the roof.	1/2

Seasons: 1—cold season, 2—warm season.

The main aim of this paper is to propose a new approach to the economic evaluation of thermal modernization in a building. This new approach takes into account thermo-modernization measures from different seasons, creating a year-round assessment. This is especially important in the Central European area at the moment, where climate change means that cooling demand will play an increasingly important role in the summer season [26]. A case study of production space in Lviv in Ukraine is considered in which the options included walls insulation, window replacement and the utilization of devices like radiant heaters and TFAD working in variable mode. These measures led to the improvement of inner conditions throughout the year. The of economic calculation concepts are recommended by UNIDO.

2. Materials and Methods

2.1. Economic Indicators

Every investment process aimed at generating economic profits should undergo a thorough analysis. This is particularly crucial for investment processes where the returns are spread over an extended period, such as in the construction industry. Economic analysis provides information to determine whether a project is financially viable and if the proposed solutions are economically sound. Numerous examples from past practice demonstrate the use of economic analysis as a decision-support tool in investment decision-making [48].

Considering the operation of heating and ventilation systems throughout the year, the following abbreviations are used:

- The Thermal Modernization Measure (TMM) is an undertaking aimed at reducing the demand for heat or cooling energy in a building;
- The Seasonal Thermal Modernization Measure (STMM) separately considers the cold and warm seasons, and refers to the insulation of the building envelopes, as well as the heating and ventilation systems;
- The Year-Round Thermal Modernization Measure (YTMM) refers to the cumulative effects of STMMs in both seasons, i.e., throughout the year;
- The Thermal Modernization Option (TMO) describes the cumulative effect of several STMMs, considered separately for the cold and warm season. In other words, the TMO is the combination of several STMMs in the corresponding period of the year.

The economic indicators of STMMs and TMOs are determined in publications [16,49].

Savings due to the application of electric infrared heaters (K_d) in EUR/year were calculated following formula:

$$K_d = Q_H \cdot (C_H - C_E) \quad (1)$$

where

K_d—annual energy savings due to the difference in heat and electrical energy costs, EUR/year;

C_H and C_E—the costs of heat and electricity, respectively, EUR/GJ;

Q_H—the year-round energy demand of the heating system, GJ/year, which is calculated based on heat losses in W, determined by the formula:

$$q_h = U \cdot A \cdot (t_{in} - t_5) \quad (2)$$

where

U—heat transfer coefficient, W/(m^2K);

A—the area of the building element (window, wall, etc.), m^2;

t_{in}—indoor temperature during the cold season, °C;

t_5—the temperature of the coldest five days, °C;

According to duration of the heating season and the mean external temperature of the heating season t_{hs}, the temperature ratio is $(t_{in} - t_{hs})/(t_{in} - t_5)$.

The warm season calculation procedure contains the cooling demand calculations determined by the formula for heat gains in W:

$$q_c = c \cdot \rho \cdot L \cdot (t_{ex} - t_{in}) \quad (3)$$

where

c—air specific heat, J/(kg·K);

ρ—air density, kg/m^3;

L—volume flow rate of air, m^3/s;

t_{ex}—temperature of exhaust, °C;

t_{in}—temperature of supply air, °C.

It can be noted that the proposed approach has some limitations. There is a simple method of calculating the heat demand and cooling load of a building. In the future, building cooling loads can be estimated based on rough sets and deep extreme learning machines [50]. Furthermore, deep learning models based on EWKM, random forest algorithms, SSA and BiLSTM for building energy consumption prediction can be also implemented [51].

The value of savings K_{iCS} as a result of each thermomodernization process in the cold season is determined according to formula:

$$K_{iCS} = \Delta Q_{iCS} \cdot C_{HE} \quad (4)$$

where

K_{iCS}—savings for the cold season, EUR/year;

ΔQ_{iCS}—energy savings for one STMM, GJ/year;

C_{HE}—the cost of energy in the cold season; EUR/year.

The value of savings K_{iWS} as a result of each thermomodernization process in the warm season is determined according to formula:

$$K_{iWS} = \Delta Q_{iWS} \cdot C_{EC} \quad (5)$$

where

K_{iWS}—savings for the warm season, EUR/year;

ΔQ_{iWS}—energy savings for one STMM, GJ/year;

C_{EC}—the cost of energy in the warm season, EUR/year.

The equation to calculate the cost savings throughout the year K (EUR/year) as an effect of the YTMM takes the form:

$$K = \Delta Q_{CS} \cdot C_{HE} + \Delta Q_{WS} \cdot C_{EC} \quad (6)$$

where

ΔQ_{CS} and ΔQ_{WS}—saved heat energy in the cold season and cooling in the warm season, respectively, GJ/year;

C_{HE} and C_{EC}—the cost of energy in the cold and warm seasons, respectively, EUR/year.

Investment costs I_i are the sum of investment costs of thermal modernization measures I_{iCS} for the cold season and I_{iWS} for the warm season, and are determined by:

$$I_i = I_{iCS} + I_{iWS} \tag{7}$$

where

I_{iCS} and I_{iWS}—investment costs of STMMs in the cold and warm seasons, respectively, EUR.

