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A technical and economic analysis of the thermal modernisation of historic buildings using an innovative thermal insulating paint

Key words: thermal modernisation, thermal insulating paint, outer facade

Introduction

In Poland, after World War II and after the period of devastating post-war communist occupation, the majority of historic buildings had ceased to exist, and currently there are few buildings of historical features. Those which have survived require due preservation, and particularly their facades should be preserved in their original form. This is the heritage that has survived to these days, and the descendants' duty is to retain, maintain and preserve it (Wysoczarska, 2010). Not always is it possible to preserve the original facades of buildings. Some authors call the thermal modernisation method that has been extremely fashionable in recent years by the term thermal rape of historic buildings by covering their facades with expanded polystyrene. By doing this, the original appearance of, many times, very interesting buildings, such as those with the use of so-called Prussian wall, stone facades, or even red brick tenements, are obscured. And still, very often, it is these facades that tell us the whole story of the buildings, reflecting the culture of a given region, etc. On the other hand, what we observe currently is a kind of longing for the beauty of the past (Popek & Romik, 2015). All cities worldwide are striving for restoring, e.g. their old towns in their original style and character, where people enjoy meeting, sitting and walking, thus being able to feel better and happier. And it is where the thermal modernisation of these buildings comes in, obscuring our view of their whole history. Some say, though, that the facades of old tenement buildings are chipped and dirty, and thus not worthy of being preserved. This only indicative of the culture of contemporary generation, and especially the current authorities of the city. Obviously, there will never be a situation where there is enough money for everything; nevertheless, the maintenance of historic buildings should be extensively subsidized. If we don't do this today, tomorrow might be too late (Byrdy, 2002).

The most efficient building thermal insulation methods, as for today, is by external thermal insulation using expanded polystyrene or rock wool panels, whereby we eliminate any possible thermal bridges through which heat escapes from the house (Francuz, Kusina & Machnik, 2011). Thanks to this, it is really warmer. Besides, by applying thermal insulation from the outside, no useful floor area of the building's rooms is taken up. There is also a method of thermally insulating historic buildings from the inside. But it is a much more expensive method because, if we lined the same wall from the inside, we would have to carry out a major interior renovation, including plastering, painting, etc. When it is externally thermally insulated, the wall warms up along with the room, attaining the same temperature as that of the interior air – heat accumulation occurs thereby in the wall. Thanks to the heat accumulation phenomenon, the interior will not overheat during hot days, and will stay long warm in the wintertime. Thermal insulation on the interior side is very rarely applied; and if so, it is practised mostly for historic buildings, whose appearance needs to be accurately preserved. It can also be used in temporarily heated buildings. In that case, the user is able to heat up the room fast, without having to heat the wall (Piotrowski & Dominiak, 2006).

The authors of this article have proposed another thermal insulation solution, namely the one with the use of thermo-reflexive paints. It is an interesting alternative or complement to traditional insulating materials, particularly for the thermal modernisation of historic buildings in view of new, more stringent wall thermal insulation regulations, whereby, as of 1 January 2021, the heat-transfer coefficient will have to be obligatorily maintained at a level of $U = 0.2\ \mathrm{W{\cdot}m^{-2}{\cdot}K^{-1}}$, so lower by 0.05 U compared to the year 2019 (Dzierżewicz & Starosolski, 2010).

The surfaces of historic building walls, coated with thermo-reflexive paints, are able to reflect even up to 90% of thermal energy that they receive. When referring to the above-mentioned energy, one should have in mind both heat and cold, as any physical body emits thermal energy starting from a temperature of around –273°C, that is the absolute zero (Michalik, 2014a, 2014b). This means that a paint coat protects against both low and high temperatures (Michalik, 2014c). One of the thermo-reflexive paint components that significantly influence the thermal insulation effect is a vacuum ceramic insulating additive in the form of microspheres with a wall thickness of 1–2 μm and a diameter of 4–10 μm (comparable to the human hair diameter). In the production process, air from the microsphere interior is removed to form a vacuum (Byrdy, 2011). As the paint dries up, the microspheres get compacted, thus forming a protective barrier that makes the transfer of thermal energy in either direction difficult. Microspheres are characterized by very high bending strength, and their melting point is 1,800°C; moreover, they have a very favourable heat-transfer coefficient, which is approx. $k = 0.1\ \mathrm{W{\cdot}m^{-2}{\cdot}K^{-1}}$.

