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Climate-neutral historic buildings, Slowacki Theatre in Poland - case study

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Abstract. Global policy identifies achieving neutrality in sectors with the highest energy intensity rates as a priority for action. Countries are taking important and necessary measures to achieve this goal. The European Union has introduced a near-zero energy building standard in the construction sector. The next step is the Fit to 55 package, which is a milestone for Europe to achieve total neutrality in 2025. The climate-neutral policy has resulted in requirements and regulations already implemented in the sectors that consume the most energy and emit the most greenhouse gases. One such sector is construction, which accounts for around 40% of total energy consumption. Buildings newly designed in EU countries must now meet stringent thermal protection requirements. In Europe and Poland, governments are allocating substantial funds for the thermal modernisation of existing buildings. The exceptions to this are listed buildings and buildings under preservationist care. Such buildings are not subject to thermal protection regulations. In historic buildings, the priority is to protect the national heritage. However, the recent Energy Performance Directive introduced, for the first time, a recommendation that historic buildings should also be investigated for energy efficiency measures, under strict protection of the historic character of the building, of course. In this article, the authors present an analysis of a historic building of great historical significance. It is the Słowacki Theatre in Krakow. The research question the authors answer in their analysis is whether and how a historic building can be brought to a level of zero energy and climate neutrality. The second research question is whether, in addition to aspects related to energy saving and reducing greenhouse gas emissions, other aspects of designing the improvement of the historic building and its surroundings should also be considered in the analysis. The results of the authors' analysis indicate that a building level of near-zero energy demand can only be achieved for a listed building if the building undergoes thermal modernisation measures approved by the conservation officer and then the heat source is replaced with biomass or a heat pump powered by photovoltaic panels. To the aspects related to the preservation of the historical heritage, the improvement of energy efficiency and the reduction of CO_2 emissions, the authors propose to include aspects related to the comfort of use of the building and aspects

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related to the accessibility of the building for people with special needs (the elderly and people with disabilities).

1 Introduction

Improving energy efficiency in economic sectors, especially those with the highest energy intensity rates, is now a priority worldwide. Climate change causes catastrophic consequences for the Earth such as earthquakes, fires, droughts, floods, hurricanes, melting glaciers. Climate disasters have led to the death of many lives and are contributing to the extinction of animal and plant species. To prevent climate disasters, it is necessary to reduce greenhouse gas emissions and promote sustainable development. This requires action at global, national and local levels and international cooperation to find solutions to this serious problem. Europe has long been taking action to help halt rapid climate change in the future. A landmark document of the European Parliament was Directive 2010/31/EU [1]. In this document, the definition of a new building standard was introduced, namely near-zero energy buildings (so-called nZEB). According to the definition, such a standard means a building with very high energy performance in which a significant part of the energy should come from renewable sources. In accordance with the provisions of the Directive, measures taken to reduce energy consumption in the European Union, accompanied by an increase in the use of energy from renewable sources, would enable the Union to comply with the Kyoto Protocol to the United Nations Framework Convention on Climate Change (UNFCCC), to meet its long-term commitment to keep the global temperature rise below 2° C and to reduce its overall greenhouse gas emissions. The topics of energy consumption and emissions of harmful compounds in the aspect of entire residential areas were presented in the paper [2]. The near-zero energy building standard is mandatory for all newly designed buildings from 2021 and for buildings undergoing deep thermal retrofitting. Historic buildings have been exempted from the need to improve energy performance. Here, historical values and the protection of national heritage must come first.

For the purpose of this article, the authors undertook the difficult task of determining to what level the energy performance of a listed building can be improved without compromising its historical value. At the same time, the authors have carried out an analysis in this article to answer the question of whether a historic building can be a climate-neutral building. Additional arguments for the development of optimal methods to improve the energy efficiency of historic buildings while preserving their historic qualities include the first provisions in the 2018 Energy Performance of Buildings Directive [3]. For the first time, the EPDE Directive introduced a provision for historic and conservation-led buildings "Research into and testing of new solutions to improve the energy performance of historic buildings and structures should be promoted, while at the same time ensuring the protection and preservation of cultural heritage." Under the directive, member states have started to implement its provisions in national legislation.