An evaluation of the profitability of investments was carried out based on methods recommended by the United Nations Industrial Development Organization (UNIDO) [52]. This is a specialized agency of the United Nations (UN) that promotes industrial development for poverty reduction, inclusive globalization and environmental sustainability. It was established in 1966 and obtained the status of specialized UN agency in 1985. Currently, UNIDO has 170 member states. The organization's main areas of interest are divided into four strategic priorities—creating shared prosperity, increasing the competitiveness of the economy, environmental protection, and strengthening knowledge and institutions.

The decision to undertake a thermal modernization investment is made when the "sum" of positive values, benefits resulting from the project, is greater than the expenses related to the investment. Various types of economic efficiency indicators are used. In accordance with UNIDO recommendations, the values of such indicators should be calculated according to Simple Payback Time (SPBT) and common dynamic indices, namely Net Present Value Ratio (NPVR) and Internal Rate of Return (IRR). The methodology recommended by UNIDO presents the method for conducting financial analysis and evaluating investment projects. According to this methodology, the financial profitability of the project from the investor's point of view is the primary criterion in the investment assessment, more important than other advantages of the project.

Simple Payback Time (SPBT) is defined as the time needed to recover the capital expenses incurred for the investment. It is calculated from the moment the investment is launched until the sum of gross benefits obtained as a result of the investment balances the incurred expenditure. Since the SPBT for STMMs is determined from [2,5], the SPBT for YTMMs is calculated as follows:

$$SPBT = \frac{I_{iCS} + I_{iWS}}{K_{iCS} + K_{iWS}} \tag{8}$$

where

K_{iCS} and K_{iWS}—the cost of energy saved in the cold and warm seasons, respectively. These costs correspond to the STMM, EUR/year.

The net present value ratio is described by the following formula:

$$NPVR = \frac{K_i \cdot t}{(1 + r)^t} - I_i \tag{9}$$

where

K_i—the cost of energy saved throughout the year for the corresponding i-th YTMM, EUR/year, and is determined from (6);

t—current time in years (the maximum time is defined to be 15 years);

r—discount rate, r = 0.08;

I_i—determined by Formula (7).

The method is exposed to the typical limitations found in economic analysis, namely, the adoption of the value of the discount rate r-factor. The r-value is a bank value that is constantly adjusted; that is, it changes slightly depending on the economic situation in the country. The current economic situation in Ukraine is unstable for objective reasons, so the value of r is very unstable and difficult to predict. During the initial work on this article, the r-value was changed several times according to the NBU (National Bank of Ukraine). As a result, the calculations become much more complicated and require additional assumptions and simplifications. In this regard, a fixed value of r was adopted for the conditions of a stable economic situation. If we consider another arithmetic value of r, then this does not change the essence of the matter, but will only lead to obtaining another corresponding arithmetic value of NPVR.

The NPVR value takes into account the entire duration of the project. This is its basic advantage. It encourages risk by showing the full benefits of making a given investment. The disadvantage is the difficulty in selecting the observation period for which the benefits expressed in the NPVR value are calculated. One of the parameters for choosing the length of this period may be the period until the project will generate benefits, i.e., until its "economic death", or more clearly, the period of full depreciation of the purchased machinery and equipment. In some cases, the investor may impose different, shorter periods when assessing the benefits of the project in the light of their expectations as to when the benefits of the invested funds will be realized. In certain cases, the length of the analysis period may be determined by one of the interested parties, e.g., a bank or by law. In order for the thermal renovation option to be profitable, it is necessary that its Simple Payback Time is shorter than 15 years, and the Internal Rate of Return is greater than 8% [49,53]. Thus, in Poland and Ukraine, a period of 15 years is assumed for thermal modernization investments.

As per guidance from UNIDO, the net present value ratio stands out as the pivotal measure for evaluating the optimality of annual thermal renovation options. The NPVR not only serves as an indicator, but also plays a crucial role in discerning the financial viability of different thermal upgrading alternatives. A notable aspect is that a higher NPVR value is indicative of the specific thermal renovation choice that not only enhances energy efficiency but also promises the utmost financial gain over the anticipated operational lifespan of the building. This criterion thus offers a comprehensive perspective, combining both economic and thermal performance considerations, in order to guide decision-makers towards the most financially lucrative and sustainable thermal modernization strategy. It should be noted that other economic indexes are also important but are not a priority. In particular, the SPBT can be compared with the normative operating time of 15 years and the Internal Rate of Return, with the normative value r = 0.08 (8%), to draw appropriate conclusions.

The thermal modernization options that combine two (or more) energy-saving measures—one of which is profitable (NPVR > 0) and the other unprofitable (NPVR < 0) —are interesting. They can be both profitable but not optimal, and finally unprofitable. First of all, everything depends on the NPVR indicator, and the rest of the economic characteristics are its consequences. This is clear in the analyzed case, as window replacement generates a negative NPVR, but when used with other STMMs, it allows for a positive net present value.