Historic heritage conservators claim that historic buildings should be thermally insulated from the inside only (Markiewicz, 2011). However, the authors of the present study have proposed still another solution: thermo-reflexive paints that can provide a trade-off solution to such a disputable issue as the thermal insulation of historic buildings (Pawas, 2018).

Thermo-reflexive paints effectiveness in historic building thermal insulation

The building shown in Figure 1 is subjected to the analysis of its thermal modernisation using paints designed for thermal insulation. The historic building was erected in the 18th century in traditional masonry construction with walls made of bricks. For finishing the building's walls, traditional plaster was used. The historic building is supervised by the conservation officer, and is situated in a park, far away from dwelling areas. It is gas-heated using conventional radiators with heat regulation.

The advantage of thermal insulation with the innovative paint is the fact that we preserve the original character of the historic building's facade, which has been approved by the conservator officer, and that no scaffolding is foreseen to be used when carrying out repair work, because of the need for painting the facade with spray guns using a man basket crane. No removal of flashing elements, gutters and downpipes, as it is the case for conventional expanded polystyrene thermal insulation, is foreseen either, except only for taping up to protect against undesirable painting. Prior to the application of a paint coat, the surface of the facade to be thermally insulated needs to be high-pressure washed, next primed with an undercoater, and then twice gun spray painted. As per the manufacturer's declaration and the information provided on the NASA website (a few year ago NASA commercialized their thermal insulation paint technology), this paint reflexes the majority of thermal radiation back into the interior, thus "insulating" the painted room – therefore, instead of a thick EPS layer, only a thin paint coat is needed, and the effect should be identical. It was decided to verify this.

From the data provided by the manufacturer and from the diagram plotted based on tests carried out in a model building in the condition prior to (Fig. 2),

FIGURE 1. The palace from the 18th century. The thermal modernisation of the buildings using thermo-reflexive paint (the author's study)

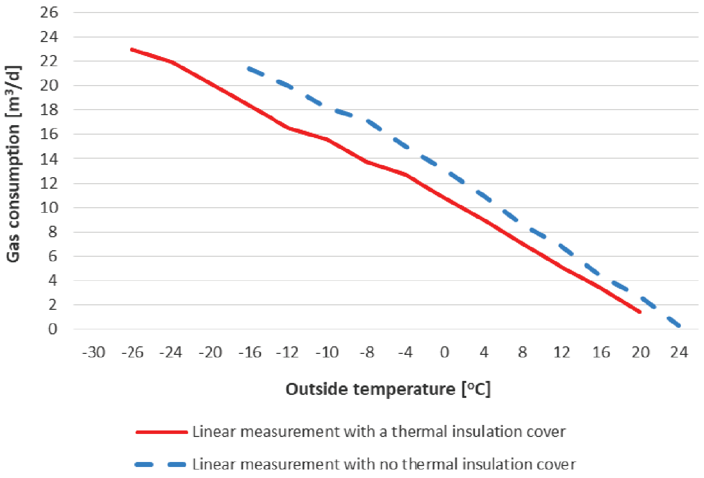

FIGURE 2. Average daily natural gas consumption as dependent on the outside temperature (the author's study)

and after being thermally insulated with the thermal insulating paint it can be observed that the paint fulfils its function and, after being applied on the facade, a building thermal insulation effect is visible in the form of a reduced heating gas consumption.

