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CHOOSING THERMAL CHARACTERISTICS FOR A BUILDING'S TRANSPARENT PARTITION TAKING SOLAR EFFECTS INTO CONSIDERATION

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ABSTRCT: Ensuring a sufficient level of thermal protection is currently one of the more important issues pertaining to buildings. It stems from the necessity to reduce operational energy consumption of the construction sector and the need to reduce the adverse effects of using "dirty" energy on the environment. This requirement pertains to both newly erected buildings and the ones being modernized. Decisions regarding choosing thermal parameters of partitions, including transparent ones, can be made by referencing the applicable insulation criteria, but also by using appropriate optimization procedures. These should be based on the heat balance measurement of the analyzed component that is as accurate as possible. In this article, the results of using an optimization procedure for windows proposed in energy audit methodology were compared to its extension which includes a component of solar heat gains. The presented extended method may be helpful to future investors, energy auditors, etc. in deciding on the thermal characteristics of transparent partitions.

KEY WORDS: window optimization, window thermo-modernization, solar heat gains

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JEL: L74, O13, Q42

Introduction

Due to an ongoing deterioration of our natural environment, all initiatives that serve the purpose of stopping the destruction of the ecosystem, of which we are – after all – an integral part, become increasingly important. This pertains to every aspect of human life, including the construction sector. It is without a doubt that acquisition and usage of energy resources and all of the associated consequences can be a significant burden on our environment. This is particularly applicable to "traditional" carriers of energy as they are primarily responsible for emitting greenhouse gases and particulates into the atmosphere – first of all CO_2 (Fenger, 2009). According to various estimates, the construction sector in the European Union is responsible for between 30 and 50% (41% on average) of energy consumption. Within the UE, operational demand for heating and ventilation purposes in buildings reaches 30% (for southern-European countries, such as Spain or Portugal), through 60% (Sweden and Great Britain), and even up to 75% (for Germany and the Netherlands) (Lis, 2011). Here, a dependency of heating energy consumption on climate conditions is fairly conspicuous.

As was previously noted, a continuously deteriorating air quality is one of the negative consequences of using energy based on "dirty" fuels. Daily smog alerts became a norm, and we almost routinely check smog reports in the mornings. The main cause of a classic smog (also known as acid smog or London smog) is considered to be the burning of solid fuels: mostly coal (Kerimray et al., 2017). Air pollution is therefore determined by the presence of boiler rooms for single and multiple family houses, as well as industrial boiler rooms (MPiT, 2018). Energy quality, their operational energy consumption and the efficiency of energy-generating systems, all clearly translate into the amounts of energy resources being burnt and the emissions of pollutants that stem from this process. Making sure that buildings are properly thermally protected is one way of mitigating high energy demand of building resources. That is why, various types of regulation are in place to limit thermal properties of construction partitions. They result directly from the construction law – point f of Article 5 (Prawo Budowlane, 2018). Selection of thermal parameters of building envelope elements, including transparent components, can be carried out based on the applicable requirements, but can also take advantage of "optimization algorithms" for that purpose. The analysis of selection of window parameters of the residential building was carried out e.g. at work (Borowska, Jezierski, 2018).

In Poland, it is possible to apply the methodology included in the resolution on form and scope of energy and renovation audits (Audyt energ. i rem., 2009). While it is primarily dedicated to thermo-modernization, it can be successfully translated into the context of newly-erected buildings, using thermal characteristics demanded by technical conditions for buildings and their placement (hereinafter referred to as TC) as a starting point. Outside of other restrictions pertaining e.g. to the aforementioned minimum heat insulation properties of a partition (WT, 2013), the lowest obtained values of Simple Payback Time (*SPBT*) for the variants being compared of a given enterprise determines its optimum: the most viable option of its delivery (Manteuffel-Szoege, 2006). In this context, transparent partitions seem like an interesting element of a building's envelope. That is because they are typically the source of relatively higher per-unit thermal energy losses than full components (e.g. walls), but – on the other hand – generate heat gains from solar radiation. The share of heat consumption through windows in the energy balance of a building ranges from 12% for traditional buildings to 45% for passive buildings with an 11% share in the total area of external partitions. Heat gains from solar radiation can cover up to 44% of the seasonal heat demand for a building (Idczak, Firląg, 2006). Thus, they make windows possible to introduce a renewable carrier of clean energy into the building's heat balance. The analysis of the impact of window parameters and the location of the building on its energy performance was carried out at work (Jezierski, Święcicki, 2018).

