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Article

Multi-Aspect Shaping of the Building's Heat Balance

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Abstract: In the European Union, buildings account for 42% of the energy consumption and 36% of the direct and indirect energy-related greenhouse gas emissions. Reducing thermal power for heating purposes is crucial to achieve climate neutrality. The main purpose of this article is to identify the places in the building where it is possible to significantly improve energy efficiency through the use of appropriate construction and material solutions. This article contains a multi-aspect approach to the heat balance of a building. Solutions that have a direct impact on building energy consumption were analysed, taking into account architectural, technological, and material aspects. Particular attention was paid to energy-efficient design and material solutions for non-transparent and transparent external walls and thermal storage walls (Trombe walls). An analysis of heat transfer through building elements was carried out, along with the optimisation of energy-efficient solutions for non-transparent and transparent barriers. Two methods for determining the equivalent heat transfer coefficient U_e for solar active partitions are presented. The analysis presented in the work using the original method of the balanced heat transfer coefficient U_e is a testing ground for identifying unfavourable features of the building structure, as well as the most energy-efficient solutions that can be used in establishing standards for the construction and modernisation of buildings. The value of the U_e coefficient illustrates the actual heat transfer through the partition. Having U_e values for various structural solutions of building envelopes, the designer can easily select the most effective ones. The use of the presented methodology will allow for the optimisation of technical solutions for building elements to improve its energy efficiency.

Keywords: building envelope; heat transfer; passive solar systems; Trombe wall; building heat balance

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Citation: Starakiewicz, A.; Miąsik, P.; Krasoń, J.; Babiarz, B. Multi-Aspect Shaping of the Building's Heat Balance. *Energies* **2024**, *17*, 2702. https://doi.org/10.3390/en17112702

Academic Editor: Antonio Gagliano

Received: 19 April 2024
Revised: 24 May 2024
Accepted: 30 May 2024
Published: 2 June 2024

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1. Introduction

Energy efficiency measures in buildings are a priority to save energy and achieve zero emission and fully decarbonised buildings by 2050. In the European Union, 85% of buildings were built before 2000 and of these, 75% have poor energy performance. Buildings account for 42% of the energy consumed in the EU in 2021 and 36% of direct and indirect energy-related greenhouse gas emissions [1,2]. The burning of fossil fuels also causes air pollution, which has a negative impact on human health both directly, by penetrating the body and causing allergies and lung diseases, and indirectly, by being a carrier of heavy metals, microorganisms, and bacteria. The Directive 2008/50/CE of the European Union [3] determines the maximum daily allowed concentration of air pollutions. Therefore, it is important to monitor both the concentrations of pollutants in the air and to effectively control the amounts of pollutants emitted [4].

Every person living in a single-family or multifamily residential building has similar expectations about their property, primarily in terms of ensuring thermal comfort inside the apartment throughout the year and incurring minimal costs related to its operation [5,6].

Meeting these expectations is related to the issues taken into account when designing energy-sustainable buildings [7].

The energy efficiency of a building directly affects the level of energy consumption for various purposes, such as heating and cooling [8–11], preparation of domestic hot water [12], ventilation [13], and lighting. An effective way of using energy for these purposes should be implemented while ensuring the comfort of use of people staying in the building. Energy consumption depends on many external factors, such as climatic conditions, the method of using solar energy, etc. The applied construction and material solutions of building partitions also play an important role, affecting the dynamics of heat transfer [14] and the types and functioning of energy saving installations in the building, as well as the appropriate management of the heat supply [15].

The use of solar energy in a building depends, among others, on its location and terrain [16,17]. Flat land is a so-called neutral area for the location of a building, and is often devoid of many advantages, including diverse topography, occurrence of natural water reservoirs, and vegetation. Attractive areas in terms of construction include areas with a diversified topography, hills, and slopes towards the greatest amount of sunlight. The location of the building on the plot should be in its northern part. High greenery should be located on the north side and in the most frequently blowing winds, to protect the building against additional air infiltration and heat loss. The façade of the building with the largest area of transparent vertical partitions should be towards the south or with a slight deviation towards the east or west, and the building should not be shaded [18]. The least convenient location for plots is on northern slopes, on the tops of hills, in valleys, and with trees on the south side or around the building. In practice, there are many factors that prevent the selection of the optimal location. These include existing underground and above-ground infrastructure, buildings, and greenery in neighbouring plots.

The shape of the building also has an impact on its energy consumption [19]. When considering the shape of the building in terms of reducing heat losses, the shape of the building should be compact [20], similar to a cube or a hemisphere. If it is a rectangular building, the longer side of the building should face the greatest amount of sunlight [21]. The building should have the largest possible heated volume V with the smallest possible partition area limiting this volume A. Therefore, the shape factor of the building (A/V) should be as low as possible. A fragmented-shape building causes an increase value in the shape factor and, consequently, greater heat losses. Each fragmented building form (L-, T-, U-, E-shaped buildings; terraces above rooms; arcades) will generate higher heat losses throughout the life of the building compared to a compact shape. Buildings with an optimal shape are, for example, those built by the Eskimos (igloos).

Another factor influencing energy consumption is the functional arrangement of rooms [20]. It is considered in terms of its location in relation to the cardinal directions and the adjustment of the layout of the room in terms of internal temperature [22]. The rooms with the highest expected temperatures are mainly located on the eastern, southern, and western sides. The north side should generally be treated as a thermal buffer, where rooms with the lowest temperatures should be located. An example of room layout is shown in Figure 1.

The structural and material solutions of the building partitions also have a significant impact on the energy consumption of the building [23]. This mainly depends on the thermal insulation of the external elements of the heated zone of the building [24] and the related heat loss coefficient through penetration and ventilation H [W/K] of the entire building. The thickness of the thermal insulation of building envelopes has an impact on reducing energy demand, heating costs, and harmful emissions, as well as parameters that influence the thermal comfort of rooms [25]. Furthermore, to maintain their high insulation, building partitions should be operated continuously under dry conditions so that mould does not develop on their surface and condensation does not occur in the volume of the partition [26].