In addition to aspects related to the preservation of a building's historical heritage, minimisation of energy consumption and minimisation of greenhouse gas emissions, the authors propose additional criteria for the assessment of historic buildings. The criteria proposed by the authors are a criterion for ensuring the comfort of the building and a criterion related to accessibility for people with special needs, the elderly and people with disabilities. This is an innovative approach to the design of activities in historic buildings so that they can achieve a level of climate neutrality and at the same time be user-friendly buildings. Fig. 1 shows the criteria proposed by the authors that need to be taken into account for measures to achieve climate neutrality of a heritage building.

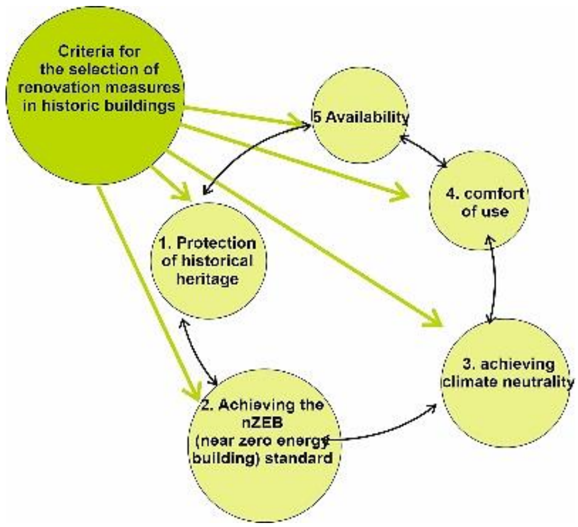


Fig. 1. Criteria proposed by the authors that must be taken into account when working towards the climate neutrality of a historic building (authors' own source).

2 Methodology

2.1 Protection of historical heritage

Historic buildings are a unique group of buildings that should be treated with special respect for history. They are our cultural heritage and we should make every effort to keep their appearance intact. This is particularly important in the case of the shape and massing of the building, which show us how our ancestors built and the choice of materials that were originally used to construct the building, and knowledge of these tells us about the availability of building materials, preferences or experience in building our ancestors. Equally priceless are the paintings, frescoes and sculptures that are manifestations of historical artistry and often chronicle our history. In Poland, it is customary to define a historic building as one that is more than 50 years old. This was the law before World War II. Legally, the concept of a monument is defined in the Act of 23 July 2003. A monument is an element of heritage according to the conventions ratified by Poland, including the UNESCO Convention concerning the Protection of the World Cultural and Natural Heritage, the UNESCO Convention concerning Intangible Cultural Heritage of 2003 and later. Any building can become a monument, but it must be of outstanding importance for the history or time in which it was built. Therefore, buildings erected in the 1930s or 1960s may become monuments. The youngest Polish monument in terms of the period of its erection is a wooden chapel in Mazovia, erected a dozen or so years ago. This object shows the characteristics of the architecture of the period. At the same time, bearing in mind the national good, we are obliged to prevent its destruction through possible and consistent with the conservator's recommendations repair actions, improving the technical condition of the monuments. When a historic building is out of use or a change of use function is planned, a Strategic Plan for the Conservation of the Historic Monument should be developed. This plan, on the basis of preliminary studies, should determine the essential role of the monument, and a possible safe social function, e.g. an object of representative character intended for museum functions and limited use, a permanent ruin acting as a tourist attraction, an object possible to give a public function. The strategic plan is a concept for the management of the site with a preliminary version of the conservation project, defining the full issues associated with it and including indications of, for example, the types of research and expertise needed to identify it. Another indispensable document in the case of planning modernisation measures in a historic building is the Conservation Design developed on the basis of a conservational analysis of the results of multidisciplinary research. Only on the basis of the results of the research can the scope of conservation and restoration activities necessary to preserve the historic features of the historic building be determined. The conservation and restoration tasks should include the object's surroundings, the object itself and its furnishings.

2.2 Achieving the nearly zero energy demand building (nZEB) standard.

At the end of 2020, around 80,000 listed buildings and areas were entered in the Register. In addition to the Register of Historical Monuments, communal and provincial registers are kept, which include as many as ca. 700 thousand objects [5]. Monuments are divided into groups of immovable, movable and archaeological monuments.