Optimizing transparent partitions taking solar gains into consideration – research methods

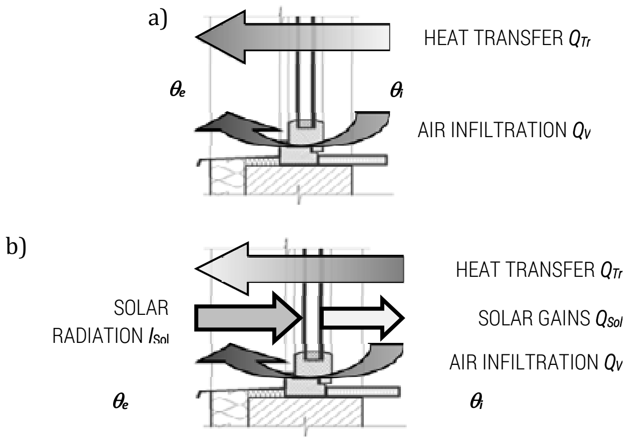
A formula for optimizing transparent partitions proposed in the resolution was designed based on heat loss balance as presented in a schematic form in figure 1 (figure 1a).

Bringing the energy balance of a transparent partition to the sum of heat losses through the penetration and heat necessary to increase the temperature of the infiltrating air is reflected in formula (1) (Audyt energ. i rem., 2009):

$$SPBT = \frac{N_W + N_V}{\Delta O_{rW} + \Delta O_{rV}}, \text{[year]} \tag{1}$$

where:
N_W – investment connected to modernizing the transparent partition (PLN),
N_V – investment connected to modernizing the ventilation system (PLN),
ΔO_{rW} – annual savings in energy cost obtained through modernizing the transparent partition (PLN/year),
ΔO_{rV} – annual savings in energy cost obtained through modernizing the ventilation system (PLN/year).

Figure 1. Energy balance of a glazing: a) current optimization procedure; b) taking into consideration solar gains



Source: author's own work.

In the current method, the financial outcome stems from reducing the heat flux being lost due to permeating through the glazing's gross surface Q_{Tr} and eliminating an undesirable infiltration stream Q_V, where seasonal demand for heat Q_w of a transparent partition is described by formula (2):

$$Q_W = Q_r + Q_V \text{, [GJ/year]} \tag{2}$$

From a practical standpoint, heat balance of a transparent partition is additionally dependent on the component of solar thermal energy gains Q_{Sol} (figure 1b). This dependency can be written as (3) (PN-EN ISO 13790, 2009):

$$Q_W = Q_{Tr} + Q_V - Q_{Sol} \text{, [GJ/year]} \tag{3}$$

The amount of free solar thermal energy which can be absorbed for the purpose of heating a building during the heating season is described by the formula (4) (PN-EN ISO 13790, 2009):

$$\sum Q_{Sol} = \eta_{H,gn} \cdot \sum_j I_{Sj} \cdot \sum_n A_{Snj} \text{, [GJ/year]} \tag{4}$$

where:

$\eta_{H,gn}$ – gains usage coefficient,

I_{sj} – energy of total solar radiation during the heating season for a unit of n-surface and j-orientation of the glazing GJ/(m^2·year) (Dane klimatyczne, 2018),

A_S – n-effective collecting surface of the j-orientation m^2.