The Internal Rate of Return (IRR) is a certain degree of discount when NPVR = 0. Since, by the definition t = 15 years, IRR with parameters described above is determined by the formula:

$$\mathrm{IRR} = \left(\frac{15 \cdot \mathrm{K_i}}{\mathrm{I_i}}\right)^{\frac{1}{15}} - 1 \tag{10}$$

The year-round interest rates are proposed to be determined from Formulas (9) and (10).

Indicators of the economic criterion of investment are also the service life of the installation, defined as a guarantee of durability, resistance to corrosion and damage, and economic uncertainty, described as the probability that the actual economic parameters will differ significantly from the estimated ones, e.g., due to an unexpected increase in the cost of installing equipment or fuel.

2.2. New Approach

Thermal modernization activities include the adoption of assumptions for the selection and assessment of the thermal modernization package. The criteria for assessing the effects of their use are as follows [54]:

- Demand for usable energy, EU index;
- Capital expenditure;
- Saving the annual energy cost;
- Simple payback period;
- Net present value ratio.

According to the UNIDO recommendations, the optimality criterion of the annual thermal renovation option is the NPVR. The maximum value of the NPVR indicates the option of thermal upgrading that provides the maximum profit over the assumed period of operation of the building.

The new approach consider several thermomodernization measures from different seasons, creating a year-round assessment. In order to determine the YTMM, the authors propose to calculate it as the linked effect of both STMMs for the cold and warm seasons, and then to pinpoint the TMO with the highest NPVR value.

Preliminary activities require comprehensive in situ thermal diagnostics of buildings in order to determine the scope of thermal modernization of the facility and to estimate the energy consumption of a given facility.

Thermal modernization improvement options are proposed separately for the cold and warm seasons (STMM).

Next, two seasonal thermal modernization measures are combined as the YTMM. Their number is obtained according to the rule of combinatorics. For example, when the cold season includes three options, and the warm season two options, the number of YTMMs is six. Since there is a difference between energy costs in the cold and warm seasons, these values were considered separately. However, these values must be considered aggregate in order to estimate the annual effect.

In the next step, the annual energy savings are estimated, which allows us to calculate the SPBT, NPVR and IRR for each YTMM. In order to achieve the maximum saving effect level for the best options, namely thermal modernization options (TMOs) linked to several TMM from both seasons, the investment cost, the annual savings and the investment profitability indices are juxtaposed in a table (Table 2) using a special algorithm: annual energy-saving measures must be arranged vertically in order of increasing Simple Payback Time from minimum to maximum, while their cumulative effect are arrange horizontally, marked with a "+" sign. Generally, one should take into account the possibility of their simultaneous action, for example, the replacement of windows and sealing of windows. Such measures cannot be implemented simultaneously.

Table 2. Design of table for the optimization of combinations of STMMs.

YTMM	**Thermal Modernization Options (TMO)**				
	I	**II**	...	...	...
TMM for cold + TMM for warm season	+	+	+	+	+
TMM for cold + TMM for warm season		+	+	+	+
TMM for cold + TMM for warm season			+	+	+
TMM for cold + TMM for warm season				+	+
TMM for cold + TMM for warm season					+
Indicators					
Investment cost I Annual savings K SPBT, year NPVR, EUR IRR, %	$SPBT_I$ <	$SPBT_{II}$ <	$SPBT_i$ < $NPVR_{max}$	$SPBT_{ii}$ <	$SPBT_{nmax}$

Two pluses in the column mean that TMO II includes the TMM for the winter season plus the TMM for the summer season (i.e., TMO I), plus an additional TMM, for the summer or winter season, selected from the next YTMM pair. The new TMM is, of course, additionally included in the investment costs, and the option is positioned in line with the increase in the SPBT. For TMO III, a new, previously unconsidered TMM is added from the new YTMM pair. If the TMM was already included in the previous option, the new TMO does not introduce new information and the cost indexes are equal to the previous TMO.

The scheme of activities within the designation of the TMO with the maximum value of NPVR is presented in Figure 1.