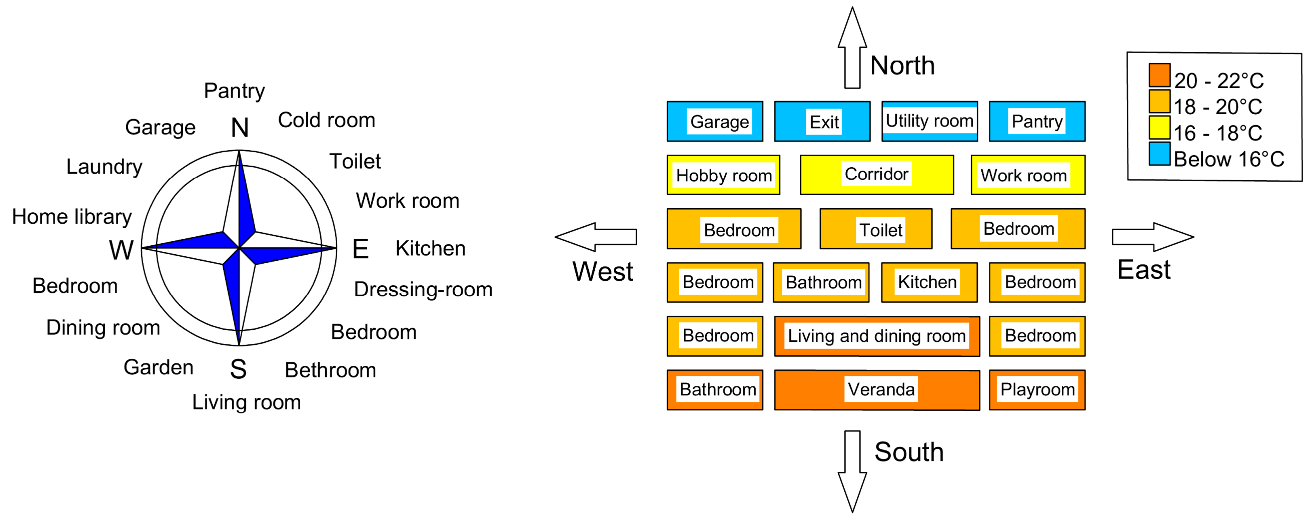

Figure 1. Sample arrangement of rooms relative to cardinal directions.

In addition to the appropriate insulation of external partitions, the structure of the wall itself also plays an important role. Increasing the capacity to accumulate heat, for example, in the masonry layer, stabilises the indoor air temperature and improves thermal comfort [27]. In the case of large glazing areas in the building, a massive partition during the transition period may contribute to reducing the heating demand in the building by approximately 40% [23].

When trying to reduce heat losses in a building, solutions in the form of passive solar systems integrated into the building envelope should be considered, along with highly insulating partitions. One of such solutions are various types of Trombe walls [28]. The use of solutions that use solar energy allows for an increase in heat gains, which in turn has a positive effect on the overall heating balance of the building [29].

To achieve a high level of energy efficiency in a building, at least several energy-saving solutions should be used, both in the architectural, construction, and installation areas. If all possible solutions are used, it is possible to achieve the highest level of energy efficiency, i.e., a building with a zero energy balance [10] or an energy-plus building, i.e., a building that generates more energy than it needs.

The purpose of this article is to present the possibilities of using various technological and material solutions for building partitions, which can have a positive impact on the thermal balance of the building, justifying their choice in the design and construction stage of the building.

2. Trends in the Changes in Thermal Insulation of Buildings

Changes in the thermal insulation of building envelopes in the European Union have evolved over the years. In Poland, the first requirements regarding thermal insulation of non-transparent building partitions were published on 1 July 1958. They underwent subsequent transformations, introducing increasingly higher requirements for thermal insulation for external building partitions. The history of subsequent legal acts regarding the heat transfer coefficient is presented in Table 1.

Table 1. History of the permissible values of heat transfer coefficient of building barriers according to laws [30].

Duration of the Legal Act	U_{max} [W/m²K]					
	External Wall	Flat Roof	Ceiling under the Attic	Ceiling above the Basement	Floor on the Ground	Windows/Roof Windows/External Doors
1.07.1958–31.12.1967	1.42 (1) 1.16 (2)	0.87	1.16 (1) 1.05 (2)	1.16	-	-
1.01.1968–31.06.1976	1.47 (3) 1.16 (2)	0.87	1.16 (3) 1.05 (2)	1.16	-	-
1.07.1976–31.12.1982	1.16	0.70	0.93	1.16	-	-
1.01.1983–31.12.1991	0.75	0.45	0.40	1.00	-	2.0 (4); 2.6 (2) /-/-
1.01.1992–27.04.1998	0.55	030	0.30	0.60	-	2.0 (4); 2.6 (2) /-/-
28.04.1998–31.12.2008	0.3–0.5	0.30	0.30	0.60	-	2.0 (4); 2.6 (2) /-/-
1.01.2009–31.12.2013	0.30	0.25	0.25	0.45	-	1.7 (4); 1.8 (2) /-/-
1.01.2014–31.12.2016	0.25	0.20	0.20	0.25	0.30	1.3/1.5/1.7
1.01.2017–30.12.2020	0.23	0.18	0.18	0.25	0.30	1.1/1.3/1.5
31.12.2020–to the present	0.20	0.15	0.15	0.25	0.30	0.9/1.1/1.3
Passive buildings	0.15	0.15	0.15	0.15	0.15	0.8/0.8/0.8

(1) In climate zone I; (2) In the remaining climate zones; (3) In climate zones I and II; (4) In climate zones IV and V.

3. Analysis of Heat Loss for Traditional Structures

The currently applicable requirements (Table 1) with respect to partition insulation seem to be insufficient to meet the purpose of climate neutrality. This necessitates the search for other solutions for the construction of energy-efficient partitions that have a positive impact on the building's heat balance.

This article focuses on a comparative analysis of masonry wall solutions. When designing the wall structure, the following is used: single-layer wall (L1); two-layer wall (L2); three-layer wall (L3). These structures are shown in Figure 2.