Given the very large number of listed buildings and the fact that they were constructed in different years when most did not have thermal protection regulations, listed buildings represent a huge potential for reducing heat and electricity consumption. At the same time, historic buildings constructed over centuries are often in a poor state of repair, which can accelerate the process of degradation and destruction. Every effort should therefore be made to improve the technical condition of the buildings. All repair and thermo-modernisation measures must respect historical values and protect national assets. The Nearly Zero Energy Building (nZEB) standard is regulated by the technical and building regulations in force in each European Union country. Buildings to achieve the nZEB standard must meet two criteria. The thermal insulation coefficients of the building envelope must be equal to or less than those shown in Table 1.

Table 1. Maximum thermal insulation coefficients of the building envelope for nZEB standard [4].

Housing component	U-value [W/(m^2 K)
External wall	0,20
Roof/ceiling	0,30
Floor on the ground	0,15
Windows	0,90
Doors	1,30

The second parameter is the non-renewable primary energy indicator EP [kWh/(m^2 a)]. The EP is calculated for heating, ventilation and domestic hot water, for cooling and for lighting. This parameter depends on the function of the building and may not be lower than the values given in Table 2.

Table 2. Maximum EP ratios$_{H+W}$ for the nZEB standard [4].

Purpose of buildings	ΔEP_{H+W}	ΔEP_C	ΔEP_L
		[kWh/(m^2 a)]	
Single-family residential building	70	$\Delta EPC = 5 - A_{f,C}/A_f$	0
Multi-family residential building	65		
Public utility building - healthcare	190	$\Delta EPC = 25 - A_{f,C}/A_f$	for $t_0 < 2500$ $\Delta EP_L = 25$ for $t_0 \geq 2500$ $\Delta EP_L = 50$
Other public buildings	45		
Storage buildings	70		

* $A_{f,C}$ - cooled area, A_f - usable area, t_0 - hours when using artificial light per year

Not all requirements for the nZEB standard are the same for newly designed buildings and buildings undergoing thermal upgrading. Table 3 shows which parameters new and thermo-modernised buildings and listed buildings must achieve.

Table 3. Parameters that buildings must meet from 2021 in Poland.

Building:	U-value [W/m^2 K].	EP indicator [kWh/m^2 year]
newly designed	mandatory	mandatory
Existing, thoroughly thermo-modernised	mandatory	not required
Historic, under conservation care	not required	not required

As shown in the table, historic buildings and those under the protection of the conservator are exempt from any requirements to improve energy efficiency. The provisions of Article 5 of the Act - Construction Law (consolidated text: Journal of Laws 2006, No. 156, item 1118 as amended) - exempt from the obligation to determine the energy performance for buildings subject to protection under the provisions on the protection and care of monuments. All buildings listed in the register of monuments are fully exempt from the obligation to determine their energy performance in the form of an energy certificate.

The authors in this paper have adopted their own nZEB standard for historic buildings. This is an innovative approach.

2.3 Achieving the climate neutral building standard.

In October 2022, the Council of Europe reached an agreement (general approach) on a proposed revision of the Energy Performance of Buildings Directive. The revision primarily serves to:

- by 2030, all new buildings are zero-emission
- existing buildings are converted into climate-neutral buildings by 2050.

The Council recognised that only a reduction in emissions - through greater energy efficiency or less energy consumption and the use of RES - would achieve climate neutrality by 2050 [6].

A climate-neutral building is a building that has no net emissions of greenhouse gases into the atmosphere over the course of a year. This means that the CO_2 emissions produced during the operation of the building (e.g. by heating, cooling, lighting, ventilation) are offset by reducing emissions or removing them from the atmosphere.

Extensive knowledge of both engineering, history and building physics is needed to develop a suitable methodology for working on historic buildings. Firstly, the most important criterion is conservation, but also supported by works that will keep the building in a good state of repair. Achieving low or zero energy intensity should be tailored to the capabilities of the building. Also, achieving neutrality should not be an overriding criterion. In contrast, the case study presented below on a building that is one of Krakow's most important monuments shows that the right choice of works allows for many possibilities.

