

Advantages of using insulation with lower thermal conductivity versus WT 2021 – comparison of the costs of materials, buying and operating a heating device, and a carbon footprint generated

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Abstract:

This article presents a comparative analysis of the use of standard insulation material compliant with the current Technical Conditions WT 2021, compared to insulation material with improved thermal conductivity parameters on building partitions. The information collected shows the impact on construction costs and the facility's carbon footprint during operation for the two solutions analysed. The main objective of the study was to identify the differences between the two options and to evaluate the cost-effectiveness of choosing the most advantageous result in economic and environmental terms, i.e. insulation material with optimal thermal conductivity parameters. For research purposes, information on a completed architectural project was used. This is a single-family house in which the recommended thermal insulation with optimal thickness and thermal conductivity parameters was used. The study enabled calculating the pay-back period and comparing CO₂ emissions over ten years. The data presented, showing the benefits of choosing a sustainable solution, can serve as recommendations for the design of new buildings, but also represent potential for the thermal modernisation of existing architectural facilities.

Keywords:

thermal insulation, energy efficiency, building maintenance, carbon footprint, pay-back period

1. Introduction

Global warming and climate change are currently among the most critical and urgent issues facing the world [1]. The global economy is highly dependent on the exploitation of fossil fuels [2,3]. The building sector is a significant contributor to energy consumption, which is associated with the use of fossil fuels and accounts for up to 33% of global carbon dioxide emissions [4,5]. The development of energy-efficient construction is one of the European Union's main goals, with a recommendation to achieve climate neutrality in this sector by 2050 [6].

The growing need to reduce the destructive impact of human activity on the environment obliges designers and investors to use higher-quality, environmentally friendly building materials [7]. Materials affect the natural environment already from the stage of the extraction of resources and the production of goods. Environmental protection through the use of appropriate building products involves using low-processing building materials, materials that prevent heat loss during building operation, and materials that can be recycled or removed with minimal energy in the final phase of a building's life cycle [8,9]. Despite the creation of numerous modern materials that fulfil all construction requirements, traditional products well known to most building contractors are still used, maintaining standard construction costs for the execution of works. Unfortunately, a significant portion of insulation materials has a major impact on the environment, health, energy consumption during their production, and costs incurred [10,11]. One of the most commonly used insulation materials is polystyrene foam, due to its relatively low production costs and uncomplicated manufacturing process [12-15], but also mineral wool [16]. Investors who want to protect the environment can opt for standard materials with significantly

better quality coefficients [17], which will also contribute to climate protection. Choosing a building material with a low thermal conductivity coefficient is a basic approach to improving thermal comfort in a building [18,19].

At the same time, economic considerations make it necessary to strive for the use of sustainable materials, whose purchase and maintenance costs will be the most optimal. Among all building materials used in construction, insulation materials contribute to the building's overall structure, enhance thermal comfort in interior spaces, and significantly affect energy consumption during building operation [20,21]. The payback period for insulation purchases is one of the main economic indicators for determining the optimal insulation thickness [22].

There are many aspects of construction and architecture that need to be considered at the design stage to minimise a building's maintenance costs and reduce the negative impact of the building sector on the environment [23], and proper insulation of a structure is a significant step in this process. Choosing the optimal insulation for walls and roofs reduces energy consumption and carbon dioxide emissions during the building's operation [24,25]. By reducing a building's operating costs, designers and investors also contribute to environmental protection [26,27]. Building is seen as one of the most cost-effective sectors where energy use can be reduced, and carbon dioxide emissions lowered [28].

2. Materials and methods

The purpose of the research was to identify the advantages and disadvantages of insulating building partitions with improved insulation materials, to evaluate the investment return in the case of using one of the solutions, and to assess the impact

on the natural environment. The calculations carried out at the stage of selecting insulation with specific thermal parameters were intended to support the decision-making process of the co-designer and investor regarding the selection of the best solution in economic and environmental terms; to support the development of research enabling the mitigation of the effects, adaptation and mitigation of climate change. The calculations relate to a building located in Poland (situated in a temperate climate zone of the warm transitional type). The aim of the balancing was to assess whether the use of a thermal insulation layer with improved thermal performance would contribute to a return on investment and reduce subsequent operating costs. Research into the economics and environmental performance of insulation materials with improved thermal conductivity shows solutions that improve the energy efficiency of buildings and the use of renewable energy sources (RES). They present the economic advantages of the investor's choice of specific solutions.