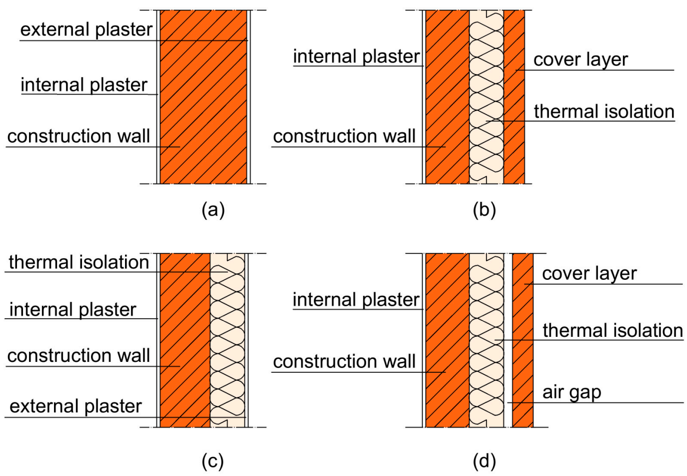

Figure 2. Traditional solutions for the construction of external masonry walls: (**a**) one-layer wall (L1); (**b**) three-layer wall (L3); (**c**) two-layer wall (L2); (**d**) three-layer wall with hollow core (L3).

Each of these structures will generate different types of thermal bridges at the junction of the building partitions. Each thermal bridge of a given type has a specific value of the linear heat transfer coefficient Ψ [31]. Therefore, in the building envelope there is a total heat loss coefficient through penetration H_{tr} [W/K], which is the sum of two coefficients: through flat elements $H_{tr,1}$ [W/K] and through linear thermal bridges $H_{tr,2}$ [W/K]. The values of the total coefficient of heat loss coefficient through penetration H_{tr} for an exemplary single-family building, depending on the insulation of the partitions and the type of external wall construction (*L1*–*L3*), are presented in Tables 2 and 3. The tables show how the values of the heat loss coefficient change by penetration and what percentage of this coefficient is thermal bridges.

Table 2. Heat loss coefficient through flat elements of the building, ($H_{tr,1}$).

Type of Building			Existing		Since 2014		Since 2017		Since 2021		Passive	
Barrier	A_i	$b_{tr,i}$	U_i	$H_{tr,1}$	U_i	$H_{tr,1}$	U_i	$H_{tr,1}$	U_i	$H_{tr,1}$	U_i	$H_{tr,1}$
-	m^2	-	W/m^{2}K	W/K	W/m^{2}K	W/K	W/m^{2}K	W/K	W/m^{2}K	W/K	W/m^{2}K	W/K
External walls	199.56	1.0	0.5	99.78	0.25	49.89	0.23	45.90	0.2	39.91	0.15	29.93
Flat roof	94.50	1.0	0.25	23.63	0.2	18.90	0.18	17.01	0.15	14.18	0.15	14.18
Ceiling above the unheated basement	94.50	0.6	0.40	22.68	0.25	14.18	0.25	14.18	0.25	14.18	0.15	8.51
Windows	22.80	1.0	1.658	37.80	1.3	29.64	1.1	25.08	0.9	20.52	0.8	18.24
External doors	1.89	1.0	2.0	3.78	1.7	3.21	1.5	2.84	1.3	2.46	0.8	1.51
Total	413.25	-	0.49	187.67	-	115.82	-	105.00	-	91.24	-	72.37

Table 3. Heat loss coefficient through linear thermal bridges ($H_{tr,2}$) and the total heat loss coefficient through transmission (H_{tr}) for the building and the share of thermal bridges for various wall structures.

Type of Thermal Bridge	Thermal Bridge Length	Thermal Bridge Type *				Heat Loss Coefficient, $H_{tr,2}$			
-	l_e	L1	L2	L3	L2 Passive	L1	L2	L3	L2 Passive
-	m	-	-	-	-	W/K	W/K	W/K	W/K
Corner	23.00	C4	C1	C2	C1	−3.45	−1.15	−2.3	−1.15
Wall/flat roof	39.00	R12	R5	R6	R11	5.85	23.4	19.5	1.95
Wall/ceiling	39.00	IF4	IF1	IF5	IF1	27.3	0	23.4	0.00
Ceiling above the basement	39.00	IF4	IF1	IF5	IF1	16.38	0	14.04	0.00
Internal wall/external wall	23.00	IW4	IW1	IW5	IW1	0	0	0	0.00
Internal wall/flat roof	19.50	IW6	IW6	IW6	IW6	0	0	0	0.00
Lintel	19.25	W10	W1	W8	W1	1.93	0	19.25	0.00
Jambs	44.30	W10	W1	W11	W1	4.43	0	0	0.00
Σ $H_{tr,2}$	246.05	-	-	-	-	52.44	22.25	73.89	0.80
$H_{tr.1}$ for buildings from 2021	-	-	-	-	-	91.24	91.24	91.24	72.37
H_{tr} ($H_{tr,1}$+ $H_{tr,2}$)	-	-	-	-	-	143.68	113.49	165.13	73.17
Thermal bridge share [%]	-	-	-	-	-	36.5	19.6	44.7	1.1

* Designations of thermal bridges according to [31].

For the calculations, a single-family, two-story building with a basement and a flat roof with an attic was assumed. The external dimensions for the heated zone of the building are as follows: length 10.5 m, width 9.0 m, and height 5.75 m. The temperature reduction coefficient for the ceiling above the basement was assumed to be b_{tr} = 0.6.

Attention is drawn to the two-layer structure of the external wall, which generates the lowest values of thermal bridges and, as a result, the lowest values of the total heat loss coefficient through penetration H_{tr} for the building.

In addition to the values for external walls, Tables 2 and 3 include the values of the heat loss coefficient through penetration for the ceiling of the top floor and the flat roof. For technological reasons, these elements do not pose any major problems due to the thickness of the thermal insulation being installed and its type. Due to the natural upward flow of warm air, they require the thickest thermal insulation in the group of external partitions. In these partitions, it is worth using thermal insulation that is thicker than the standard requirements. Ceilings above the ground floor (basement) should have very good thermal insulation due to the differences in temperature between heated and unheated rooms.

