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THERMAL EFFICIENCY ASSESSMENT OF ECO-ORIENTED PREFABRICATED MODULAR BUILDINGS: CASE STUDY

The relevance of eco-oriented modular construction is constantly growing due to the aggravation of housing and environmental problems associated with military operations on the territory of Ukraine. At the same time, there are certain challenges limiting the widespread use of modular buildings in Ukraine, which are mainly associated with a high level of consumer skepticism regarding the quality and energy efficiency of modular buildings compared to traditional construction practices. On the example of a frame modular single-family building «QHome-26», located on the outskirts of the Chernihiv city, the thermal characteristics of prefabricated modular construction were studied. By using infrared thermography, monitoring of existing cold bridges and the main heat losses in the building's envelope was carried out. It was experimentally established that the potential source of heat loss of the building is translucent structural elements that does not meet modern standards, as well as the foundation of the building. At the same time, the results of the thermal calculation of the building's enclosing structures showed that the main source of heat loss at the level of 38.5 % of the total losses are walls. Heat losses for heating ventilated air are 26.3 %. While up to 14.5 % of heat is lost throughout the windows. Heat losses through the roof and floor are 12.6 % and 9.9 %, respectively.

Keywords: *Sustainability; modular buildings; eco-construction; thermal efficiency.*
Fig.: 5. Table: 4. References: 18.

Urgency of the research. The construction industry is one of the major pollutant as well as the largest natural resources user, which affects negatively the worldwide sustainability. The conventional construction practices has always been a huge contributor to the global greenhouse gases and carbon dioxide emissions [1; 2].

According to the International Energy Agency (IEA), construction industry consumes more than 50 % of steel production, 60-70 % of cement production, 40-50 % of overall energy. On top of that, the modern buildings releases about 30-40 % of CO_2 emission on atmosphere [3].

All of these increased dramatically the environmental concerns among the government and other stakeholders all over the globe.

Target setting. The intentions to go green and minimize natural resources consumption requires shifting of our habitual construction practices toward the more sustainable and energy-efficient ones [4]. In this context, the modularization in construction become one of the modern trend. This is mainly due to the fact that modular prefabrications focuses directly on the ecological and energy saving approaches in building construction that allows to downsize hazardous environmental impact, resources and energy consumption and construction waste.

The idea of modularization in house construction isn`t new. It refers to the 1947 when French modernist architect Le Corbusier first provides his concept called “Unit of Dwelling” as an early example of modular house architecture. His well-known work “The Modulor” allowed for modularization and standardization in architectural design [5].

It noteworthy that World War II became a booster for modular buildings development as the rapid and affordable housing.

In Ukraine the demand in modular prafabs steadily growing after the full-scale Russian invasion in 2022. According to the UN statistics, the amount of internally displaced people in Ukraine from February 2022 by the beginning of 2025 counts more than 3.6 million people [6].

Modular prefabrications or modular prefabs implies the off-site manufacturing where whole building or its separate components are manufactured in controlled factory environment with further transportation and installation on construction site [7].

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Actual scientific researches and issues analysis. It should be noted, that the prevalent majority of studies have focused mainly on sustainable performances of modular buildings, it`s life cycle, operation and maintenance. For instance, the works [8; 9] explores the environmental benefits of modular housing in terms of CO_2 reduction by using of more eco-friendly materials. In work [10], the advantages of the off-site construction regarding the construction time reduction, higher level of prefabricated components quality control and minimization of on-site errors was shown. The works [11, 12] was dedicated to the newest advancements in modular buildings manufacturing based on the BIM technologies application. BIM tools allows the digital planning and design of building`s components with high level of precision ensuring durability and sustainability during whole life cycle of a building.

However, there are some challenges limiting the modular buildings widespread application particularly in Ukraine that mainly related with the high level of consumer`s skepticism regarding the quality and thermal efficiency of modular buildings compare to the traditional brick or concrete made. In our opinion, such a perception is mainly because of lack of profound knowledge about the energy performances of eco-oriented materials, which is the basis for sustainability.

As it is known, the heat energy has a tendency to disappear by conductivity through the enclosures (walls, windows), floor (basement) and the roof. In turn, the rate of the heat losses will be determined by the thermal characteristics of insulation materials, particularly it`s thermal transmittance value.