The effective collecting surface A_S is the conversion factor of heat radiation operating on the exterior, unshaded surface of the building's envelope, into thermal energy transmitted into its interior area, based on the following relationship (5) (PN-EN ISO 13790, 2009):

$$A_S = A \cdot Z \cdot C \cdot g \cdot k_0 \,, \tag{5}$$

where:

A – gross surface of the collecting element, e.g. window surface in the reveal opening m^2,

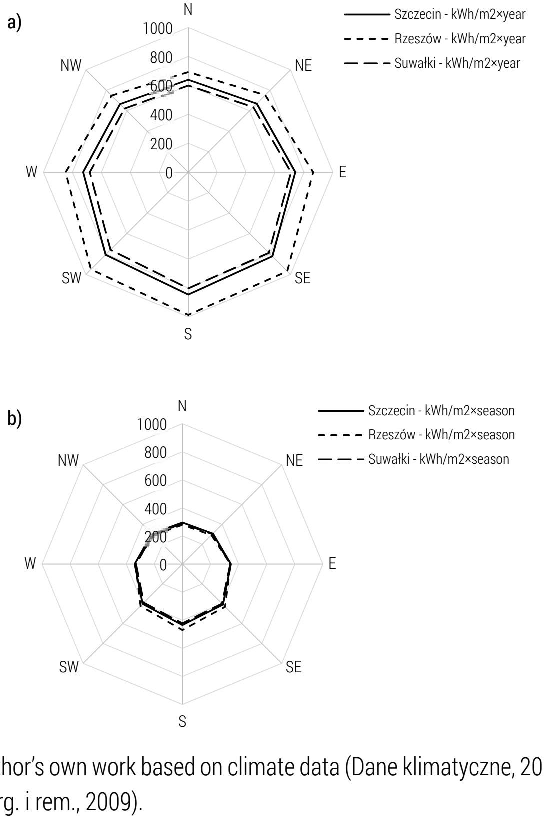
Z – shading coefficient for the collecting element,

C – frame coefficient expressing the relationship between the transparent surface and the total surface of the collecting element, e.g. glass surface/window surface,

g – transmission coefficient (permeability) of solar radiation,

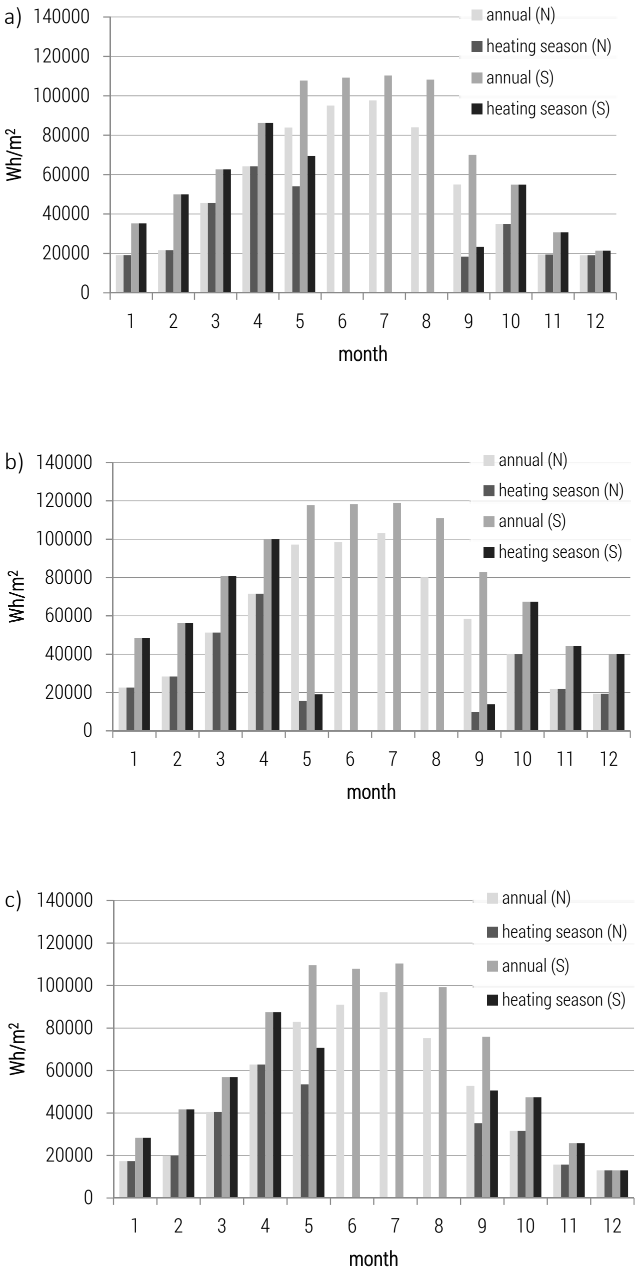
k_0 – adaptation coefficient I_S for glazing's angle ≠ 90° in relationship to the horizon.