4. Analysis of Passive Solar Systems

4.1. Transparent Partitions

The most important elements of a transparent partition include the type of material and the shape of the window frame profile, the type of insulating glass, and the type of spacer frame. The shape and division of the window itself should be taken into account during the building design process.

The thermal efficiency of the windows was assessed by the following:

- Value of the window's heat transfer coefficient U_w—estimation of heat loss through the window;
- Equivalent window heat transfer coefficient U_e—estimation of the window's potential heat balance.

In the first case, the calculation parameters are heat transfer coefficients of the cooperating elements of the window frame U_f and glass U_g, linear heat transfer coefficients (Ψ_g) and geometric dimensions (area, visible circumference of the glass in the window) of the structural elements. Depending on the profile of the window frame, the U_f coefficient varies in the range from 0.7 to 3.7 W/(m^{2}K), for insulated glass, the U_g values range from 0.3 to 3.0 W/(m^{2}K), while for thermal bridges at the profile–glass connection, the linear heat transfer coefficient Ψ_g varies from 0.024 to 0.2 W/(mK).

In the second case, the basis for the evaluation is the window heat balance, where the main calculation parameters are climatic data (T_e, I_i); glass coefficient C_g ranging from 0.25 to 0.75 [-]; shading coefficient Z ranging from 0.45 to 1.0 [-]; transmittance coefficient of total solar radiation of insulating glass g varying in the range from 0.08 to 0.85 [-].

One of the principles of window design is the design of window surfaces in a building, which determines the minimum and maximum of their surface, the principle of "standard guidelines" [30]. This is the basic principle of window design in terms of size and number. Another principle of window design, based on heat balance and "standard guidelines", is the "effective window selection method". It allows you to select windows with the highest thermal efficiency for a given area and structure. The most favourable parameters are sought, such as the following:

- Glazing coefficient;
- Type of window profile;
- Type of insulating glass;
- Type of spacer frame.

The C_g values are significantly dependent on the type of window construction (number of sashes) and its surface. The C_g values for the available catalogue windows are summarised in Figure 3.

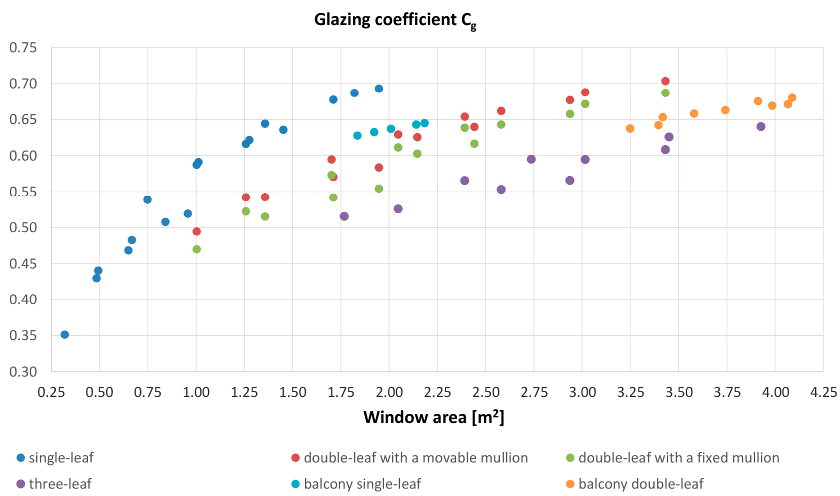

Figure 3. Glazing coefficient (C_g) of the catalogue windows available on the market.

The influence of the spacer frame on the value of the heat transfer coefficient U_w of the windows is shown in Figures 4 and 5. A significant reduction in the U_w value is visible when using a "warm" frame with a coefficient of Ψ_g = 0.03 compared to a classic frame with Ψ_g = 0.08.

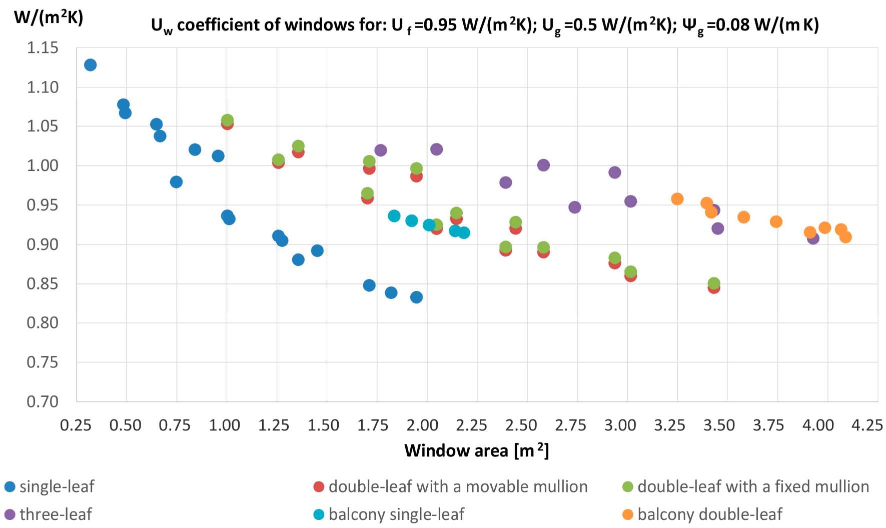

Figure 4. U_w coefficient of windows of various designs for a classic spacer frame with coefficient Ψ_g = 0.08.