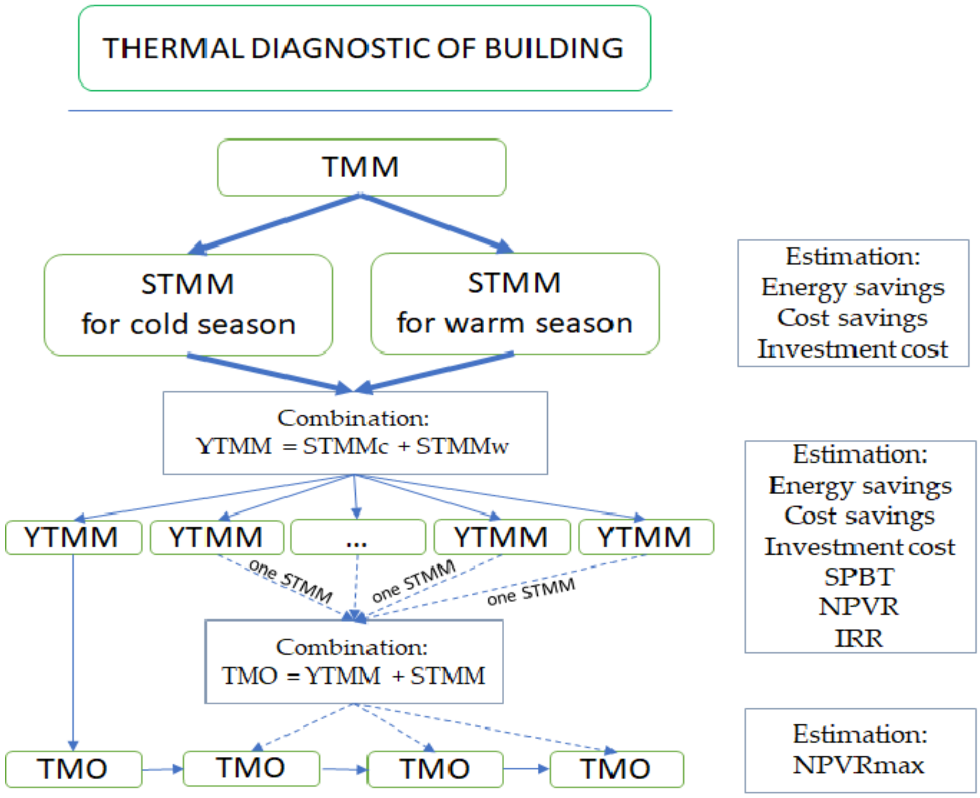

Figure 1. Scheme of activities within the designation of the TMO.

The use of a new approach to identify a thermal modernization option combining several thermal modernization measures for two seasons is shown as an example of a real production building as a case study.

3. Case Study

3.1. Building Characteristic and Its Location

The considered space is a production building, originally equipped with a traditional water heating system, located in Lviv city in Ukraine (Figure 2), an area with a Central European climate that is of interest due to the increasing need for cooling in summer and the large differences between summer and winter outdoor air temperatures. The naturally ventilated facility was built in 1995 and consists of one floor. The volume of the building is 245 m^3, while the usable area is 70 m^2 (5 m × 14 m). The window surface area was calculated as about 9.7 m^2. During the cold season, a temperature t_{in} of 18 °C is maintained indoors, while in warm season, a supply temperature of 23 °C and exhaust of 26 °C are designed. The layout of the investigated space, including the locations of two infrared heaters and two TFADs, proposed as a thermomodernization options, is presented in Figure 3. The internal walls are on axes 1 and 2, and the external walls are on axes A and B.

Figure 2. Lviv city in Ukraine [55].

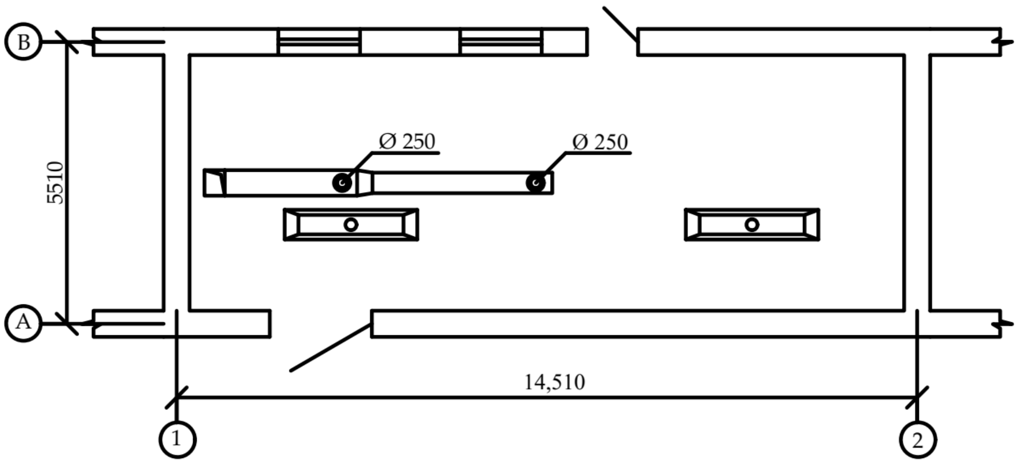

Figure 3. The layout of the production space.

The main climatic characteristics of Lviv city are as follows:

- First climate zone according to the DBN V.2.6-31 standard [56];
- Climate zone 5A according to the ASHRAE;
- The mean annual air temperature is 8.8 °C;
- The mean temperature of the coldest five days in the cold season is −19 °C;
- The duration of the heating season (cold season) is 179 days and the remaining days of the year are the warm season. There are no specific regulations governing the heating season, including when it starts and ends. Nevertheless, a certain period of time has been defined and confirmed by case law. Accordingly, the heating season starts in October, when the mean daily external temperature of three consecutive days is lower than 12 °C;
- The mean temperature of the heating season is +0.4 °C;
- The mean temperature of the five hottest days in the warm season is +23 °C.