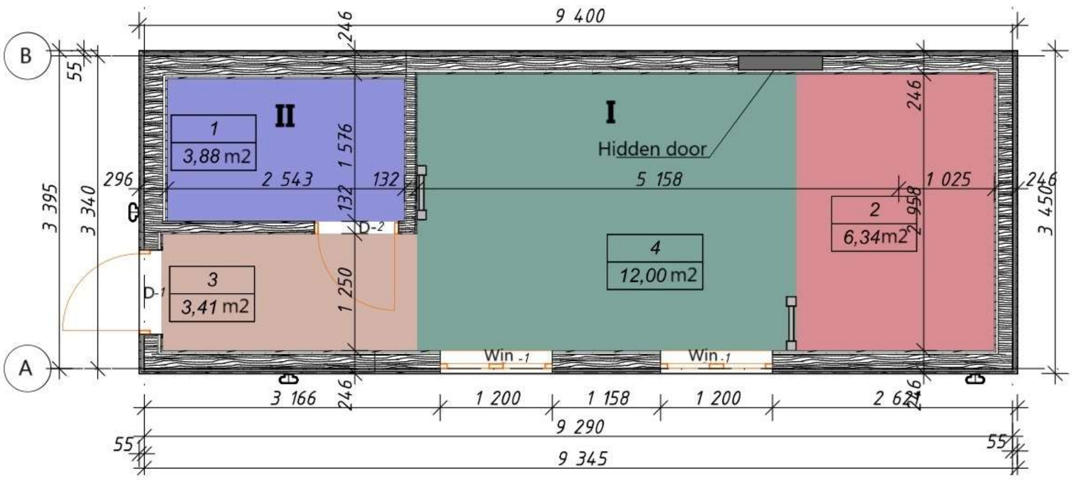
The research objective. In this case, the aim of current research is to provide a deeper understanding of thermal performances of eco-oriented prefabricated modular housing based on the real example.

The statement of basic materials. Our case study is the single-family modular prefab “QHome-26” [13], which was off-site manufactured in 2023 by the Ukrainian company “QHome” supported by the UN Refugee Agency (UNHCR) and installed in the vicinity of Chernihiv city in Novoselivka village. As a foundation of the building, the FBS base blocks were used. The building`s exterior, its installation process, 3D model of the timber carcass as well as the premises plan with its explication are given in Fig. 1.

a

b

c



Explication of premises

N°	Name	Area, m2
I	Living room/Kitchen	21.75
II	Bathroom	3.88
	Total living area	25.63
	Total area of the house	31.96

d

Fig. 1. External view of studied single-family modular prefab (a), its installation process (b), 3D model of the timber carcass (c) and the plan of the premises with its explication (d)

The basis of the house is a timber-made frame with the dimensions of 9400×3450 mm and the thickness of the partitions of 300 mm. The building is made up of two premises, particularly, combined living room and kitchen with the area of 21.75 m^2 and the bathroom of 3.88 m^2. Thus, the living area of 25.63 m^2 and the total area of the building of 31.96 m^2.

As far as it's known, the building`s envelope plays a crucial role in terms of thermal performances of the buildings especially when it comes to the modular ones. In this case, the core content of the building`s energy efficiency and sustainability is the thermal insulation performance of enclosure structures.

In our case study, as the insulator the ecologically friendly basalt wool was used which provides a high level of thermal efficiency with the low coefficient of heat conductivity about 0.038 W/m·K. On top of that, the basalt wool well-known as non-combustible, vapor permeable and soundproofing one.

The enclosing structures were manufactured as the sandwiches, which are made up of the timber frame, hydro barrier membrane, OSB plates, insulator, vapor barrier, and wooden lining as an internal decorative layer. The roofing consists of two layers of felt paper, OSB, timber checkrails, hydro barrier membrane, insulated timber rafter, vapor barrier, checkrails and wooden lining. The floor is detached from the ground on a distance of 250 mm and made up of the timber checkrails, two layers of felt paper, OSB, timber beams, insulator, OSB and PVC internal lining.