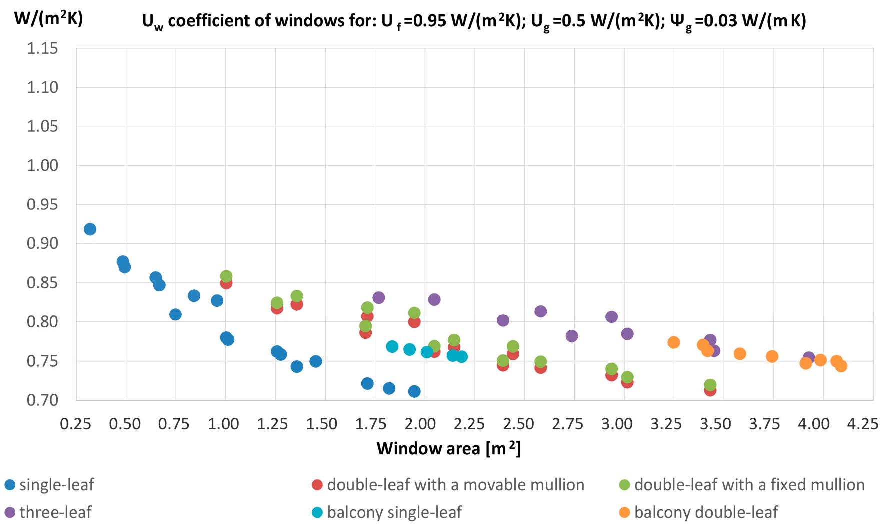

Figure 5. U_w coefficient of windows of various designs for a "warm" spacer with coefficient Ψ_g = 0.03.

4.2. Thermal Storage Walls (TSWs)

The thermal storage wall (Trombe wall) combines the functions of a collector (glazing) and heat accumulation (storage wall), creating a whole [32]. There are various material solutions for these elements for the thermal storage wall. The classic "solar wall" is a construction without any additional elements of heat distribution and regulation. The structure of the partition is shown in Figure 6. The collector consists of glazing, a frame, and an air void. The absorber is usually black external plaster and the structural wall is usually made of massive elements that allow for heat accumulation.

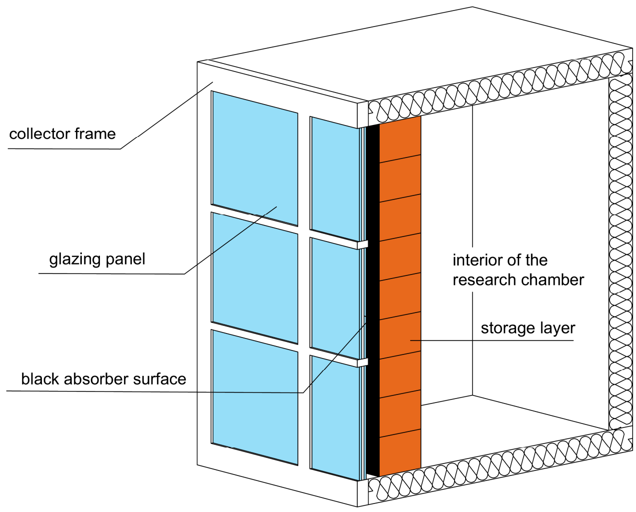

Figure 6. Construction of the thermal storage wall.

The parameters of the glazing and window profile in the collector affect the thermal efficiency of the Trombe wall and make it possible to determine an important value, which is the "collector parameter"—B. The analysis included two window profiles that have the following parameters:

- Classic profile B_{clasic}: U_f = 1.6 W/(m^{2}K), spacer with Ψ_g = 0.08 W/(mK);
- Passive profile $B_{passive}$: U_f = 0.79 W/(m^{2}K), spacer frame with Ψ_g = 0.03 W/(mK).

The collector parameter B was calculated according to the following formulas:

$$B = a \cdot g \cdot C_g \cdot Z \cdot \left(R_p + \frac{1}{U_{kol}} - R_{si} \right) \tag{1}$$

$$U_{col} = \frac{A_g \cdot U_g + A_f \cdot U_f + l_g \cdot \Psi_g}{A_g + A_f} = C_g \cdot U_g + \left(1 - C_g\right) \cdot U_f + \frac{l_g \cdot \Psi_g}{A_g + A_f} \tag{2}$$

$$C_g = \frac{A_g}{A_g + A_f} \tag{3}$$

where:

a—absorption coefficient of the surface of the outer wall (absorber) [-] for which the value of 0.9 was assumed;

g—coefficient of solar radiation transmission through the glazing [-];

C_g—collector glass factor [-] for which the calculated value is 0.766;

Z—partition shading factor [-] for which the value is 1.0;

R_p—thermal resistance of the unventilated air layer (between the absorber and the glazing) (Table 2 in [33]) [m^{2}K/W], assumed for a layer with a thickness of 3 cm;

R_{si}—heat transfer resistance on the inner surface of the partition (Table 1 in [33]) [m^{2}K/W];

U_{col}—collector heat transfer coefficient, (calculated for a window according to [34] [W/(m^{2}K)];

U_g—heat transfer coefficient of the glass in the collector [W/(m^{2}K)];

U_f—heat transfer coefficient of the collector frame [W/(m^{2}K)];

Ψ_g—linear heat transfer coefficient resulting from the combined thermal effects of the glass, the spacer frame, and the collector frame [W/(mK)];

A_g—surface area of glass in the collector [m^2] with a calculated value of 2.934 m^2;

A_f—surface area of the collector frame [m2] with a calculated value of 0.896 m^2;

l_g—visible circumference of the collector glass at a given mating element [m] with a calculated value of 16.82 m.

Depending on the type of window profile and glazing, Table 4 presents the obtained values of the "collector parameter" B.

Table 4. Parameters of the collector made of different variants.

Type of Glazing	Symbol	Glazing Structure	U_g	$U_{col,classic}$	$U_{col,passive}$	g	$B_{classic}$	$B_{passive}$
-	-	-	[W/m^{2}K]	[W/m^{2}K]	[W/m^{2}K]	-	[m^{2}K/W]	[m^{2}K/W]
One-chamber, ordinary glass	S1	4/12/4	3.0	3.02	2.61	0.74	0.194	0.221
One-chamber, ordinary and low-emissivity glass	S2	4/12/4T	1.9	2.18	1.77	0.72	0.252	0.305
One-chamber, ordinary and low-emissivity glass plus Argon	S3	4/16Ar/4T	1.5	1.87	1.47	0.72	0.290	0.364
One-chamber, ordinary and low-emissivity glass plus Argon	S4	4/15Ar/4TP	1.1	1.57	1.16	0.62	0.294	0.390
One-chamber, ordinary glass plus Argon	S5	4/16Ar/4	2.6	2.72	2.31	0.83	0.239	0.277
Two-chamber, ordinary glass plus Argon	S6	4/14Ar/4/ 14Ar/4	1.7	2.03	1.62	0.76	0.285	0.350
Two-chamber, ordinary and low-emissivity glass plus Argon	S7	4TRIIIE/16Ar/4/ 16Ar/4TRIIIE	0.7	1.26	0.85	0.62	0.360	0.523
Two-chamber, ordinary and low-emissivity glass plus Argon	S8	4LE/16Ar/4/ 16Ar/33.1LE	0.6	1.19	0.78	0.5	0.308	0.461
Two-chamber, low-emissivity glass plus Krypton	S9	4Ew/12Kr/4Ew/ 12Kr/4Ew	0.6	1.19	0.78	0.66	0.407	0.609