3.2. Thermal Modernization Improvements Options

The wall and window heat transfer coefficients should adhere to the specified maximum values outlined in the standards and regulations set by individual countries. The thermal insulation requirements in Ukraine are considerably less stringent compared to other countries [21,22]. The minimum thermal insulation requirements for Ukraine are visible in Table 3.

Table 3. Heat transfer coefficients U for building envelopes.

Building Envelope	U [W/(m²·K)]
Exterior walls	0.30
Flat roof above heated spaces	0.20
Floor on the ground	0.20
Flat roof over unheated attic	0.20
Flat roof over unheated basement	0.27
Exterior windows	1.33
Exterior doors	1.67

For the analysis of thermomodernization improvements, window replacement and external wall insulation were proposed, as well as elements of the building installations dedicated to the cold (heating) and warm seasons (ventilation).

The following STMMs for cold season were implemented:

- Window replacement (from R = 0.36 m^2K/W to R = 0.9 m^2K/W). The U value can be simply calculated, i.e., old windows with U-value of 2.8 $W/(m^2K)$ were replaced by new windows with U = 1.1 $W/(m^2K)$;
- The insulation of the external walls was improved from R = 1 m^2K/W to R = 3.3 m^2K/W (achieved by polystyrene foam boards with a thickness of 100 mm), i.e., U before thermomodernization equaled 1 $W/(m^2K)$, while after U = 0.3 $W/(m^2K)$;
- Installation of the infrared heaters.

For the warm season, the STMMs are as follows:

- Installation of two-flow air diffuser TFAD;
- Use of variable air volume (VAV) in the ventilation system by application of an integrated actuator.

Based on the aforementioned STMMs, the following six YTMM combinations were proposed:

- Window replacement and installation of two-flow air diffuser TFAD,
- Window replacement and implementation of VAV,
- Insulating the walls and installation of two-flow air diffuser TFAD,
- Insulating the walls and implementation of VAV,
- Installation of infrared heaters and two-flow air diffuser TFAD,
- Installation of infrared heaters and implementation of VAV.

The economic performance indicators determined from Equations (1)–(10) can be applied to YTMO, which is the aggregate effect of different TMOs in different periods of the year.

The following energy costs were adopted in the analysis [49,53]:

- For electricity, C_{EE} = 0.036 EUR/kWh (10 EUR/GJ),
- For heating, C_{HE} = 14 EUR/GJ,
- For cooling, C_{EC} = 40 EUR/GJ.

During the warm season investigation, the conversion factor of the cooling device was taken into account in order to determine energy consumption. This value was calculated based on the operation data of the electric motor of the compressor of the refrigerating device and the ranges ε = 3–5. For further calculations, the average ε value of 4 was assumed to be optimal.

3.3. Modernization of Building Installation

Proposed thermomodernization measures comprising the modernization of the building installation consisted of application solutions dedicated the warm and cold seasons separately. For the cold season and industrial premises, the use of radiant heating systems with infrared heaters deserves attention [57]. Infrared heaters [58–60], by directing infrared radiation straight into the occupied zone, create comfort and uniform thermal conditions. These devices are powered by electricity or gas. They are safe and work in a wide range of temperatures with high efficiency, while the high inertia and high-quality regulation provide a reduction in the running costs of the heating system. The aforementioned features of infrared heaters and issues such as uniformity of temperature field, mounting height, thermal efficiency, thermal load, air temperature and the temperature of the surrounding surfaces, i.e., walls, ceilings, and floors, and the reduction of operating costs are described in [61,62]. These publications also sought ways to increase the technical and thermal efficiency of the devices.

The infrared heater type NL–12 R, adapted for analysis as a thermomodernization option for the cold season, provides local heating via electromagnetic waves and has the ability for the power settings to be quickly adjusted, thus creating dynamically changing indoor conditions in the production space. The height and angle position of the heater, which can be adjusted, affects the irradiation area, while the reflector, which is an integral part of the device, directs infrared rays straight into the heating zone, increasing the efficiency of the heater and the comfort of occupants.