Reinforced timber frame of the building is the dry calibrated timber with the OSB-3 plates, bitumen primer, vapor and waterproof, roofing material (roofing felt EPP 2.5 and EPP 4.0.). The construction details of the enclosures (walls, floor, and the roof) are given in Fig. 2. It should be noted that the thickness of the walls and roof is 250 mm while the thickness of the floor is 300 mm.

On the Southern facade, there are two triple-glazed windows of 4-10-4-10-4 type with the three air filled chambers profile system with the dimensions of 1.2×1.2 m were installed.

The house is heated up by the solid fuel boiler with the power of 7 kW, which is easily allows to heat the building up to the total area of 100 m^2.

Before the assessment of studied building`s thermal efficiency the infrared thermography inspection in order to get the information about the existing thermal bridges and the main heat loss in the building envelope was conducted.

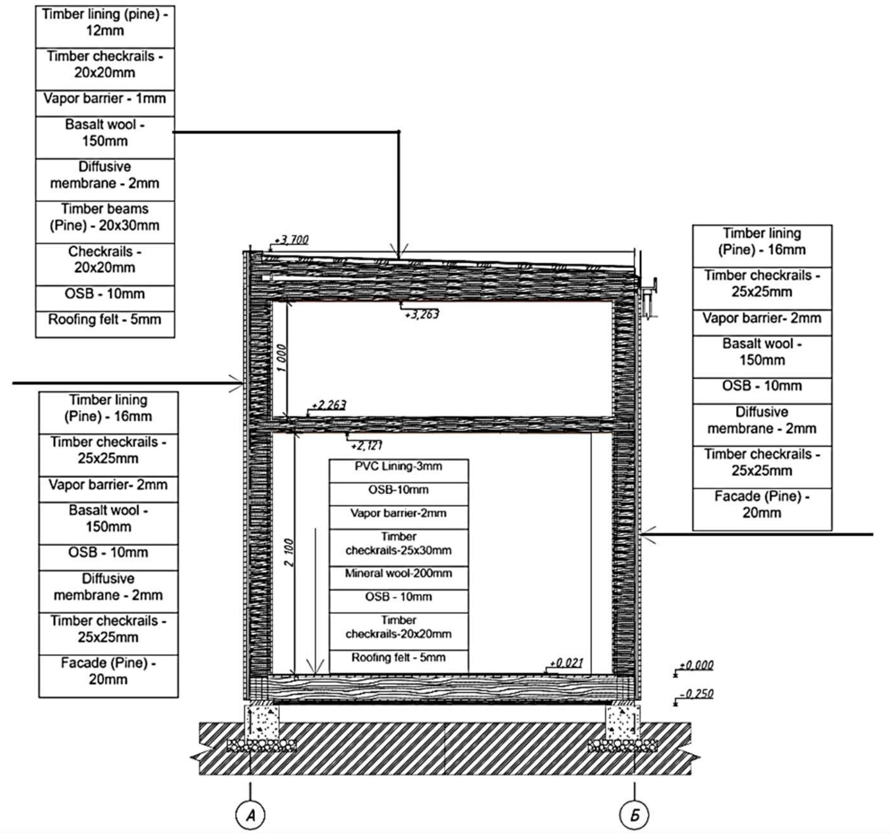


Fig. 2. The detailed content of the enclosures of studied modular building

The inspections were carried out on 12th of February 2025 approximately from 10:00 to 11:00 am when the weather was overcast, the temperature of the environment was about – 16 °C, wind speed doesn`t exceed of 3 m/s with the humidity level of 60 %. The probability of precipitations was about 10 %. It should be noted that inside temperature at the time of inspection was fixed at a level of 21 °C more the 12 hour. The inspections of thermal bridges were carried out with HTi thermal imaging camera.

The inspection methodology consists of the following steps:

1. Checking the total heat loss through the walls, windows and roof;
2. Searching for areas with increased heat loss in typical problem zones;
3. Analyzing heat dissipation through gaps in window sashes and doorways;
4. Assessing heat leaks through ventilation and air conditioning systems (if available).

The results of infrared thermography are given in Fig. 3.