The multi-criteria analysis indicates the most optimal decision in terms of economics and the environment. The multi-criteria analysis enabled the identification, comparison, and selection of the most advantageous option [29,30]. The choice of the indicated research method enabled the selection of a sustainable thermal insulation option for a single-family residential building. At the beginning of the study, the average prices of specific products across different quality variants were expressed in terms of the material's thermal conductivity parameter. Current prices of building material manufacturers and the practical knowledge of the author of this article were used. After that, the results were compared with data on the costs of purchasing technical infrastructure components, like a heat pump for the building. The collected data were used to create a graph showing the return on investment in better insulation materials and another illustrating the differences in carbon dioxide emissions. Based on the research, conclusions were drawn and the optimal solution for the indicated facility was selected. The results of the research presented in this article can be an important guideline for the design of new building projects and the thermal modernisation of architectural facilities.

2.1. Description of the building under study

The research objectives presented in this article were achieved by conducting research on a completed single-family residential building located in Poland, in the Poznań County (Fig. 1). The building was designed in 2022 by Diana Wólczyńska, Wiesław Skrzypczak and Patrycja Zawiska, author of the article. It was commissioned in 2025. The building has a usable area of 122 m², a simple structure with a 45-degree-pitched roof, large glazed areas on the façade, and a living room with a cathedral ceiling. The building is heated by a heat pump with underfloor heating distributed throughout the entire floor area, and ventilation is provided mechanically through a recuperation system.

2.2. Comparative analysis of building insulation materials, including prices in the first and second solutions

The single-family residential building was insulated with thermal insulation materials with very low thermal conductivity. A comparison was made between the basic thermal insulation solution that complies with the requirements of Technical Conditions WT 2021 and a solution involving the use of insulation materials with significantly improved thermal coefficients λ . A comparative analysis was made of the prices of insulation materials of equal thickness, but with different thermal conductivity coefficients.

Table 1 summarises data on the insulation of building structures with insulation materials in two solutions, indicating the i – insulation thickness and s – size of the building partitions and providing detailed information on thermal conductivity parameters and material prices, where: λ_1 – thermal conductivity coefficient lambda of the insulation material in solution 1 and λ_2 – the same in solution 2; m_1 – average unit price per 1 m² of insulation material in solution 1 and m_2 – the same in solution 2; p_1 – total purchase price of insulation material for the building in solution 1 and p_2 – the same in solution 2.