The analysis has been carried out taking into account the methodology of standard EN 15978. The embedded carbon footprint is the sum of the greenhouse gas emissions that occur during life-cycle material flow operations (e.g. construction or reconstruction or demolition processes). It is the carbon footprint in the following life cycle stages: product phase: A1-A3, construction process phase: A4-A5, the use phase, modules B1-B5 and the end-of-life phase C1-C4. This is not a rigid definition. In the industry circulation, it is also possible to encounter a definition that includes only modules A1-A5. Table 4 shows the life cycle modules that should be included in the climate neutrality analysis of buildings. A major problem is the lack of available data for many products. The easiest way to estimate the Operational Carbon Footprint is directly related to the use phase of the building.

Table 4. phases of the life cycle of a building.

Product phase			**Process phase construction**		**Use phase**							**End of life phase**				**Benefits beyond the life cycle**		
A1 Extraction and supply of	**A2** Transport	**A3** Product manufacturing	**A4** Transport	**A5** Construction process	**B1** Use	**B2** Maintenance	**B3** Repair	**B4** Replacement	**B5** Renovation	**B6** Energy consumption	**B7** Water consumption	**C1** Demolition/demolition	**C2** Transport for disposal	**C3** Recycling	**C4** Disposal	**D1** Re-use	**D2** Recovery	**D3** Recycling
									X	**X**								
Built-in carbon footprint										Operational carbon footprint		Built-in carbon footprint						

This study was limited only to module B5 and, which shows the emissions associated with the product phase and transport from the construction process phase of the renovation and the B6 operational carbon footprint phase of the energy consumption. The emissivity factors used to calculate the production of materials were taken from the EPDs of products primarily from Poland and, where this was not possible, from European countries. Emission factors for transport were adopted from data published by DEFRA. Due to the lack of publicly available emission factors and national guidelines, the share of emissions related to the implementation of physical construction (retrofitting) works, such as travel of manual workers to the project site, or the use of energy and fuels for construction works was omitted. Due to lack of data, works and materials related to the retrofitting of lighting and ventilation systems were not analysed.

The study did not analyse the end-of-life phase modules of the building and individual materials. Given the expected life of the investment - at least 30 years, it was considered unreasonable to assess the disposal or recycling method in 30 years.

The operational carbon footprint for energy consumption was adopted based on energy analyses for the existing state and the proposed thermal upgrading of the building.

2.4 Building comfort

The comfort of buildings is of paramount importance to users. It should not be overlooked when planning thermo-modernisation measures. Among the many aspects of comfort, we can mention those presented in Fig. 2. Thermal comfort is very important and perceptible [7, 8]. Whether we feel hot or cold influences our wellbeing. However, other aspects of our comfort also affect how we feel. It is worth mentioning vibroacoustic [9] or lighting comfort and air quality comfort [10, 11, 12]. Thermo-modernisation and renovation measures for historic buildings should be preceded by comfort analyses. These measures should also take into account the improvement of user comfort in many aspects.

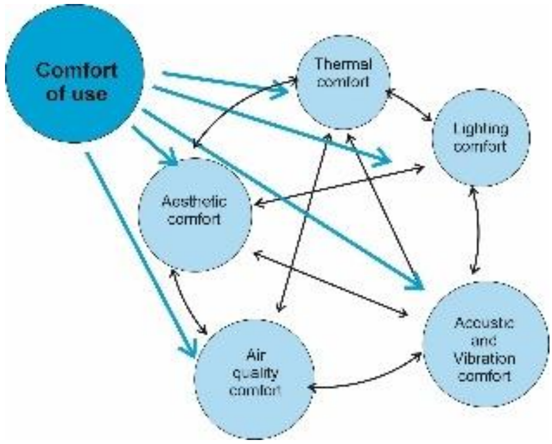


Fig. 2. Various aspects of comfort in historic buildings and their interrelationships (authors' own source).

2.5 Accessibility for people with special requirements.

Accessibility of buildings for people with special requirements is about ensuring that buildings and public spaces can be used by people with different types of disabilities. This means that the building should be adapted to the needs of people with disabilities so that they can move around and use the space without obstacles or restrictions.

The accessibility of buildings for people with disabilities covers many aspects, such as:

1. Entrance to the building - should be barrier-free, complying with accessibility standards and regulations so that people with disabilities can enter the building without difficulty.
2. Lift or ramp - if the building has more than one floor, it should be equipped with a lift or ramp that allows people with disabilities to move freely around the building.
3. Bathrooms - buildings should have bathrooms that are accessible to people with disabilities, such as grab bars, special facilities for wheelchair users, etc.
4. Wide doors - doors should be wide enough for wheelchair users to move freely through the building.
5. Height of handles and grips - handles and grips should be positioned at a height that allows easy access for people with disabilities.
6. Lighting - there should be adequate lighting in buildings to facilitate mobility for people with disabilities.
7. Public address system - buildings should be equipped with a public address system that allows communication for people with hearing difficulties.