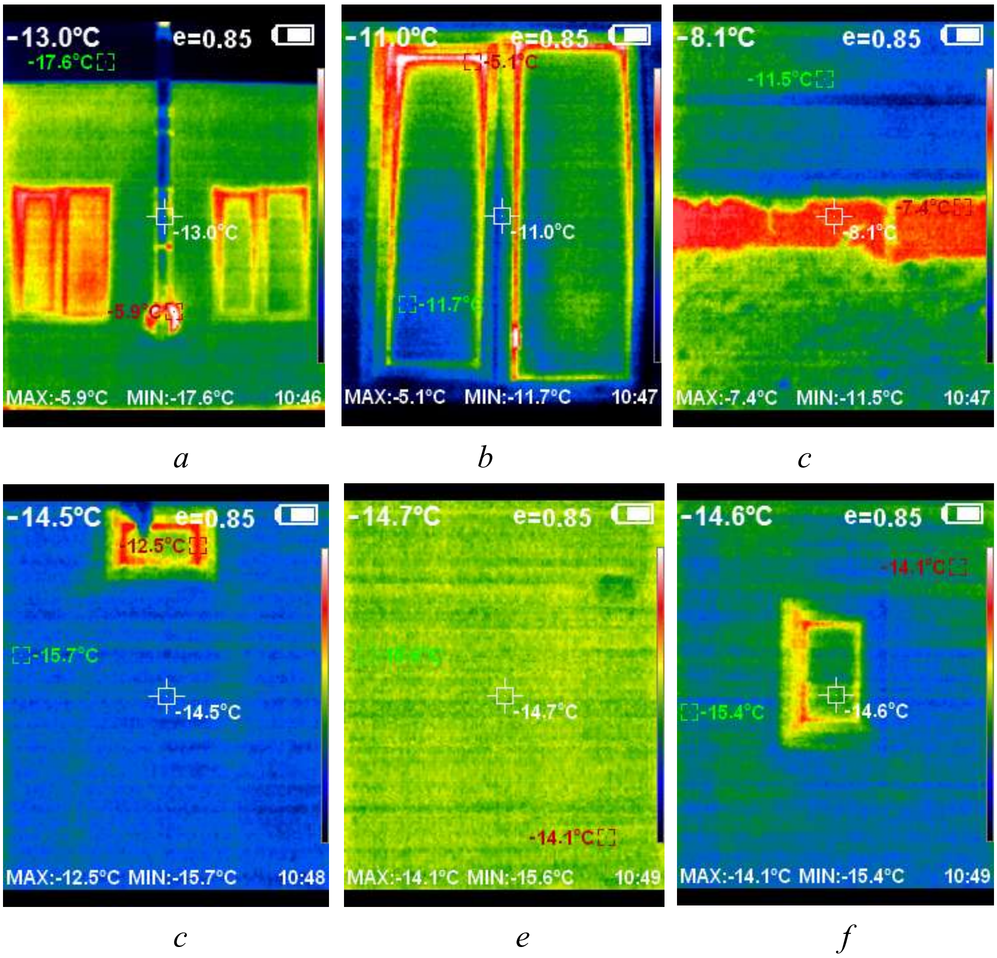


Fig. 3. Thermogram of Southern facade (a), window (b), basement (c), Eastern facade (d), Western facade (e) and Northern facade (f) of inspected building

Analyzing the obtained infrared thermal images of studied building it can be noticed that the main weaknesses that affect negatively of enclosure`s thermal behavior is the windows. The thermal bridges concentrated directly along the window`s frame contour, which can evidenced both the poor quality of installation, as well as the low quality of manufactured frame and insulating glass. It can be seen that on the surface of one window the temperature varies from -11 up to – 5 ˚C depending on the measurement point, which indicates the heterogeneity of the heat flow passing through the window and the heterogeneity of the thermal resistances of its components accordingly. From the other hand, as it was already mentioned, the off-site manufacturing excludes the fabrication errors because of meticulous quality control of all production stages.

The other significant aspect of heat loss that weakens thermal performances of examined building this is foundation. Remind that our case study contains the FBS base blocks as a foundation without external thermal insulation frames. Additionally, there are no any heat leakages through the heat exchanger as well as the split air conditioning system were detected.