The heat-transfer coefficient of the paint is determined from relationship:

$$k = \frac{Q_{\text{aver\_daily}} \cdot 36{,}160 \cdot 1{,}000}{F_{\text{wall}} \cdot (21 - T_{\text{outside}}) \cdot 24 \cdot 3{,}600} \left[\frac{W}{\text{m}^2 \cdot \text{K}}\right] \quad (1)$$

where:
k – heat-transfer coefficient [W·m^{-2}·K^{-1}],
$Q_{\text{aver\_daily}}$ – average daily gas consumption for the test building [m^3·day^{-1}],
F_{wall} – total surface area of the paint coated wall – the surface area of the wall designed for thermal insulation is taken as per the take-off and amounts to approx. 368 m^2,
T_{outside} – averaged outside temperature in the winter season, i.e. from October to April in the years of conducted tests, 2017/2018, is 2.4°C.

Thermal insulating paints perform their function mainly due to their reflectiveness, or the ability to reflect thermal radiation. This feature, known and utilized in the case of other materials, has also been activated for paints. Using thermal radiation reflecting paints makes it possible to considerably improve the thermal insulating capacity of buildings by reducing frost penetration through the painted partitions in the wintertime, as well as their excessive heating up in the summer. In practice, this is translated into measurable savings in heating costs of around 15% and the comfort of a cool interior at high outside temperatures – savings in air conditioning costs of up to 40% (Grzyl, 2011).

The basic properties of the thermal insulating paint and the calculations shown earlier (Fig. 3, 4) enable one to

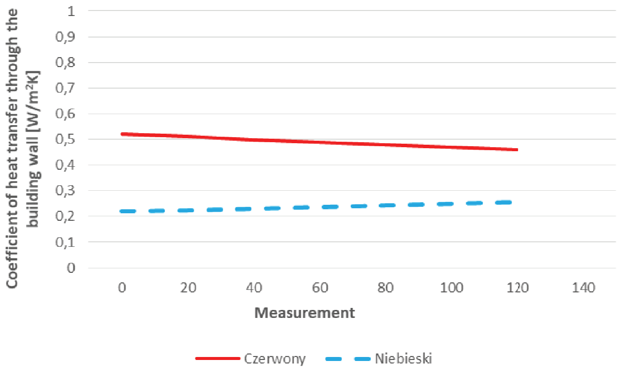

FIGURE 3. Comparison of the values of the coefficient of heat transfer through the uncoated wall and through the paint coated wall, respectively (the author's study)

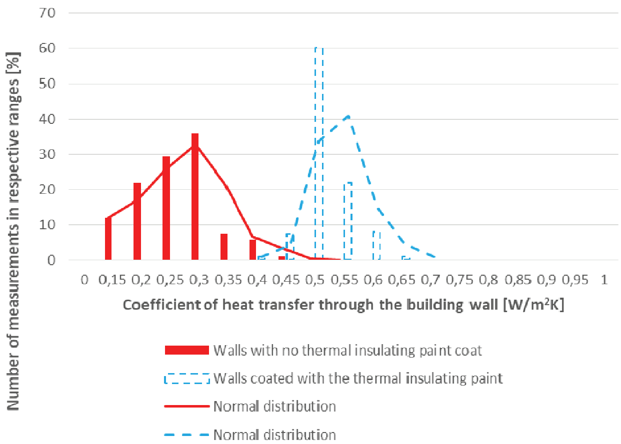

FIGURE 4. Comparison of heat transfer coefficient values for building walls coated with the thermal insulating paint and uncoated (the author's study)

notice a considerable difference compared to conventional insulating materials. Conventional insulating materials, such as expanded polystyrene, mineral wood and their derivatives insulate on the principle of thermal resistance, while the paint under consideration performs its function through reflection. Figure 5 juxtaposes the values of the coefficient of heat transfer through the partition for the building under study.