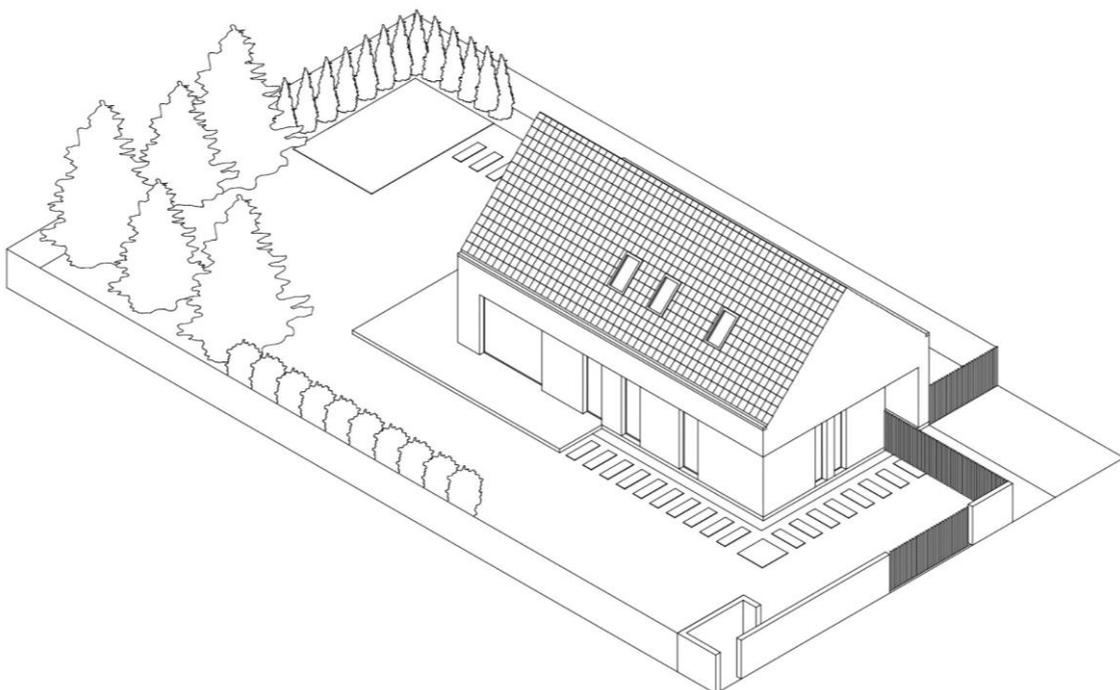


Fig. 1. Aksonometry of the building concept

Table 1. Average costs of purchasing insulation materials for building partitions, based on prices of building material suppliers

building partition	insulation material	i [m]	s [m ²]	λ_1 [W/(mK)]	λ_2 [W/(mK)]	m ₁ [PLN]	m ₂ [PLN]	p ₁ [PLN]	p ₂ [PLN]
external wall at ground level	EPS 100 aqua polystyrene foam	0.15	45	0.038	0.031	42.15	51.45	1896.75	2315.10
		0.20	50	0.040	0.031	41.49	55.10	2074.50	2755.17
external wall	EPS 100 polystyrene foam	0.22	125	0.040	0.031	44.20	62.96	5524.58	7870.00
		0.10	90	0.038	0.031	24.80	39.40	2232.30	3546.00
ground floor	styrofoam concrete	0.10	90	0.060	0.060	44.00	44.00	3960.00	3960.00
		0.08	60	0.040		19.94		1196.40	
floor	EPS 100 polystyrene foam	0.28	90	0.040	0.032	57.44	107.63	5169.30	9687.00
		0.32	40	0.040	0.032	49.36	94.41	1974.40	3776.40
roof	mineral wool								
sum								24028.23	35106.07

2.3. Comparative analysis of annual energy consumption, operating costs and carbon dioxide emissions during heat pump operation for the solutions 1 and 2

2.3.1. Heat pump purchase cost

During the planning of the investment, an important stage of the work is the selection of a heat pump. The EP value of the building is an important factor, which depends, among other things, on the quality of the insulation system used in the building partitions. Heat pumps are characterised by varying power, which has an impact on the cost of purchasing the device. A heat pump with a higher power output is more expensive. Buying a heat pump with a lower wattage means lower costs for the investor. For the purpose of this article, air source heat pump prices were compared depending on the power of the heat pump, assuming the same unit parameters with an indoor and outdoor installation and a 200-litre water buffer. The costs of the device, excluding installation, were compared. The results clearly show that the average equipment purchase price is significantly lower when purchasing a heat pump with a lower power output. In addition, Poland currently offers a partial grant for the purchase of heat pumps for buildings with a low EP index not exceeding 55 kWh/(m² × year), i.e. low-energy, passive, zero-energy and positive-energy buildings. The „Moje Ciepło” priority programme is implemented with funds from the Modernisation Fund, a new European Union instrument in meeting EU targets.

The proposal to use a thermal insulation system with lower thermal conductivity coefficients made it possible to install a heat pump with lower power than in the case of insulating the building with thermal insulation with basic thermal conductivity parameters meeting the minimum requirements of Technical Conditions 2021 WT 2021. The products available on the market are characterised by very different prices. For the purposes of the calculations, three products from different reputable heat pump manufacturers were compared. The average purchase price of the devices without installation was then calculated for 7 kW and 8 kW pumps (Table 2).

Table 2. Average purchase costs for heat pumps with a power rating of 7 and 8 kW, based on manufacturers' prices

heat pump power [kW]	product 1 [PLN]	product 2 [PLN]	product 3 [PLN]
7	36229.00	23900.00	28400.00
8	44679.00	19444.00	35162.00

The following table (Table 3) shows the total cost of purchasing a heat pump for solutions 1 and 2, including the possibility of obtaining a government subsidy.