The higher the value of the collector parameter B, the more favourable it is for the TSW balance. It is visible that the passive profile is more energy-efficient than the classic profile for each of the analysed types of glazing (S1–S9).

5. Equivalent Heat Transfer Coefficient as a Measure of the Energy Efficiency of Passive Solar Systems

The thermal efficiency of a solar partition (passive system) determines how much thermal energy penetrates a specific surface, with a given thermal forcing in a specific time period. In conventional partitions, the heat flow flows towards a lower temperature and the thermal efficiency of this partition is equivalent to its thermal insulation and is usually expressed as the value of the heat transfer coefficient U.

In partitions using solar radiation energy, the direction of heat flow is variable, and depending on the thermal forcing, it may be directed outside or inside the room. The thermal efficiency of these partitions can be based on their heat balance Q_H, i.e., the difference between heat losses Q_T and heat gains Q_{sol}, or expressed by the value of the equivalent heat transfer coefficient U_e. When preparing the energy characteristics of a building, it is important to know the heat gains and losses through such a partition.

The classically reported U value for the partitions only shows the amount of potential heat loss through the partition. The value of the U_e coefficient shows the actual heat flow through the partition (it takes into account both heat gains and losses). Based on the U_e coefficient values calculated for various configurations of building partitions, the designer can easily select the most effective ones under specific conditions.

5.1. Equivalent Heat Transfer Coefficient of the Window

The equivalent window heat transfer coefficient U_e [W/(m^{2}K)] was calculated on the basis of three parameters: window heat transfer coefficient U_w; heating index A_{ind}; and window efficiency parameter C, according to Equation (4):

$$U_e(m) = U_W - A_{ind,i}(m) \cdot C \tag{4}$$

The value of the helium heating index $A_{ind,i}$ was defined as the monthly sum of total solar radiation falling on the vertical plane with i-th orientation I_i divided by the number of degree hours of the month. The window efficiency parameter C is determined based on Equation (5):

$$C = g \cdot C_g \cdot Z \tag{5}$$

where:

g—total solar energy transmittance factor [-];
C_g—glazing coefficient [-];
Z—shading coefficient [-].

Example values of the equivalent heat transfer coefficient U_e of three-leaf windows in the heating season (from 26 September to 5 May—222 days) for a typical meteorological year (TMY), for the Rzeszów-Jasionka meteorological station, are presented in Table 5. The windows are designed with elements with the following parameters: passive profile with U_f = 0.79 W/(m^{2}K), double-chamber glass unit (S7) with U_g = 0.7 W/(m^{2}K), spacer frame (so-called "warm edge") with Ψ_g = 0.03 W/(mK), shading coefficient Z = 1.0, total solar energy transmittance factor g = 0.62.

Table 5. Equivalent heat transfer coefficient (U_e) of three-sash windows in the heating season for four orientations.

Catalogue Symbol *	W_e *	H_e *	C_g	C	U_w	$U_{e,S}$	$U_{e,W}$	$U_{e,N}$	$U_{e,E}$
-	m	m	-	-	W/m^{2}K	W/m^{2}K	W/m^{2}K	W/m^{2}K	W/m^{2}K
OW1	2.08	0.85	0.515	0.320	0.857	−1.29	−0.81	−0.52	−0.84
OW4	1.78	1.15	0.526	0.326	0.858	−1.34	−0.86	−0.56	−0.88
OW5	2.08	1.15	0.565	0.351	0.845	−1.51	−1.00	−0.67	−1.02
OW6	2.38	1.15	0.595	0.369	0.836	−1.64	−1.10	−0.76	−1.12
OW8	1.78	1.45	0.553	0.343	0.853	−1.46	−0.95	−0.64	−0.98
OW9	2.08	1.45	0.595	0.369	0.839	−1.65	−1.10	−0.76	−1.13
OW10	2.38	1.45	0.626	0.388	0.828	−1.79	−1.21	−0.85	−1.24
OW12	1.78	1.65	0.566	0.351	0.850	−1.52	−1.00	−0.68	−1.02
OW13	2.08	1.65	0.608	0.377	0.835	−1.71	−1.15	−0.80	−1.18
OW14	2.38	1.65	0.640	0.397	0.825	−1.85	−1.26	−0.90	−1.29

* The designations OW1–OW14 are catalogue symbols of selected three-leaf windows, W_e—external window width, H_e—external window height.

Figure 7 shows the equivalent heat transfer coefficient U_e of a three-sash window (OW5) throughout the year for four orientations to the cardinal directions. U_e values were obtained on the basis of the adopted TMY.

As shown in Table 5 and Figure 7 U_e, they are lower than the U_w values of the windows presented in each month and for each orientation. The graph shows how the value of this coefficient changes each month in a given orientation. They take positive and negative values. Positive values mean that heat losses predominate over heat gains. However, negative values mean that heat gains prevail over heat losses.