All of these elements should be considered when designing buildings to ensure accessibility for people with disabilities and to create an even playing field for all.

3 Climate-neutral building with accessibility elements on the example of the historic Slovak Theatre in Krakow

3.1 Description of the building

The analysis was conducted on a historic theatre building located in south-eastern Poland in Krakow. The theatre was built in 1893. It is one of the most recognisable theatre stages in

Poland and abroad. From its inception, the theatre has been regarded as the cradle of Polish directing, stage design, staging and acting. The building is located on St. Spirit Square in Krakow. The location of the building is on an east-west line. Fig. 3 shows the west elevation of the theatre.

Fig. 3. Main entrance to the Theatre. West elevation (authors' own source).

A major refurbishment of the theatre was carried out in the 1980s. In addition to the renovation of the historic interiors, the replacement of installations, the installation of air conditioning and the construction of underground rooms were carried out. Thanks to the renovation work, the building has two additional underground storeys, completely sunk into the ground, with no access to daylight. The design of the underground floors was carried out by a team from the Cracow University of Technology. The underground floors house storage space, but also rooms such as tailoring, modelling and technical studios. Currently, the premises are in a very poor technical condition. Fig. 4 shows a view of the underground parts of the Theatre.

Fig. 4. The destroyed underground rooms of the Theatre, made in the 1980s (authors' own source).

The calculation of the floor area and volume was based on a design provided by the Theatre's management. The design was made using 3D scanning technology.

The usable area of the building is:

- Overground storeys: 3365.1 m^2 ,
- underground storeys: 5059.9 m^2

The volume of the building is (the figures given may be subject to error as the heights in the rooms vary):

- Overground storeys: 10864.1 m^3 ,
- underground storeys: 22479.7 m^3

An energy diagnostic was carried out for the Theatre. The uninsulated partitions, the roof and the windows with a low heat factor result in significant energy losses. In addition, the Theatre is equipped with heating and cooling systems but without an exhaust air heat recovery system. The building is supplied with heat and cooling from five gas furnaces. Fig. 5a shows the mechanical ventilation system of the Theatre. Fig. 5b shows the plates describing the heating system in the building.

(a) (b)

Fig. 5 a, b. Mechanical ventilation ducts without heat recovery. Gas boilers (authors' own source).

Lighting in the Theatre generates a large waste of electricity. Energy-intensive incandescent and fluorescent lamps are installed in the building. The theatre is in need of renovation and thermo-modernisation measures. The roof is completely uninsulated and the windows are in very poor condition. Fig. 6a shows the outdated lighting and Fig. 6b shows the uninsulated roof of the Theatre.

(a) (b)

Fig. 6 a, b. Energy-intensive lighting and the Theatre's uninsulated roof (authors' own source).

3.2 Energy performance - a building with near-zero energy requirements

Four energy performance calculations were carried out for the Theatre building:

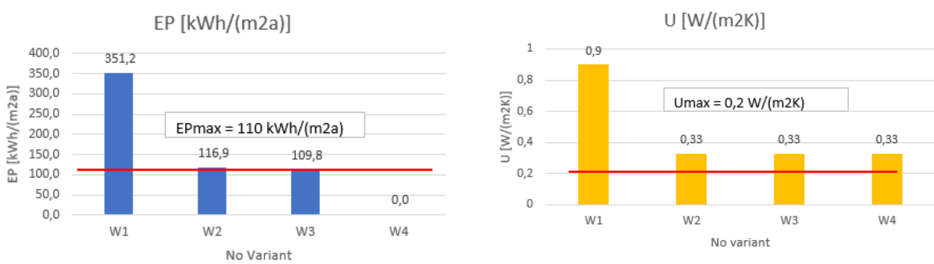
Option 1 - existing condition;

Variant 2 is a feasible option. Insulation of walls using a method adapted to historic buildings (U = 0.33 W/m^2 K) Due to the historic nature of the building, insulation of walls is foreseen on the inside only where possible. Replacement of windows with U = 0.9 W/m^2 K and insulation of soffits/roofs (U = 0.15 W/m^2 K), recuperation fitted to the mechanical ventilation system, replacement of lighting with LED.