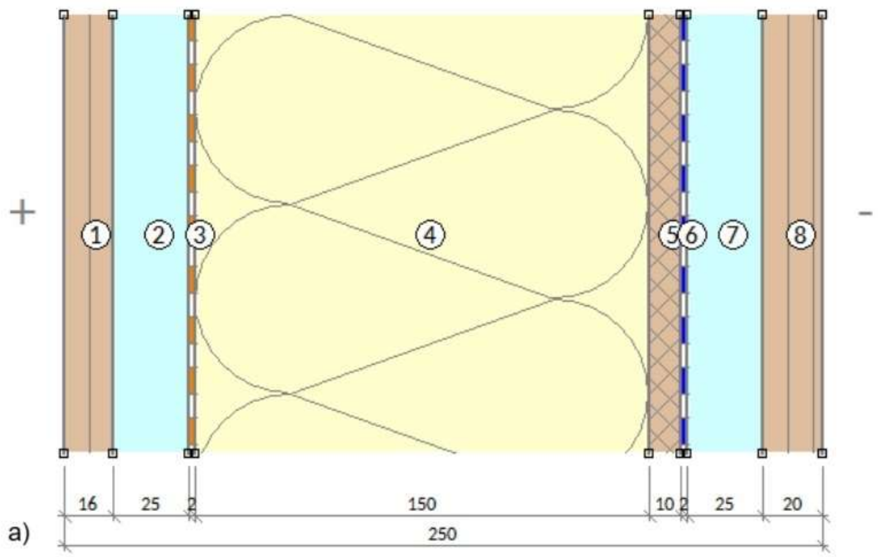
For deeper understanding of building's envelope energy performance, the meticulous thermal engineering calculation is required. The calculation is carried out to determine suitability of actual state of the enclosure structures thermal insulation to the regulatory requirements. Normally, it begins with determination of thermal characteristics of building`s envelope. The material properties of the walls, floor and roofing are given in pivot Table 1.

Table 1 – Material characteristics of enclosure structures

№ of layer	Material	Thickness	Thermal conductivity	Ref.	Thermal resistance
		δ, m	λ, W/(m·K)		m^2·K/W
External walls characteristics					
1	Timber lining (Pine)	0.016	0.18	[14]	0.089
2*	Closed air gap	0.025	–	[14]	0.155
3	Vapor barrier	0,002	0,3	[14]	0.0066
4	Basalt wool	0.15	0.038	[14]	3.947
5	OSB	0.01	0.13	[14]	0.077
6	Diffusive membrane	0.002	0.23	[14]	0.0087
7	Closed air gap	0.025	–	[14]	0.155
8	Facade (Pine)	0.02	0.18	[14]	0.111
Characteristics of the floor					
1	PVC Lining	0.003	0.33	[14]	0.009
2	OSB	0.010	0.13	[14]	0.077
3*	Closed air gap	0.03	–	[14]	0.155
4	Vapor barrier	0,002	0,3	[14]	0.006
5	Mineral wool	0.2	0.044	[14]	4.762
6	OSB	0.01	0.13	[14]	0.077
7*	Closed air gap	0.02	–	[14]	0.155
8	Check rail (Pine)	0.03	0.18	[14]	0.167
9	Roofing felt	0.005	0.17	[14]	0.029
Characteristics of the roof					
1	Timber lining (pine)	0.012	0.18	[14]	0.067
2*	Closed air gap	0.02	–	[14]	0.155
3	Vapor barrier	0,001	0,3	[14]	0,003
4	Basalt wool	0.15	0.038	[14]	3.947
5	Diffusive membrane	0.002	0.23	[14]	0,0086
6	Timber beams (Pine)	0.03	0.18	[14]	0.167
7*	Closed air gap	0.02	–	[14]	0.155
8	OSB	0.01	0.13	[14]	0.077
9	Roofing felt	0.005	0.17	[14]	0.029

*The systems of closed air gaps with the thickness of 0.025-0.03 m were provided by timber checkrails frame.