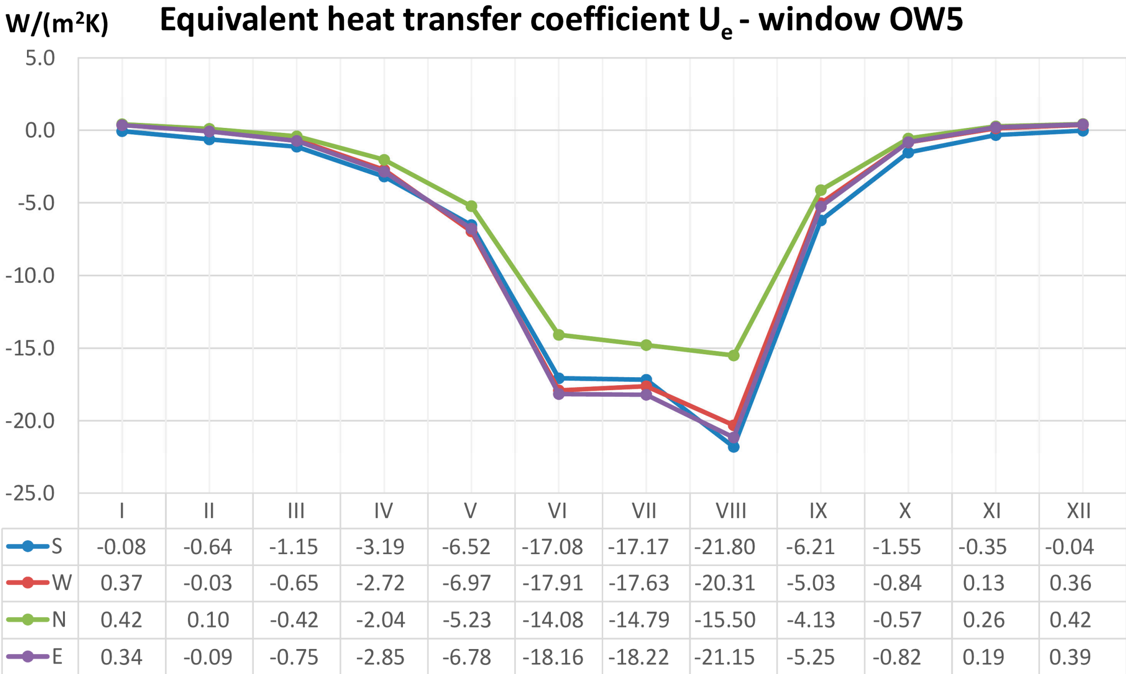

Figure 7. Equivalent heat transfer coefficient U_e of the OW5 window for four orientations.

5.2. Equivalent Heat Transfer Coefficient of the Thermal Storage Partition (Trombe Walls)

The equivalent heat transfer coefficient of the thermal storage wall $U_{e,TSW}$ [W/m^{2}K] was calculated on the basis of three parameters: heat transfer coefficient of the thermal storage wall U_{TSW}; helioheating index; A_{ind} and collector parameter B, according to Equation (6):

$$U_{e,TSW} = U_{TSW} \cdot (1 - A_{ind,i} \cdot B) \left[\frac{W}{m^2 \cdot K} \right], \tag{6}$$

where

$$U_{TSW} = \frac{1}{R_T} = \frac{1}{R_{si} + \sum R_\lambda + R_p + R_{kol} + R_{se}} \left[\frac{W}{m^2 \cdot K} \right] \tag{7}$$

R_T—total heat transfer resistance of the partition [m^{2}K/W];
ΣR_λ—sum of thermal resistances of homogeneous layers [m^{2}K/W];
R_p—thermal resistance of the unventilated air layer (between the absorber and the glazing) [m^{2}K/W];
R_{kol}—collector thermal resistance [m^{2}K/W];
R_{si}, R_{se}—heat transfer resistances on the inner and outer surfaces of the partition, respectively [m^{2}K/W].

The equivalent heat transfer coefficient $U_{e,N}$ [W/m^{2}K] of north-orientated collector-storage partitions in December for *TMY*, for the city of Rzeszów, is presented in Table 6. Calculations were made for a masonry layer designed from various materials (M1–M7), which serves as a storage layer and for various insulating glass units S1–S9 (Table 4) placed in the collector. A collector made of the $B_{passive}$ profile was assumed for the calculations. The values of the equivalent heat transfer coefficient, lower than the current requirements for the heat transfer coefficient for external walls $U_{max} \leq 0.2$ W/m^{2}K, are marked in bold.

Table 6. Equivalent heat transfer coefficient of thermal storage walls $U_{e,TSW}$ [W/m^{2}K] with a northern orientation in December.

Type of Construction Material	Wall Thickness	Conductivity Coefficient	Symbol	Type of Glazing—Symbol								
	[m]	[W/(mK)]		S1	S2	S3	S4	S5	S6	S7	S8	S9
Concrete	0.25	1.7	M1	0.99	0.68	0.54	0.43	0.84	0.59	0.24	0.26	**0.15** *
Silicate bricks	0.38	0.9	M2	0.72	0.53	0.42	0.35	0.62	0.46	0.20	0.23	**0.13**
Solid ceramic bricks	0.38	0.77	M3	0.68	0.50	0.40	0.33	0.58	0.43	**0.19**	0.22	**0.13**
Hollowed ceramic blocks	0.38	0.32	M4	0.41	0.32	0.27	0.23	0.36	0.28	**0.14**	**0.16**	**0.09**
Autoclaved aerated concrete blocks	0.36	0.21	M5	0.32	0.25	0.21	**0.19**	0.28	0.23	**0.12**	**0.14**	**0.08**
Porous ceramic blocks	0.38	0.143	M6	0.22	**0.18**	**0.16**	**0.14**	0.20	**0.16**	**0.09**	**0.10**	**0.06**
Porous ceramic blocks filled with PCM and mineral wool	0.26	0.132	M7	0.28	0.23	**0.19**	**0.17**	0.25	0.20	**0.11**	**0.12**	**0.07**

* The bold indicates values below $U_{max} \leq 0.2$ W/m^{2}K.

Table 6 assumes a modified ceramic block filled with two layers of phase change material (PCM) on the outside environment side and two layers of mineral wool on the inner environment side [35]. Using wall solutions modified with phase change materials, attention should be paid to their thermal safety. The main advantage of PCM is the improvement in the thermal stability of modified structural solutions. The disadvantage of these materials is their flammability; therefore, in future practical solutions, the phase change material should be modified using flame-retardant additives [36]. The bold values of the $U_{e,TSW}$ coefficient presented in Table 6 are lower than the current requirements for the external wall heat transfer coefficient in Poland [30].