In the warm season, the thermal and humidity conditions in the room must also meet the user's expectations and the legal and technological requirements [13,63]. Simultaneously, the mechanical ventilation and air conditioning systems must meet energy saving and efficiency requirements [64]. The positive cooling effect, through a greater convective heat exchange with the human body, without the input of additional energy for cooling, which is desirable in the warm season, can be achieved through increased airflow. The description of the solutions based on periodic change in the volume flow rate and the initial velocity of air diffusers are described in [65,66]. This current article proposes, as one of the thermomodernization measure, the utilization of the original, proprietary technical solution, namely, the two-flow air diffuser (TFAD) presented in Figure 4 [67]. A TFAD, together with an energy-efficient ventilation system, is able to form air flows with an intensive attenuation of air velocity and temperature. It has the ability to regulate air flow and create a prompt and dynamic change in indoor microclimate conditions [65]. The design of the TFAD (Figure 4) allows air flow geometry to be changed in two ways, namely, as a swirled air stream directed downward (vertical), and as a flat air stream directed to the surface of the ceiling (horizontal), depending on actual needs. The TFAD has an inlet nozzle installed against the inlet section of the device with a deflector that forms an adjustable annular gap. Additionally, it is equipped with blades that are attached to the TFAD by a rod with a control handle with a changeable angle. The twisting blades of the TFAD allow the angle of expansion of the stream to be changed and enable the formation of a swirled air stream with high-intensity mixing of the supply and surrounding air, thus changing the amount of air supply. The TFAD design allows air flow to be improved by reducing the air velocity attenuation coefficient. The adjustment screw of the gap brings the change in the amount of air that enters the adjustable annular gap. The integration of the TFAD with an LM24A electric actuator, manufactured by the company Belimo, allows the change of the inclination angle of the twisting blades, thus supplying air in the required direction according to the required parameters. Connecting the electric actuator, which is controlled from the automation unit, enables the smooth change in volumetric air flow and intensity. As a result, the device works with air volume, which can be increased with a stable air velocity maintained within regulatory limits without any disruptions, and thus, the TFAD is dedicated to variable air volume ventilation systems (VAV) [66].

Further improvement of the aerodynamic characteristics of the two-flow air diffuser and the properties of air flow (velocity and temperature fields, velocity and temperature attenuation coefficients, and the influence of the angles of inclination of the twist blades) in terms of aerodynamic resistance and acoustic characteristics of aerodynamic noise, can be achieved as proposed in publication [65]. In order to confirm the effectiveness of the devices implemented to reduce energy consumption, it would be necessary to conduct additional experimental studies applying mathematical models [68–71] and numerical modelling methods as described in [72–74].

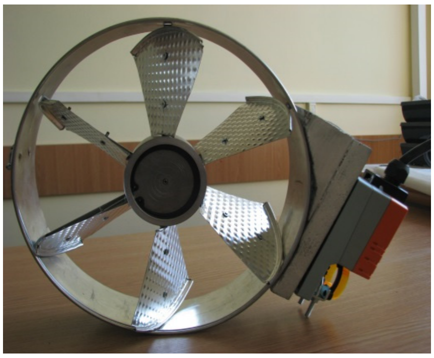

Figure 4. A two-flow air diffuser (TFAD), equipped with electric actuator Belimo LM24A.

The application of a TFAD allows for energy savings in air conditioning systems for small-scale premises (such as the one presented in this article) and the maintenance of normative air velocity and temperature, creating dynamic and comfortable indoor conditions in a room. The energy efficiency of cooling in an air conditioning system equipped with a TFAD integrated with an electric actuator during the warm season is examined in [49].

3.4. Results and Discussion

Considering the climatic characteristics of Lviv, the heat loss of the building in the cold season before thermal modernization was calculated in order to determine the base value of the energy demand Q_0. After each thermal modernization measure was performed, a new heat loss Q_i was calculated. Energy saving ΔQ_{cs} and ΔQ_{WS} were determined as the differences between the energy demand before the thermal modernization process Q_0 and the energy demand after the thermal modernization process Q_i. More precisely, the state before and after the thermal modernization:

- Heat losses q_h were determined from the Formula (2), the temperature of the coldest five days $t_5 = -19$ °C, $t_{in} = 18$ °C, and the U coefficients of the thermal modernization measures;
- The determination of the building energy demand Q_0 in GJ during the cold season, in accordance with the average temperature of the heating season, that is, +0.4 °C, and taking into account the duration of cold season (179 days);
- Similarly, the determination of the building energy demand Q_i in GJ for each STMM separately;
- The determination of energy saving: $\Delta Q_{CS} = Q_0 - Q_i$ for each STMM separately;
- The determination of investments in EUR for each STMM separately, in accordance with Equations (1), (4) and (5);
- The determination of annual energy and savings by the combination of two seasonal thermal modernization measures (one each for the cold and warm seasons) as a sum of both savings.

While the thermal modernization measures in the cold season reduce the value of U W/(m^{2}K), the need for energy for heating decreases. The use of the VAV mode allows for a reduction in the value of L; additionally, TFAD devices are efficient and cheap while maintaining comfortable indoor conditions in the warm season; thus, the need for energy for cooling is reduced.

In the cold season, three STMMs were considered. In Table 4, the obtained data are presented, including energy demand Q_0 and Q_i, energy saving ΔQ_{cs} and savings K_i for all year, EUR/year, following Formula (6). The data in Table 4 show that the installation of infrared heaters provided the smallest energy and cost savings, while the most effective was the window replacement. The thermal insulation of walls produces effects with values between the other STMMs.

Table 4. Energy and savings in a cold season.

STMM	Energy Demand, Q_0, GJ/year	Energy Demand Q_i, GJ/Year	Energy Saving ΔQ_{CS}, GJ/Year	Savings K_i, EUR/Year
	Before Change	After Change		
Window replacement	40	20	20	280
Wall thermal insulation	40	22	18	252
Installation of infrared heaters	40	24	16	224

The data in Table 5 show the effect of two STMMs in a warm season. Energy needs before thermal modernization Q_0 and after Q_i, energy saving ΔQ_{cs} and savings K_i for the warm season were obtained. The installation of the two-flow air diffuser (TFAD) gives nearly as little savings in thermal energy and costs as the variable mode of the ventilation system with automation system.