Table 3. The purchase price of the heat pump, including the possible government subsidy, is based on manufacturers' prices

heat pump power [kW]	average price of a heat pump [PLN]	maximum grant amount [PLN]	average purchase price of a heat pump with government grant [PLN]
solution 1	33095.00	none	33095.00
solution 2	29509.67	7000.00	22509.67

The final purchase price of a heat pump depends not only on the price of the product but also on the amount of subsidy that can be obtained. Due to the introduction of a limit on the EP value of a building as a criterion for receiving a subsidy for the purchase of a heat pump, it has been found that houses with low energy requirements and, therefore, cheaper heat pumps with lower power ratings have a better chance of obtaining a subsidy.

2.3.2. Electricity consumption, operating costs incurred and carbon dioxide emissions generated by a heat pump

For research purposes, the energy consumption values, operating costs and carbon footprint of the heat pump in solutions 1 and 2 were compiled. Considering that a 7 kW heat pump operates at an average COP¹ of 4 and runs for 6 hours a day during the heating season for a period of 6 months², the average annual consumption will be 1921.5 kWh. In contrast, for an 8 kW

¹ COP (Coefficient of Performance) value is a measure of the efficiency of heating and cooling systems. The value represents the ratio of usable power to energy consumption. The higher the COP value, the more economical the system is [31].

² It is assumed that the average heating season in Poland lasts from September to May [32]. The calculations take into account the most intensive pump operation from December to February and assign

a weight of 1 to the calculations. The months from September to November and March to May are assigned a weight of 0.5. The average heating period for homes is 6 months. As the demand for heating in December (average 12 hours) is higher than in September (average 1 hour), a constant average of 6 hours of intensive operation was assumed for the 6-month period.

pump, the average annual consumption under similar conditions will be 2196 kWh.

In Poland, the average price per kilowatt-hour as of 10 June 2025 is PLN 1.02³. The price is currently lower due to government regulations. For the purposes of this article, the actual average current price per kWh of electricity set by the seller was used in the calculations. The CO₂ emission factor per kilowatt-hour is variable and depends, among other factors, on the amount of renewable sources used in energy production. This article uses the average CO₂eq/kWh emission in Poland in 2024, which is 652 g [A], for its calculations. The table shows the consumption of tonnes of carbon dioxide in subsequent years of use of the investment for the first and second solutions.

The Table 4 presents data on megawatt-hour consumption, operating costs and carbon dioxide emissions for each year over a ten-year period of use of the investment, where sn1 – solution 1, sn2 – solution 2, e – heat pump energy consumption, c – cost of heat pump energy consumption, CO₂ – amount of carbon dioxide produced.

The Table 4 displays a systematic increase in electricity consumption, rising operating costs of the facility, and carbon dioxide emissions in subsequent years of use. Solution 2 is characterised by significantly lower values for all analysed criteria.

For the purposes of this article, the costs of purchasing insulation materials, heat pumps and operating equipment were calculated using a simplified method. Presenting the costs over a ten-year period made it possible to determine the return on investment and the upward trend. No calculations were made for

the thirty-year life of the building because they were not needed for the study specified at the beginning of the article, i.e., calculating the costs of retiring the building from service or demolition.

It was assumed that for a ten-year investment period, the service life of the building's systems and parts, while maintaining maximum care during construction works (related, for example, to ensuring good water quality in the heating system; protecting polystyrene and wool from water, which reduces insulation efficiency), but also minor repair work during the operation of the facility (e.g. replacing window seals) would enable the fixed operating costs of the facility to be maintained.

2.4. Research results

The data regarding the purchase of insulation materials, heat pumps and the operating costs of the devices over a period of 10 years, shown in Tables 1-4, have been summarised.

Figure 2 shows the pay-back period for the purchase of insulation materials, heat pumps and operating costs for solution 2. The payback for using better building insulation will occur within just 2 years. Over a period of ten years, there is also an increasing difference in the operating costs of heat pumps between the implementation of solutions 1 and 2. The use of solution 2 will reduce the investment's maintenance costs.

The following Figure 3 shows the forecast carbon dioxide emissions for solutions 1 and 2.