Figure 2. Annual (a) and seasonal (b) solar radiation energy for a unit of vertical surface in the examined locations: Szczecin, Rzeszów and Suwałki



Source: author's own work based on climate data (Dane klimatyczne, 2018) and heating days number (Audyt energ. i rem., 2009).

Figure 3. Monthly balance of annual and seasonal insolation for a unit of vertical surface of southern (S) and northern (N) orientations in the examined locations: a) Szczecin; b) Rzeszów; c) Suwałki



Source: author's own work based on the climate data (Dane klimatyczne, 2018) and heating days number (Audyt energ. i rem., 2009).

The location, which determines – among other things – the level of insolation, has a significant influence on the efficiency of the glazing. This is an important relationship in the context of the proposed modification to the optimization formula. When comparing data on total annual insolation of a vertical surface in selected actinometrical stations, e.g. Szczecin-Dąbie (hereinafter referred to as Szczecin), Rzeszów–Jasionka (hereinafter referred to as Rzeszów) and Suwałki, it is easy to notice differences reaching 23% (Rzeszów–Suwałki) (figure 2). Similar disproportions exist in relation to the orientation and can reach up to 43% (Rzeszów). It translates directly into the differences in insolation recorded during the heating season. For the adopted three locations, these can reach up to 11% (Rzeszów–Suwałki) and reach 67% (Rzeszów), when it comes to insolation of variously oriented vertical surfaces in a given location. Therefore, it can be considered a mistake to try to introduce representative solar values for the entire area of Poland and to average solar gains from particular orientations.

The distribution of solar radiation intensity for a vertical surface in a year and during the heating season is shown in the figure below (figure 3).

As is obviously the case, the summer period characterized by the highest insolation does not affect the heat balance during the heating season. This part of solar heat gains – which is not the subject of this article – may, however, be the reason for overheating and necessitate the deployment of cooling systems inside the building. Orientation-averaged distribution of the solar energy acquisition during and outside of the heating season is shown in the graph (figure 4).

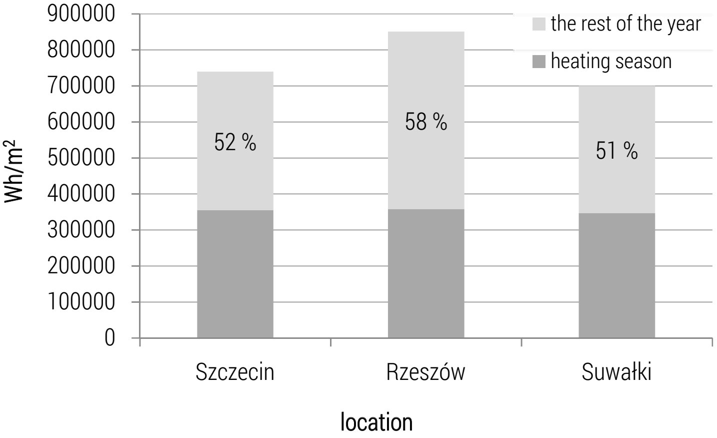
The selection of the thermal characteristics of the *n*-glazing and *j*-orientation should therefore be carried out in relation to a specific location and orientation, which brings dependencies (3) and (4) to the following forms (6) and (7):

$$Q_{W,nj} = Q_{Tr,n} + Q_{V,n} - Q_{sol,nj}\text{, [GJ/year]} \tag{6}$$

and

$$Q_{Sol,nj} = \eta_{H,gn} \cdot I_{Sj} \cdot \sum_{n} A_{Snj}\text{, [GJ/year]} \tag{7}$$

Figure 4. Orientation-averaged insolation during the heating season and in the other part of the year



Source: author's own work based on the climate data (Dane klimatyczne, 2018) and heating days number (Audyt energ. i rem., 2009).