Table 5. Energy and savings in a warm season.

STMM	Energy Needs, Q_0, GJ/Year	Energy Needs Q_i, GJ/Year	Energy Saving ΔQ_{WS} GJ/Year	Savings K_i, EUR/Year
	Before Change	After Change		
TFAD installation	9.233	6.487	2.746	109
Variable mode of the ventilation system (VAV)	9.233	6.122	3.111	124

Table 6 refers to the characteristics of the YTMMs, which are a combination of two seasonal thermal modernization measures. Their number is obtained according to the rule of combinatorics. Since the cold season includes three options, and the warm season includes two options, the number of YTMMs is six. The cost of energy in the cold and warm seasons were considered separately; however, in order to estimate the annual effect, these values must be considered aggregate. Energy demand before thermal modernization Q_0 and after Q_i, energy saving ΔQ_{cs} and savings K were obtained throughout the year. Thermomodernization measures related to partition insulation provide the greatest energy savings. At the same time, the greatest financial and energy savings were obtained from a combination of window replacement and the application of variable modes of the ventilation system.

Table 6. Annual energy and savings for YTMMs.

YTMMs Combinations of STMMs	Energy Demand, Q_0, GJ/Year	Energy Demand Q_i, GJ/Year	Energy Saving ΔQ_{CS}, GJ/Year	Savings K_i, EUR/Year
	Before Change	After Change		
Window replacement and TFAD installation	49.233	26.487	22.746	390
Window replacement and VAV	49.233	26.122	23.111	404
Wall thermal insulation and TFAD installation	49.233	28.487	20.746	362
Wall thermal insulation and VAV	49.233	28.122	21.111	376
Infrared heaters installation and TFAD installation	49.233	30.487	18.746	334
Infrared heaters installation and VAV	49.233	30.122	19.111	384

However, it is important to compare the investment costs, which may have a great influence on the total costs of the final choice of the modernization option. I_i is the investment cost of STMMs in the cold and warm seasons, and their sum is presented in Table 7, where, as well as economic indicators of combinations of STMMs for year-round operation, i.e., SPBT, NPVR and IRR are displayed. The highest investment costs for the warm season are related to the options where the walls are insulated, and it leads to the highest payback time of up to 6 years. The window replacement option is also characterized by high investment costs. Simultaneously, the differences in annual savings for these four options are not very diverse; however, the NPVR is negative for options involving window replacement. For the cold season, the option related to improving the U coefficient of the walls is more favorable in terms of both investment costs and payback time. Options for the modernization of heating and ventilation systems in the building are cheaper in terms of investment costs, and bring measurably large annual savings. Radiant heaters are nearly as energy efficient as TFAD devices. The payback time of these investments is very short, less than 1 year. However, examining the data presented in Table 7 for both seasons, it is clearly visible that the application of the system based on the two-flow air diffuser (TFAD) each time is beneficial.

Table 7. Economic indicators as an effect of thermal modernization for YTMMs.

YTMM	Investment Cost, I_i, EUR	Annual Saving K_i, EUR/Year	SPBT, Year	NPVR, EUR	IRR, %
Window replacement and TFAD installation	1904	390	4.9	−60	7.8
Window replacement and VAV	2006	404	5.0	−92	7.7
Wall thermal insulation and TFAD installation	2098	362	5.8	+1710	6.9
Wall thermal insulation and VAV	2200	376	5.8	+1778	6.8
Infrared heaters and TFAD installation	157	334	0.5	+1422	26
Infrared heaters installation and VAV	259	384	0.5	+1390	22

Energy costs are related to the costs of heat energy, electricity and refrigeration energy. The proper algorithm should be implemented in the building operation management system in order to provide reliable data for building electricity consumption management [75]. Since electricity in Ukraine is cheaper than thermal energy, it is obvious that the operating annual costs of electric heating and the use of electric infrared heaters will give the expected effect compared to a traditional heating system based on gas supply. Only questions of capital costs for installing the appropriate equipment arise. When estimating the cost of cooling energy, it is necessary to take into account the coefficient of performance of the refrigerating device. The cost of cooling energy is significantly higher than the cost of thermal energy. The cooling demand in the warm season is smaller than the heating demand in the cold season, but the costs of cooling are greater. Since the cost of the equipment of the corresponding ventilation systems should be taken into account, the question of the efficiency of these systems throughout the year is also of great interest.