Table 4. Consumption of megawatt-hours, operating costs and carbon dioxide emissions during subsequent years of heat pump operation for solutions 1 and 2. Source: Author's study based on publicly available information: average CO₂ emissions in Poland, CO₂ emissions calculator [A, B]

year	1	2	3	4	5	6	7	8	9	10	
sn1	e [MWh]	2.196	4.392	6.588	8.784	10.980	13.176	15.372	17.568	19.764	21.960
	c [PLN]	2239.9	4479.8	6719.7	8959.7	11199.6	13439.5	15679.4	17919.4	20159.3	22399.2
	CO ₂ [t]	1.43	2.86	4.29	5.72	7.15	8.58	10.01	11.44	12.87	14.30
sn2	e [MWh]	1.9215	3.843	5.7645	7.686	9.6075	11.529	13.4505	15.372	17.2935	19.215
	c [PLN]	1959.9	3919.9	5879.8	7839.7	9799.7	11759.6	13719.5	15679.4	17639.4	19599.3
	CO ₂ [t]	1.25	2.50	3.75	5.00	6.25	7.50	8.75	10.00	11.25	12.50

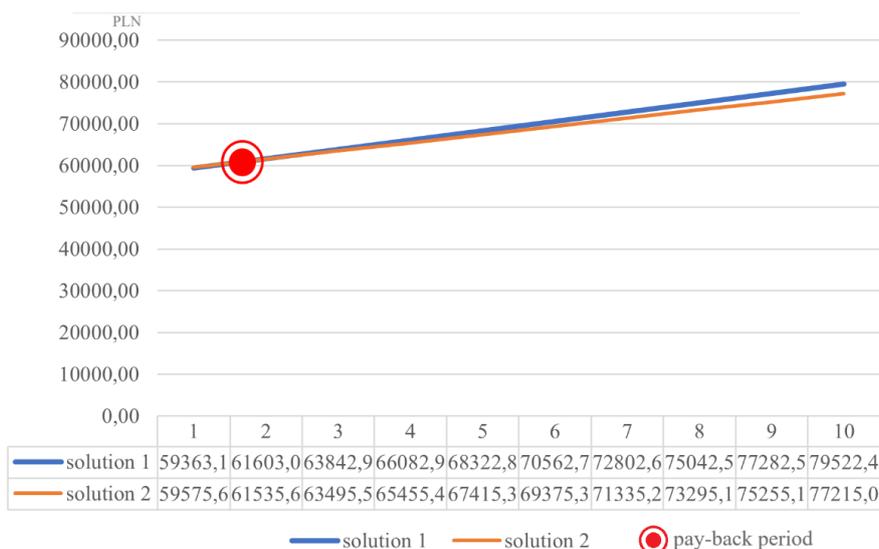


Fig. 2. The pay-back period for investing in better insulation materials and operating the facility. Source: author's work

³ The price of electricity as at 10 June 2025 was determined on the basis of the average rates (applicable in the first quarter of 2025) of

the five main electricity suppliers in Poland [C].

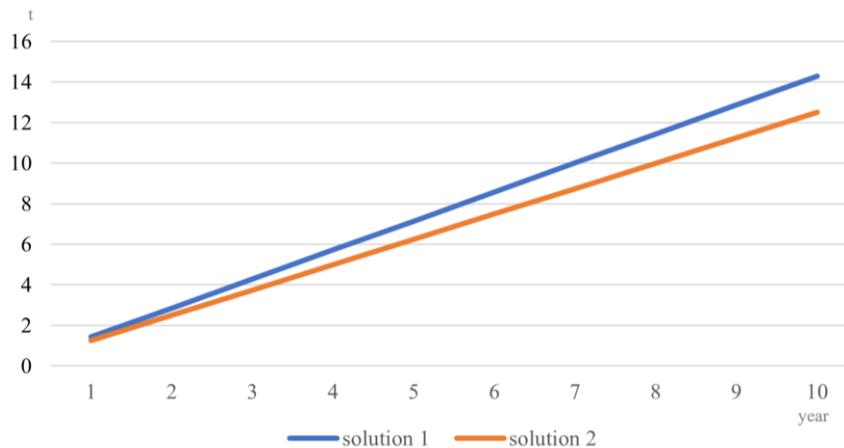


Fig. 3. Predicted carbon dioxide emissions during heat pump operation in solutions 1 and 2. Source: Author's work.

The implementation of solution 2 will contribute to improving environmental protection. Figures 2 and 3 show the same trends and increasing differences between the application of solutions 1 and 2 over the years.

The use of insulation with optimal thickness and thermal conductivity parameters will contribute to reducing energy consumption, limiting the burning of fossil fuels and carbon dioxide emissions into the atmosphere [33].