The thickness of expanded polystyrene panels, which would provide the thermal insulation effect equal to that obtained from the thermal insulating paint is determined from relationship:

$$\frac{S}{\lambda_{EPS}} = \frac{1}{k_{therm\_insul\_wall}} - \frac{1}{k_{therm\_uninsul\_wall}} \tag{2}$$

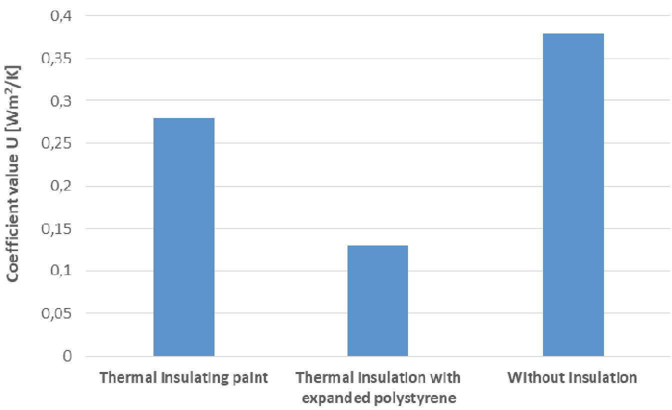

FIGURE 5. Juxtaposition of *U* coefficients for the examined wall (the author's study)

where:

s – expanded polystyrene panel thickness [m],

λ_{EPS} – thermal conductivity coefficient for expanded polystyrene, equal 0.040 $W \cdot m^{-1} \cdot K^{-1}$,

$k_{therm\_insul\_wall}$ – heat transfer coefficient for the wall with a thermo-reflexive paint coat, equal 0.284 $W \cdot m^{-2} \cdot K^{-1}$,

$k_{therm\_uninsul\_wall}$ – heat transfer coefficient for the wall with no thermal insulation, equal 0.391 $W \cdot m^{-2} \cdot K^{-1}$.

After substituting, we obtain:

$$\frac{s}{0.040} = \frac{1}{0.284} - \frac{1}{0.391} = \\ = [3.52 - 2.55] = 0.97 \quad (3)$$

Hence, we can determine the expanded polystyrene panel thickness:

$$s = 0.040 \cdot 0.97 = 0.0388 \text{ m} = 3.88 \text{ cm} \quad (4)$$

Thermally insulated wall, the facade wall should be thermally insulated with approx. four-centimeter thick expanded polystyrene with a lambda equal to 0.040.

Unfortunately, a partition designed in that manner would not meet the thermal insulating power requirements specified in the Regulation of the Minister of Transport, Construction and Maritime Management of 5 July 2013, amending the regulation for the technical conditions to be met by buildings and their situation, where the coefficient of heat transfer through the partition, as required from 1 January 2017, is a maximum of 0.23 $W \cdot m^{-2} \cdot K^{-1}$.

Thermal insulation cost analysis according to two variants

In Variant I, making thermal insulation using the traditional thermal insulating material, expanded polystyrene, in the BSO system, in light – wet technology, is analysed. The designed expanded polystyrene is assumed to be 15-centimeter thick. When making the thermal modernisation of the external wall in an existing building, it is necessary to include additional work items in the work cost calculation, such as: dismantling and installation of gutters and downpipes; dismantling and installation of new flashing elements and windowsills. Presented below are the costs of carrying out the project under consideration and the determination of heat and humidity coefficients using the KI-HUMIDITY Knauf Insulation software program (Grzyl, 2011).

The cost calculation price determined based on the assumptions made, consistent with the technology of execution.

The technology of execution includes:

- covering windows with foil,
- dismantling and re-installing PVC gutters,
- dismantling and re-installing PVC downpipes,
- dismantling sheet flashing elements,
- sticking EPS panels to the walls,
- sticking EPS panels to reveals,
- sticking reinforcing fabric to the walls using an adhesive,
- sticking reinforcing fabric to reveals using an adhesive,
- installing protective corners,
- making resin plaster work (marmurit) on the building plinth,
- laying ground plaster mix,
- laying silicone plaster on the walls,
- laying silicone plaster on reveals,
- installing flashing elements of coated sheet.