The values of the equivalent heat transfer coefficient $U_{e,TSW}$ throughout the year for the eastern orientation $U_{e,TSW,E}$, southern $U_{e,TSW,S}$, western $U_{e,TSW,W}$, and northern $U_{e,TSW,N}$ are presented in Table 7. Table 4 shows the profile adopted in the passive collector analysis ($B_{passive}$), the accumulation layer made of concrete (M1), and the S9 insulating glass.

Table 7. Equivalent heat transfer coefficient $U_{e,TSW}$ [W/m^{2}K] of the thermal storage wall for four orientations.

Months	$U_{e,TSW,E}$	$U_{e,TSW,S}$	$U_{e,TSW,W}$	$U_{e,TSW,N}$
-	[W/m^{2}K]	[W/m^{2}K]	[W/m^{2}K]	[W/m^{2}K]
January	0.07	−0.38	0.10	0.152
February	−0.39	−0.97	−0.33	−0.19
March	−1.08	−1.51	−0.98	−0.73
April	−3.32	−3.69	−3.19	−2.46
May	−6.16	−5.93	−6.32	−4.67
June	−8.41	−7.89	−8.29	−6.27
July	−7.62	−7.17	−7.37	−6.01
August	−6.71	−6.93	−6.43	−4.77
September	−4.20	−4.96	−4.03	−3.32
October	−1.16	−1.94	−1.18	−0.90
November	−0.09	−0.66	−0.15	−0.02
December	0.12	−0.33	0.09	0.15

The vast majority of the values of the equivalent heat transfer coefficient U_e presented in Table 7 (87.5%) are negative, which means that heat gains prevail over heat losses in this partition (negative heat balance). The M1 material taken for the analysis is the most unfavourable material in terms of thermal insulation compared to all other materials (M2–M7). Each of the other materials analysed (M2–M7) achieves a more favourable heat balance than M1. Traditional building partition designs, even with the highest thermal insulation, generate only heat losses (positive heat balance).

6. Conclusions

Based on the analysis, the following conclusions were formulated:

1. An important task when constructing a building is the appropriate location and orientation on the plot. A "location study" of the building on the plot should be carried out in terms of the use of solar energy by the constructed facility.
2. The high insulation of the building partitions guarantees low heat losses through penetration during the building's operation period. A passive building has the lowest value of the heat transfer coefficient through flat elements ($H_{tr,1}$ = 57.66 W/K) and is more than 36% lower compared to a building with current thermal insulation requirements ($U \leq 0.2$ W/m^{2}K).
3. The optimal technological solution for external partitions is a two-layer structure (L2). Joints (nodes) of various building partitions generate the lowest value of the heat transfer coefficient through thermal bridges $H_{tr,2}$ compared to single-layer (L1) and three-layer (L3) structures. For this structure, the share of thermal bridges in the total heat transfer coefficient H_{tr} is 19.6%.
4. The connections of building partitions should be designed to eliminate thermal bridges to the greatest extent possible (the nodes should be as technologically simple as possible). In a passive building, thermal bridges only constitute 1.4% of the total thermal transfer coefficient of the building.
5. The windows in the building (regardless of the type of profile and the number of sashes) should have the highest possible values of the glazing coefficient C_g (recommended above 0.6).
6. The window heat transfer coefficient U_w is shaped by three heat transfer coefficients: the window profile U_f, the glass Ug, and the linear heat transfer coefficient Ψ_g. Each of these coefficients should have the lowest possible values in its category.
7. The values of the heat transfer coefficient of windows U_w are inversely proportional to their surface area. The greatest impact on reducing the U_w coefficient (approx. 15%) has the so-called warm spacers in insulating glass (parameter Ψ_g) compared to commonly used aluminium frames.
8. The thermal efficiency of windows (based on their heat balance) is determined by the so-called equivalent to the heat transfer coefficient U_e. This coefficient is always lower than the heat transfer coefficient of the window U_w. With appropriately selected parameters of the insulating glass (low glass heat transfer coefficient U_g and high total solar energy transmittance factor g) and the geographical orientation of the window, in many months of the year, the U_e coefficient becomes negative, which means that heat gains through the window are greater than heat losses.
9. An energy-efficient solution for the external walls of a building is thermal storage walls. The equivalent heat transfer coefficient of these partitions U_e is always lower than their heat transfer coefficient U_{TSW}. With appropriately selected parameters of collector B and the material of the accumulating layer, in all months of the year, the U_e coefficient can obtain values lower than U_{max} = 0.2 W/m^{2}K for external walls, and in many months of the year, the U_e coefficient reaches favourable values.
10. The author's method of assessing the energy efficiency of partitions presented in the work based on the equivalent heat transfer coefficient allows for shaping the thermal balance of the building in any combination of construction and material solutions. The method can be used to optimise elements of the building structure to improve the heat balance.

11. The use of the presented methodology for calculating the equivalent heat transfer coefficient U_e in practice will allow for the optimisation of technical solutions of building elements to improve their energy efficiency.

Author Contributions: Conceptualisation, A.S., J.K., P.M. and B.B.; methodology, A.S. and B.B.; formal analysis, A.S., J.K., P.M. and B.B.; writing—original draft preparation, A.S.; writing—review and editing, A.S., J.K., P.M. and B.B.; visualisation, J.K. and P.M.; supervision, A.S. and B.B.; project administration, A.S., J.K., P.M. and B.B.; funding acquisition, B.B. All authors have read and agreed to the published version of the manuscript.

Funding: The research leading to these results has received funding from the commissioned task entitled "VIA CARPATIA Universities of Technology Network named after the President of the Republic of Poland Lech Kaczyński" under the special purpose grant from the Minister of Science, contract no. MEiN/2022/DPI/2578 action entitled "ISKRA—building inter-university research teams".

Data Availability Statement: Data is contained within the article.

Conflicts of Interest: The authors declare no conflicts of interest.

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