Results of the research

The result of considering a solar component in the optimization procedure of both thermo-modernized and designed window woodwork is illustrated by the juxtaposition of the analysis results for two variants: one in line with the current procedure, and one expanded by the addition of solar gains. A comparative analysis was carried out for the aforementioned locations in Szczecin, Rzeszów and Suwałki, i.e. I, III and V climate zones (table 1). The characteristics of the referenced and alternative window variants are presented in table 2.

Table 1. The characteristics of climate conditions in the selected locations

Location	θ_e [°C]	Heating season [days]	Degree-days Sd [K · day]	$I_{Sśr}$ [Wh/m²]
Szczecin	-16	242	3603,5	354 739
Rzeszów	-20	222	3935,6	357 619
Suwałki	-24	252	4434,7	346 157

Source: author's own work based on the climate data (Dane klimatyczne, 2018), data on the outside air temperature (PN-EN 12831:2006) and heating days number (Audyt energ. i rem., 2009).

Table 2. Parameters of the windows being compared

Parameter	U_W, W/(m^2 · K)					
	2,60 – old window	**1,10 – requirement[3)]**	**1,00**	**0,90**	**0,80**	**0,70**
g, [-]	0,75	0,60	0,55	0,55	0,50	0,50
C, [-]	0,70					
c_r, [-]	1,20			1,00		
c_m, [-]	1,35			1,00		
c_w, [-]	1,00			1,00		
N_W, [PLN/m^2] – modernization[1)]	–	530	550	580	620	670
N_W, [PLN/m^2] – new building[2)]	–	–	20	50	90	140

[1)] Fixed cost of 80 PLN/m^2 taken into account.
[2)] Investment differences in relations to the characteristics required by the regulations on Technical Conditions (TC).
[3)] Value required by the regulations on Technical Conditions (TC).

Source: author's own work.

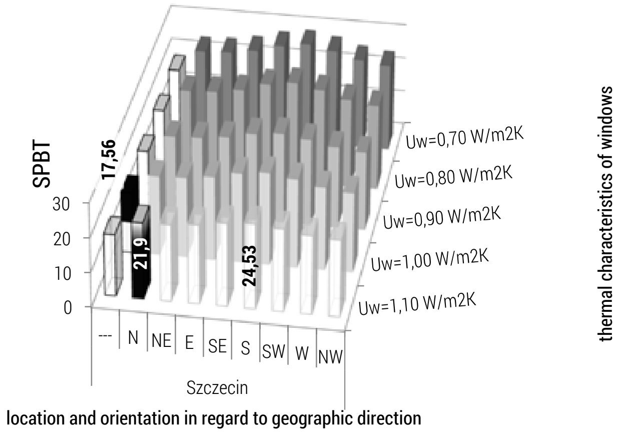
Interior calculation temperature was set at 20°C, the window surface at 1 m^2 and the ventilation stream at 5 m^3/h. Respective to the location, the cost of thermal energy being produced was adapted, assuming heating the building with network gas ($h_{H,tot}$ = 0,90 – total efficiency of the heating system – (Świadectwa energetyczne, 2015)) in the tariff group W-3.6 (Taryfy PGNiG, 2018) (Taryfy PSG, 2018). When calculating unit cost of the energy produced a VAT tax (23%) was taken into account:

- Szczecin – O_z = 46,67 PLN/GJ; Ab = 46,45 PLN/month,
- Rzeszów – O_z = 44,72 PLN/GJ; Ab = 50,33 PLN/month,
- Suwałki – O_z = 43,33 PLN/GJ; Ab = 56,36 PLN/month.