Variant 3 - this is the variant that would achieve the standard of a building with almost zero energy demand for a building (nZEB) according to Polish regulations. Wall insulation using a method adapted to historic buildings (U = 0.33 W/m^2 K) Due to the historic nature of the building, wall insulation is foreseen on the inside only where possible. Replacement of windows U = 0.8 W/m^2 K and insulation of soffits/roofs (U = 0.11 W/m^2 K), recuperation fitted to the mechanical ventilation system, replacement of lighting with LED. In addition to the thermomodernisation measures for variant 2, it was proposed to insulate the underground storeys, to insulate the floor on the ground (U = 0.20 W/m^2 K) and to use skylights to illuminate the underground storeys, thus reducing electricity consumption for artificial lighting.

Variant 5 is a thermal modernisation measure similar to Variant 3, but replaces the gas boilers with an air-source heat pump powered by photovoltaic panels.

The results of the analysis for the EP I U coefficients are shown in Figures 7 a and b.



(a) (b)

Fig. 7 a, b. EP and U coefficients for the variants considered and limit values (authors' own source).

3.3 Climate-neutral building

A carbon footprint analysis was carried out for phase B5 (which includes information on emissions from phases A1-A4) and for phase B6 on the operational carbon footprint depending on electricity and heat consumption. The calculations were carried out for a period of 30 years. Fig. 8 shows the results of the calculations.

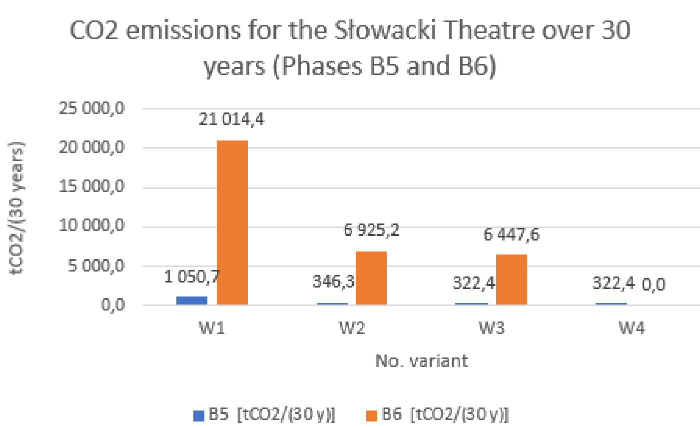
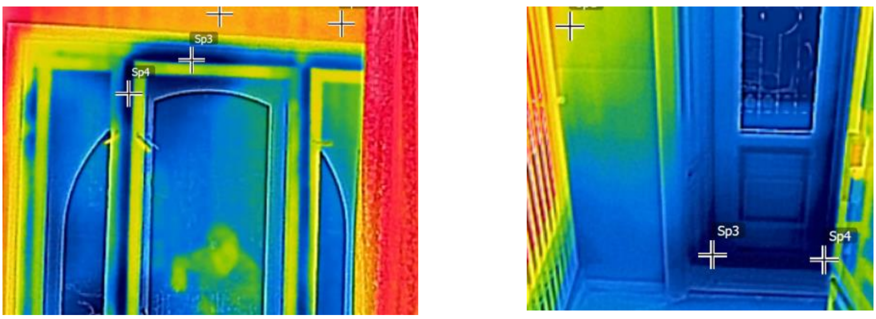


Fig. 8. Results of CO_2 emissions calculations for the options considered (authors' own source).

3.4 Utility comfort

User comfort is an important aspect in improving the energy efficiency of historic buildings. In order to correctly identify the needs of users, it is necessary to carry out an analysis based on questionnaires or interviews with people who are in the building under study. The research team interviewed the users of the Słowacki Theatre and it became clear that the employees felt thermal discomfort and those working in the underground spaces visual discomfort due to being in rooms without access to sunlight. In order to take ad hoc measures to improve these two aspects of discomfort, the research team carried out a thermal imaging inspection to identify leaks in the building envelope. The leaks are the cause of excessive heat loss, cold sensations or draughts during autumn and winter by the Theatre staff. Fig. 9 shows an example of the results of the "in situ" tests.