The cost of carrying out wall expanded polystyrene thermal insulation work is: 72,265 PLN gross.

When examining the above cost calculation for making wall thermal insulation in the conventional technology using expanded polystyrene (Variant I) it can be noticed that the labour costs is almost equal to the costs of the in-built materials. The project under consideration involves a large take-off for auxiliary work items, such as the replacement of flashing elements, including outside windowsills. The cost of the operation of equipment needed for carrying out this work is negligible, as these are operating costs. The unit cost of making 1 m^2 of wall thermal insulation is approx. 216 PLN gross, with the material prices as per today, is a satisfactory price.

In Variant II, making the thermal insulation of the facade by painting it with the innovative thermal insulating paint is analysed. The unique formula of this paint favours the improvement of the building's energy balance by reflecting radiation from the painted surface. In addition to its insulating properties, the coat offers also insulating-reflexive properties that contribute to the resistance of facades to low temperatures, and fills micro-cracks. In the case of Variant II, the use of scaffolding is not foreseen in view of the need for a man basket crane for staff painting the facade with a spray gun. No removal of flashing elements, gutters and downpipes, as it is the case for Variant I, is foreseen either, except only for taping up to protect against undesirable painting. Below, the costs of carrying out the project under consideration are shown.

The cost calculation price determined based on the assumptions made, consistent with the technology provided by the manufacturer.

The technology of execution includes:

- covering windows with foil,
- high-pressure thorough washing of outer surfaces with water,

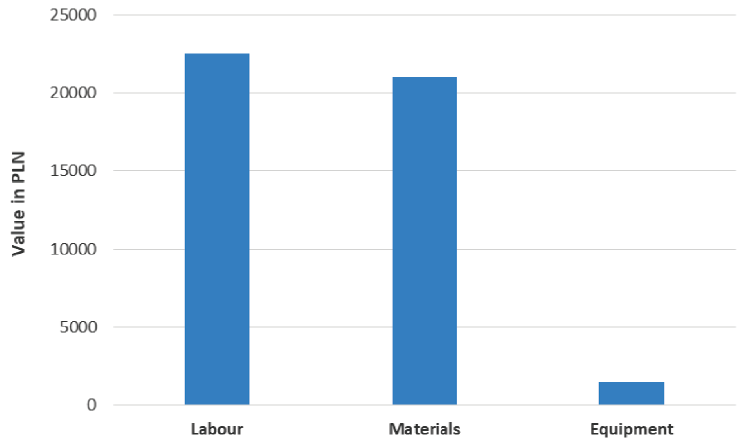

FIGURE 6. A summary of costs for the project in Variant I (the author's study)

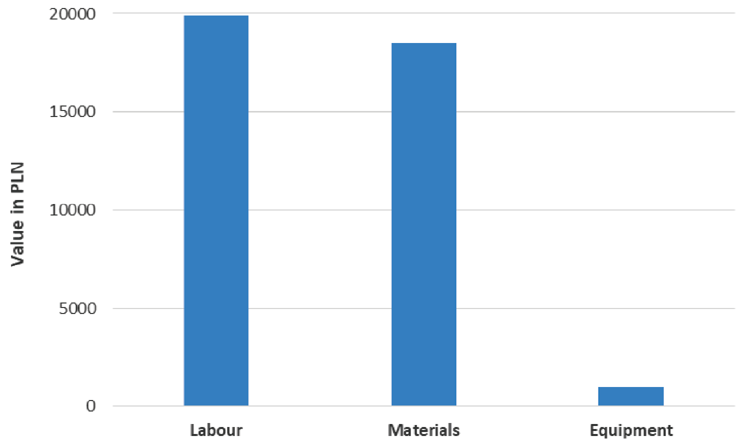

FIGURE 7. A summary of costs for the project in Variant II (the author's study)

– priming the walls with an undercoater, after they have dried off,
– painting outside surfaces twice using a spray gun.