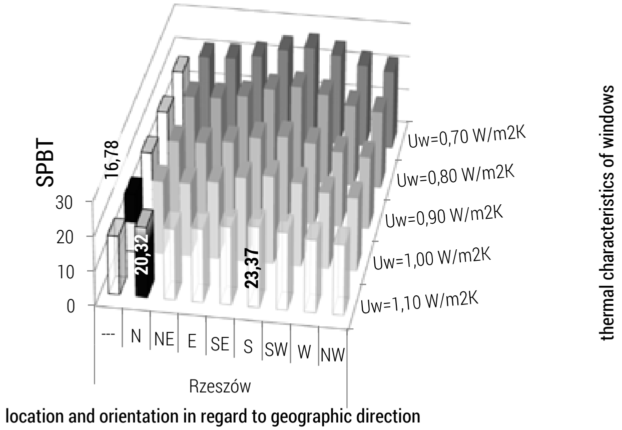
The fixed cost of thermal energy Q_m in the W-3.6 tariff group equals 0 PLN/(MW·month) – the constant components of retail and distribution equal 0 PLN/(MW·month). A juxtaposition of the achieved times of return *SPBT* when optimizing modernized windows is presented in the form of a graph (figure 5). The sign '---' used in a graph represents the current optimization procedure while the data series N–NW represent the results of optimization for the particular directions due to the suggested modification of optimization procedure.

Figure 5. Thermo-modernization of windows – *SPBT* according to the current and modified procedures: a) Szczecin; b) Rzeszów; c) Suwałki

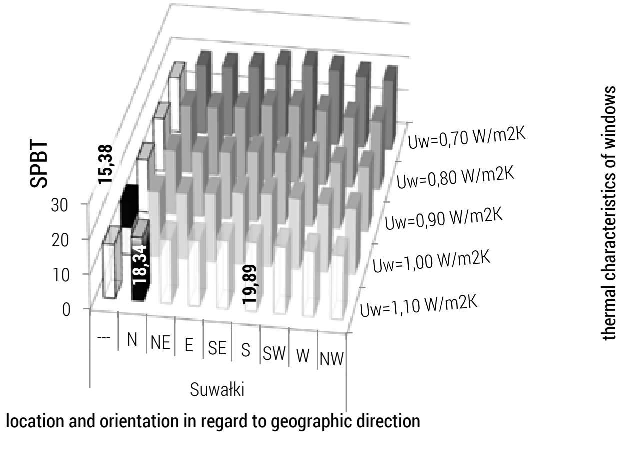
a)



b)



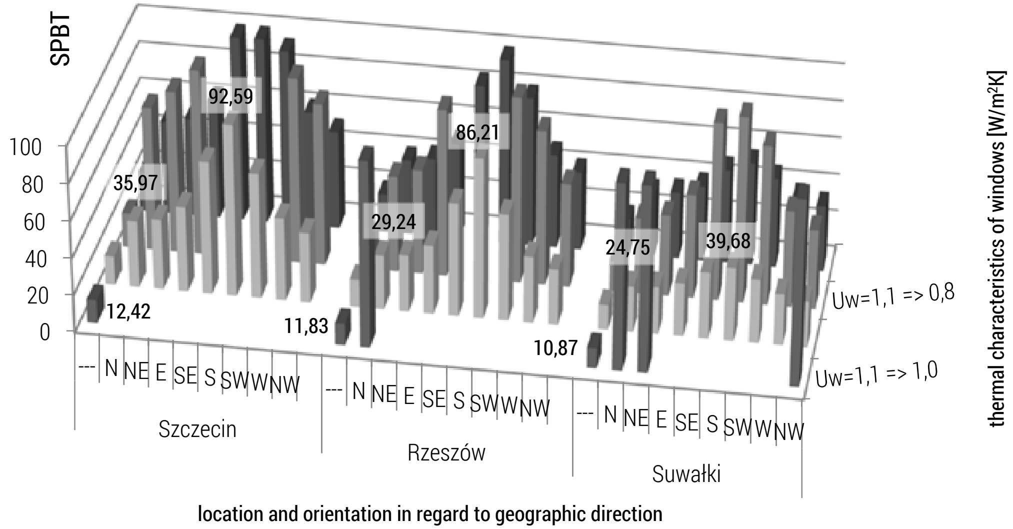
c)



Source: author's own work.