In order to optimize both thermal engineering and cost-effectiveness across all solutions, optimal options for thermal modernization, as well as heating and ventilation systems, were identified. The year-round thermal modernization measures presented in Tables 6 and 7 are arranged vertically in order of increasing Simple Payback Time from minimum to maximum, and their cumulative effect is arranged horizontally, marked with a "+" sign. Additional measures for the new TMOs were highlighted (bolded) in Table 8. Various TMOs have been determined, namely:

- TMO I: Infrared heaters and TFAD installation;
- TMO II: Infrared heater installation and TFAD installation **+ VAV;**
- TMO III: Infrared heater installation, TFAD installation and VAV + **Window replacement;**
- TMO IV (as TMO III): Infrared heater installation, TFAD installation, VAV and window replacement (no measures added);

- TMO V: Infrared heaters installation, TFAD installation, VAV and window replacement + **Wall thermal insulation**
- TMO VI (as TMO V): Infrared heater installation, TFAD installation, VAV, window replacement and wall thermal insulation (no measures added).

Table 8. Optimization of combinations of STMMs.

YTMM	Thermal Modernization Options (TMO)					
	I	II	III	IV	V	VI
Infrared heaters and TFAD installation	+	+	+	+	+	+
Infrared heater installation and **VAV**		+	+	+	+	+
Window replacement and TFAD installation			+	+	+	+
Window replacement and VAV				+	+	+
Wall thermal insulation and TFAD installation					+	+
Wall thermal insulation and VAV						+
Indicators						
Investment cost I, EUR	157	357	2163	2163	4163	4163
Annual savings K, EUR	334	458	738	738	990	990
SPBT, year	0.5	0.8	2.9	2.9	4.2	4.2
NPVR, EUR	1422	1806	1324	1324	516	516
IRR, %	26%	22%	11%	11%	9%	9%

Table 8 presents the results of the annual savings and investment profitability indices, which were calculated based on the aforementioned methods (see Section 2.1) and the optimization methodology described in [2,5].

The NPVR for the option with wall insulation had the lowest value of all optimization combinations due to the high investment costs. The IRR value for this investment was 9%, above the recommended value of 8%, which means that despite the high expenses, the investment is still profitable.

The economic indicators resulting from the TMO search (Table 8) show that the most profitable annual thermal modernization option is the aggregation of the installation of infrared heater and a two-flow air diffuser (TFAD) with variable mode of the ventilation system. The economic effect in terms of NPVR is the highest, due to energy saving of this optimal thermal modernization option over the normative 15 years.

This type of analysis is particularly significant nowadays when society is focused on environmentally friendly solutions, the prices of energy carriers change dramatically and decision processes require the consideration of many options in order to find the most optimal solution. The method described makes it easy to determine the benefits of the improvements applied for the entire year, taking into account both the cold and warm seasons. The method is based on popular and well-known indicators, and is easy to implement. This tool does not require a large amount of data, and allows for the elimination of unacceptable solutions that are not subject to detailed and more complex economic analyses.

The application of more complex methods [76], like whole-year energy simulations in the evaluation of building performance combined with complex economic evaluations of the investment, requires the involvement of additional energy simulation specialists and economic analysts, thus affecting the cost of such analyses and, ultimately, the proposed solution.

4. Conclusions

In many studies on lowering energy demand in buildings, thermal modernization measures are considered seasonally. For the cold season, these activities focus mainly on the building envelope, the heating and DHW systems, and heat sources, while in the warm season, the focus is on the ventilation system.

This work presents a new approach that allows users to determine, by the highest value of the NPVR, the economic efficiency of thermomodernization options as aggregated modernization activities, not only in the cold and warm seasons separately, but throughout the whole year. Our analysis eliminates thermomodernization options that are unacceptable or uneconomic, or not subjected to detailed sensitivity analyses.

This analysis was carried out in order to examine a new approach and to determine the optimal thermal modernization option based on a comprehensive consideration of the thermal modernization measures for the production building. Initially, seasonal thermal modernization measures for the cold and warm seasons were proposed separately. The options included wall insulation, window replacement, the installation of infrared heater, the installation of a two-flow air diffuser (TFAD) and VAV. A combination of measures for the warm and cold seasons, which create year-round thermal modernization measures, was proposed. Then, yearly cost savings and energy savings were calculated. The most profitable options were window replacement and the installation of VAV in the ventilation system by application of an integrated actuator, resulting in annual savings of 21.111 GJ of energy and 376 EUR. However, both radiant heaters and TFADs are nowhere near as investment cost-consuming as window replacement and wall thermal insulation, so an economic analysis was utilized. The economic analysis of the thermal modernization options followed the methods recommended by the United Nations Industrial Development Organization. Finally, the undertaken calculations led to the development of the optimal option in terms of the highest NPVR value. In the analyzed case, in order to decrease costs and energy usage, infrared heaters and the installation of a TFAD with a variable air volume ventilation system were recommended. Simultaneously, the Simple Payback Time for this option was less than one year. Additionally, the installation of a TFAD brings benefits in terms of economics and comfort for building users.

In future research, it is suggested that thermal modernization measures to reduce energy consumption for cooling buildings should be investigated. This is especially important in industrial facilities where heat gains in summer can be significant. Predicting energy consumption for different geographical zones and different building types under the proposed approach can also be further explored. Thus, it is necessary to take a year-round approach and define year-round indicators for evaluating thermal modernization investment in respective geographical zones.

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