The cost of carrying out wall expanded polystyrene thermal insulation work is: 62,475 PLN gross.

By examining the above cost calculation for making the thermal insulation of the outside wall in the technology using the innovative thermal insulating paint (Variant II) it is found that, similarly to Variant I – wall thermal insulation with expanded polystyrene, the labour cost also equals the cost of in-built materials. In the case of making thermal insulation by this technology, by contrast to the conventional technology, no auxiliary work items, such as replacing flashing elements or dismantling downpipes, occur. The cost of the operation of equipment necessary for carrying out this work is

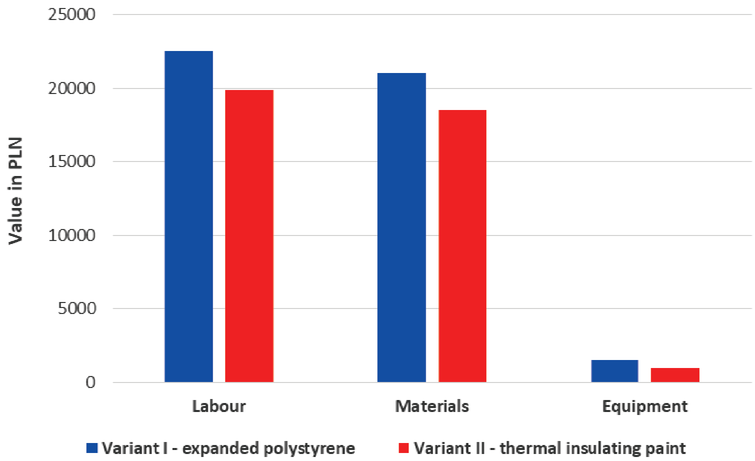

FIGURE 8. Comparison of the costs of the project in two variants (the author's study)

lower, compared to thermal insulation with expanded polystyrene, because no need for working on scaffolding occurs here. The unit cost of making 1 m^2 of wall thermal insulation using the thermal insulating paint is approx. 177 PLN gross which, with the material prices as per today, is a satisfactory price. Nevertheless, this is the price of the thermal insulation alone, without the additional work items that are necessary in Variant I.

Conclusions

The main purpose of the study was to compare two technologies of the thermal insulation of a historic building's walls: Variant I – conventional thermal insulation using expanded polystyrene, and Variant II – innovative thermal insulation using a thermal insulating paint. When selecting the material, the main aspects were the material strength, durability, workmanship, the cost of carrying out the project, and the behaviour of materials during operation, which, in the case of expanded polystyrene thermal insulation, meets these conditions better compared to the wall thermally insulated with the innovative thermal insulating paint technology. In view of the fact that this was a historic building, there was no possibility of using a expanded polystyrene thermal insulating layer; therefore, it was decided to make thermal insulation with a reflexive paint.

When analysing the two thermal insulating materials, other technologies of making wall thermal insulation can be noticed. During making expanded polystyrene thermal insulation, scaffolding is a key element, which is necessary for carrying out the work. By contrast, when making thermal insulation using the thermal insulating paint, which is applied with spray guns, no scaffolding is involved; only a man basket crane is needed for the painter. Although the handling of expanded polystyrene is easy and not very labour-intensive, it can be reasonably expected that the thermal insulation applied on the wall by spraying will be completed faster; nevertheless, the speed of execution is not the only aspect that offers the advantage over the conventional thermal insulation method. The test expanded polystyrene, as per today, has moderate thermal insulation properties, with a lambda coefficient of 0.040 $W \cdot m^{-2} \cdot K^{-1}$. From the tests carried out to compare the thermal insulating paint on the example of the historic building's wall under study it is found that the heat transfer coefficient is larger than accepted by the technical specification that stipulates the maximum permissible heat transfer coefficient, which is currently equal to 0.23 $W \cdot m^{-2} \cdot K^{-1}$.