When selecting new windows, we have considered the use of glazing with better insulation than the one given in the current requirement determined in technical conditions, to which buildings and their location should adhere and which, since 1 January 2017 is set at U_{Wmax} = 1,10 W/m^2·K. The results of the obtained *SPBT* payback times are illustrated in the form of a collective chart (figure 6). The sign '---' used in a graph represents the current optimization procedure while the data series N–NW represent the results of optimization for the particular directions due to the suggested modification of optimization procedure. In this list, empty records are to represent a negative energy effect.

Figure 6. New window selection – *SPBT* according to the current and modified procedures: a) Szczecin; b) Rzeszów; c) Suwałki



Source: author's own work.

Obtained results: discussion

In the variant where window woodwork is being thermo-modernized (figure 5), windows with a heat transfer coefficient U_W = 1,00 W/(m^2·K) were determined to be the best solution according to the current procedure (*SPBT* at 17,56 years in the Szczecin location, 16,78 years when located in Rzeszów and 15,3 years for Suwałki). After the optimization procedure was modified to include the solar effect, regardless of orientation and location, the optimal solution turned out to be windows with U_W = 1,10 W/(m^2·K). In addition, the payback period was extended by 2,96 years for Suwałki, Rzeszów by 3,54 years and by 4,34 years for Szczecin. The distribution of *SPBT* after various orientations has given the fastest returns for north-facing windows. In the case of the optimal replacement variant where old, U_w = 2,60 W/(m^2·K) windows were replaced with new, U_W = 1,10 W/(m^2·K) windows, the payback period was respectively 21,9 years (Szczecin), 20,32 years (Rzeszów) and 18,34 years (Suwałki).

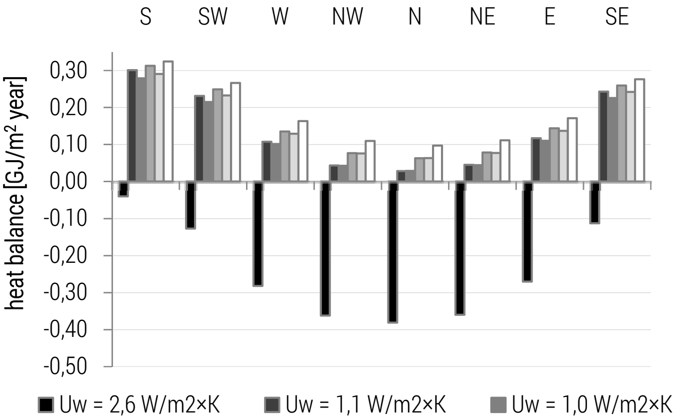
The inclusion of solar gains in the window selection procedure for a newly-erected building (figure 6) resulted in a change in the fastest return variant, but with its significant extension. The current procedure indicated that the best solution would be windows of U_W = 1,00 W/m^2·K with the respective *SPBT* of 12,42 years (Szczecin), 11,83 years (Rzeszów) and 10,87 years (Suwałki). After modifying it with solar effects, the optimum is for windows with U_W = 1,10 W/m^2·K. What was observed in that situation, was a significant increase in the investment's payback period by 13,88 years for Suwałki, 17,4 years for Rzeszów and 23,55 years for Szczecin. As was the case with modernization, the *SPBT* distribution for individual orientations showed the shortest returns for northern-facing windows. When exchanging glazing for windows with U_W = 1,00 W/m^2·K, the return period amounted to 35,97 years for Szczecin, 29,24 years for Rzeszów and 24,75 years for Suwałki.

Solar gains have positive effects on the energy balance of transparent partitions. In our geographical latitude, the southern expositions have the obvious advantage in this matter, which constitutes one of the basic principles of shaping building blocks in the northern hemisphere (figure 7: Rzeszów location).

When comparing alternative characteristics of glazing, e.g. for thermomodernization, the difference in their energy balance is important.