This study was conducted using average prices for building materials and energy. As price fluctuations in various areas of the construction sector and energy prices are difficult to predict, the environmental impact of both options was also analysed, which allowed for the final selection of option 2 for the implementation of the investment.

3. Discussion

Research shows how recommending the use of insulation with better thermal performance contributes to a return on investment and reduces subsequent operating costs for the building. The choice of insulation material is one of the most important and complex decisions when designing buildings located in climates characterised by frost or heat. There are a number of traditional and modern insulation materials, including polystyrene, mineral wool, wood wool, and also products with cellulose, rice husks, etc. Furthermore, these materials have different thermal conductivity coefficients, with polystyrene, for example, having the potential to achieve very low thermal conductivity compared to natural insulators [34]. The thermal conductivity coefficient itself is an important quality parameter in the decision-making process when selecting insulation material for a building.

This article highlights the positive aspects of using lower thermal conductivity values in the application of traditional insulation materials (including polystyrene and wool), thereby enabling better economic and environmental decisions.

The advantages of using insulation with lower thermal conductivity parameters have also been noted in other studies. These include calculations concerning the reduction of a material's thermal conductivity coefficient, which leads to the classification of a building with a better energy standard and the obtaining of subsidies for construction, followed by a quick return on investment [35]. Researchers pay particular attention to the length of the return on investment. If the investment would pay for itself after several decades, it is not worth investing in better insulation materials [36].

Studies also point to the positive effects of increasing thermal insulation thickness, with energy costs gradually decreasing as the insulation thickness increases. Of the choice of materials between EPS, PU and XPS, it is EPS that has the shortest return on investment when purchasing better quality material. At the same time, negative aspects related to the possibility of increasing the thickness of the insulation layer too much, which only leads to increased costs, are pointed out. It is suggested to look for the optimal solution regarding the thickness of the façade [37].

Studies show that increasing the thermal insulation of a building or using insulation with better coefficients reduces dependence on HVAC equipment (air conditioning and heating) and contributes to energy savings [38].

4. Conclusions

Research conducted on the described building, including: estimation of average current prices of building materials and purchase of a heat pump; multi-criteria analysis of the application of the first and second solutions; determination of the pay-back period for the purchase of insulation materials with improved thermal conductivity parameters, together with a forecast of the carbon footprint during the operation of the heat pump, allowed the following conclusions to be drawn:

- The use of insulation materials of similar thickness but with superior thermal parameters initially involves higher purchase costs, which are recouped during the life cycle of the building [36,39].
- The use of building materials with better parameters has an impact on the natural environment and enables climate protection [40,41].
- The use of insulation materials with improved thermal parameters makes it possible to achieve a better energy class and contribute to climate neutrality.
- Attention to the economic aspects of the purchase costs of insulation materials and installation in the facility is closely related to the impact of the building on the natural environment [42].
- The purchase price of a heat pump depends on the power at which it must operate. Designers and investors should consider the cost-effectiveness of using higher-performance insulation materials to reduce total investment costs, including the purchase price of the heat pump and operating the facility.
- The purchase price of a lower-power heat pump is lower, and the current subsidies are much easier to obtain if the

building's demand for a lower-power heat pump is satisfied.

- The optimal choice of insulation thickness and thermal conductivity parameters is an appropriate design practice for newly designed buildings and those undergoing renovation and thermal modernisation in order to achieve economic and environmental benefits [43,44].
- The necessity to reduce energy consumption and carbon dioxide emissions is becoming an essential change in thinking when developing new concepts in architectural design [45,46].
- The presented studies reflect and are consistent with the current construction and energy policy in Poland. They present solutions that support the development of renewable energy sources and improve building energy efficiency. They promote efforts to achieve energy neutrality in buildings by 2050 and support research to mitigate the effects of climate change and adapt to it.
- The research shows the multitude of economic and environmental benefits of using insulation materials with higher thermal conductivity. It can provide valuable information for designers of buildings, along with the opportunity to present the benefits of using better solutions to investors.

The presented research demonstrates the relevance architecture and construction solutions. The form of the building, function (purpose and how it is used), the selection of the optimal technical options for the building (including structure, the latest technological and environmental innovations, etc.), contributes to the creation of a high-quality facility.

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