The thermal insulation of the facade wall made of expanded polystyrene is more prone to possible mechanical damage; also, many execution errors can be made, which will adversely affect the quality and subsequent operation. When making thermal insulation in conventional technology, any errors made during bricklaying the walls can be rectified, e.g. correcting the plumb line of an erected wall. Thermal insulation in the conventional BSO technology lends itself to any type of construction. The manufacturers of this material offer a wide range of EPS panels with a large selection of heat transfer coefficients. By knowing the thickness and type of material, of which the wall to be thermally insulated is made, it easy to calculate the necessary EPS panel thickness, so that the planned construction meets all conditions. On the other hand, in the opinion of the authors of the present study, thermal insulating paint is an excellent alternative for walls that have already been thermally insulated, aimed at improving the heat transfer coefficient of the partition, thus meeting the requirements stipulated in the Regulation of the Minister of Transport, Construction and Maritime Management of 5 July 2013, amending the regulation for the technical conditions to be met by buildings and their situation, where the coefficient of heat transfer through the partition, as required from 1 January 2017, is a maximum of 0.23 $W \cdot m^{-2} \cdot K^{-1}$. This is also an excellent offer for historic buildings, where everything that is the most beautiful is often situated on the building's outside facade. Using the innovative technology for historic buildings, we are able to improve the aesthetic appearance and, at the same time, thermal properties of the partition during carrying out a single project, while not spoiling the historical look of the building.

By highlighting in this study all the advantages and drawbacks of both external wall thermal insulation technologies, the authors convincingly show that thermal insulation made in conventional expanded polystyrene technology is the best solution for the thermal modernisation of not only multi-storey multi-family apartment buildings, but also single-family and any other buildings, where the strength, durability, economy and, at the same time, quality are essential features. However, for historic buildings, it is preferable to use reflexive paints, thanks to which the charm and uniqueness of a building's facade, including its precious stuccowork, can be preserved unaffected.

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Rozporządzenie Ministra Transportu, Budownictwa i Gospodarki Morskiej z dnia 5 lipca 2013 r. zmieniające rozporządzenie w sprawie warunków technicznych, jakim powinny odpowiadać budynki i ich usytuowanie. Dz.U. 2013, poz. 926 [Regulation of the Minister of Transport, Construction and Maritime Management of 5 July 2013, amending the regulation for the technical conditions to be met by buildings and their situation. Journal of Laws 2013, item 926].

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Summary

A technical and economic analysis of the thermal modernisation of historic buildings using an innovative thermal insulating paint. Due to the need for making the thermal modernisation of buildings of historical value, where the conservation officer often does not approve the thermal insulation of the building's facade with a traditional method using expanded polystyrene (EPS), an innovative paint has been proposed to be used, which can substitute for an EPS layer for the thermal insulation of buildings where everything that is the most beautiful is often situated on the building's external facade. The article analyses two different thermal modernisation methods: the traditional method and the one using an innovative thermal insulating paint. During selecting the material, the main aspects were: material strength and durability, workmanship, the execution cost of a sample project, and the behaviour of materials during operation. All advantages and disadvantages of either of the external wall thermal insulation technologies are indicated. Cost calculation figures for the project under consideration carried out using

the above-mentioned technologies have also been examined.

It has been found that the technology using the innovative thermal insulating paint is fairly expensive and the obtained coefficients of heat transfer through the partition are not competitive compared to the traditional method using expanded polystyrene. However, by using the innovative technology for historic buildings, we are able to improve the aesthetic appearance of the facade and, at the same time, the thermal properties of the partition during carrying out a single project, while not spoiling the historical look of the building.

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