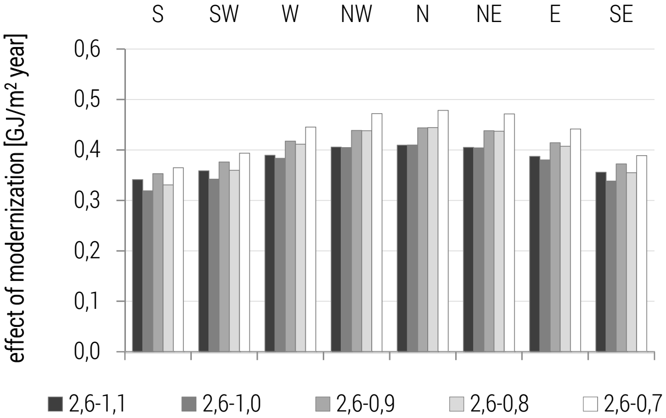
This is shown on a graph with the obtained energy savings after modernizing windows with U_W = 2,60 W/m^2·K (figure 8) as a function of orientation: Rzeszów location. In this juxtaposition, the best effect is obtained for the northern elevations. In that case, the difference in solar gains before and after the glazing modernization process turns out to be the smallest which, given the constant component of losses by permeating, gives the most significant energy savings of all orientations. A factor that serves an important role for the energy efficiency of differently-oriented glazed surfaces is thus the solar transmittance g, which unfortunately decreases together with the increase in the glazing's thermal insulation.

Figure 7. Glazing heat balance: Rzeszów location



Source: author's own work.

Figure 8. Energy effect of the glazing's modernization: Rzeszów location



Source: author's own work.

An approximate criterion of the positive balance, taking into account losses caused by permeating and solar gains can be presented as follows (8):

$$\frac{U}{g \cdot C} \leq \frac{\eta_{H,gn} \cdot Z \cdot k_0 \cdot I_{Sj}}{24 \cdot Sd}, \tag{8}$$

where the parameters characteristic for a transparent element are confronted with independent (location) factors.

Conclusions

From the analyses that were carried out, we can conclude that including a solar component generally results in the payback period *SPBT* being extended, both when modernizing and when selecting new glazing. Introducing a solar effect into the optimization formula for modernized transparent partitions can also have an effect on the technical aspects of such an endeavor. That is because it can cause a change in the most favorable glazing parameters: a change in the optimal U_w.

Applying a viability analysis with the inclusion of solar gains when selecting solutions that are alternative in regard to the required level of glazing insulation has also influenced the selection of the most advantageous energy characteristics. This analysis has also brought increased payback times, but to a much higher degree than during modernization, as there was an increase of as much as 2,9 times when compared to a version that ignores solar gains. These were values of 24,75 years and more, which significantly exceeds the currently adopted borderline payback period of 15 years. It also renders such operations inviable. The lowest *SPBT* with a traditional approach was, depending on the location between 10,87 and 12,2 years. These are significant differences that can drastically influence different investment decisions. According to the executive resolution to the "Termo" act, the construction mechanism for thermo-modernization variants is based on ordering the optimized scope of the proposed endeavors in accordance to the growing *SPBT* results and adding the subsequent listed improvements to the most viable one. This diagram is presented symbolically in table 3.

Table 3. Construction diagram for thermo-modernization variants

	Modernization measures	*SPBT* [years]	Scope of variant			
			W_1	W_2	W_{n-1}	W_n
1	Z_1	SPBT(Z_1)	+	+	+	+
2	Z_2	< SPBT(Z_2)		+	+	+
n-1	Z_{n-1}	< SPBT(Z_{n-1})			+	+
n	Z_n	< SPBT(Z_n)				+

Source: author's own work.

With small differences in the payback periods of the considered modernization projects, even a small *SPBT* change to any of them may result in their order being reshuffled and, as a result, cause a change in the scope of thermo-modernization variants. As a result, they can influence the scope of the optimal thermo-modernization variant.

However, it should be noted that the obtained results relate to a specific computational situation being considered and, when dealing with a different set of input data, this problem should be tackled individually, on a case-by-case basis.

Acknowledgements

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