(a) (b)

Fig. 9. Leakage in window and external door assembly (authors' own source).

The report carried out by the researchers identified areas in the building envelope that need to be sealed to improve thermal comfort on an ad hoc basis, prior to thermal upgrading measures.

To improve the lighting/visual comfort due to the lack of daylight access to the underground floors, the research team proposed the use of skylights/lighting windows made in the ceiling of the underground floor where the Theatre staff work. The window proposals are shown in Fig. 10.

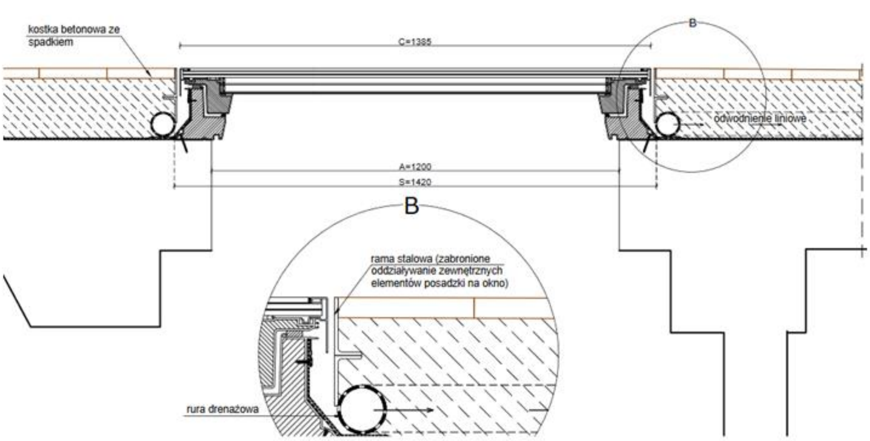


Fig. 10. Proposal for illumination of underground storeys (authors' own source).

3.5 Accessibility for people with special requirements

The Słowacki Theatre in Kraków is a good example of how a historic building can be adapted to meet the needs of older people and people with disabilities. The theatre is implementing the project 'Accessible Juliusz Słowacki Theatre - improving the accessibility of the theatre's cultural offer', funded by a 'Culture without barriers' grant. The main aim of the project is to improve the accessibility of the cultural offer of the Juliusz Słowacki Theatre in Krakow. Thanks to the project, it will be possible to ensure accessibility in further areas, as well as to broaden the existing understanding of accessibility among theatre employees and audiences (including people with disabilities). The project includes workshops (theatre and film), training (for spectators, actors, office staff), preparation of a bilingual performance with g/deaf people ("Romeo and Juliet"), preparation of accessible repertory performances for people with disabilities. The aim of the project is to increase the number of theatre activities based on a participatory model of accessibility, to build the independence of theatre staff in accessibility activities, to strengthen partnerships with communities of people with special needs, to build awareness among theatre staff and theatre makers about the introduction of ways of accessibility defined as integrated access. Other activities are also dedicated to people with special requirements. In the auditorium, thresholds have been removed and easy access has been provided for people in wheelchairs to reach the auditorium. The box office is located at the entrance and the entrance and access to the auditorium is adapted for people with mobility impairments.

4 Conclusions

In this article, the authors carried out an analysis of a listed theatre building located in south-eastern Poland. The aim of the analysis was to find out whether a listed building can achieve the standard of a nearly zero-energy building and whether it can achieve climate neutrality. The authors added user comfort criteria to their innovative approach, as well as an accessibility criterion closely related to user comfort for people with special needs. The results of the analysis indicate that a listed building can achieve the standard of a nearly zero-energy building, but on condition that comprehensive thermo-modernisation measures are carried out or that the existing heating and cooling source is replaced by one based on renewable energy sources. In the case in question, this was a heat pump powered by photovoltaic panels. Climate neutrality of the building is only achievable for the operational carbon footprint, provided that the heating and cooling source is changed from the existing one to one based on renewable energy sources. Additional occupant comfort criteria are directed at the satisfaction of the building occupants, which directly contributes to the quality of the work performed and improved health and well-being. The methodology presented by the authors has been positively verified on the real example of a historic theatre building.

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