The calculation of enclosing structures were conducted with accordance to the models are shown in Fig. 4.



a)

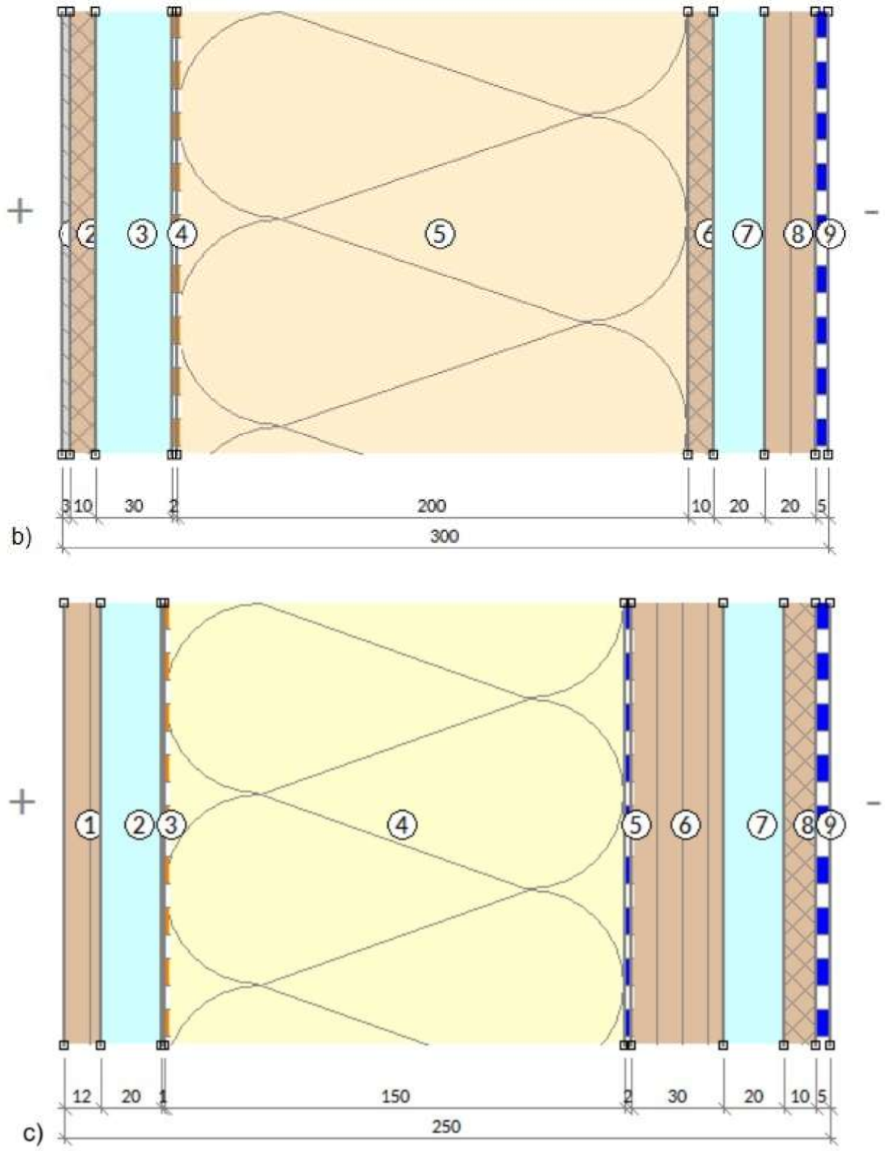


Fig. 4. The calculation models of enclosing structures:
a – walls; b – floor; c – roof

Thermal resistance of every separate enclosing layers in table 1 were determined as follows [15]:

$$R_i = \frac{\delta_i}{\lambda_i}; \qquad (1)$$

where R_i – thermal resistance of *i* layer of enclosure, ($m^2 \cdot K/W$); δ_i – the thickness of *i* layer; λ_i – thermal conductivity of *i* layer.

Thermal resistance of multilayered enclosing structure (R_0) can be determined as [15]:

$$R_0 = R_{\text{int}} + \sum_{i=1}^{n} R_i + R_{ext} = R_{\text{int}} + \sum_{i=1}^{n} \frac{\partial_i}{\lambda_i} + R_{ext}; \qquad (2)$$

where R_{int} and R_{ext} – is the heat transfer resistance on the inner and external surfaces of enclosure, ($m^2 \cdot K$)/W; ΣR_i – is the sum of layers thermal resistance, ($m^2 \cdot K$)/W.

The values of R_{int} and R_{ext} determines as follows [18]:

$$R_{\text{int}} = \frac{1}{\alpha_{\text{int}}}; R_{ext} = \frac{1}{\alpha_{ext}}; \tag{3}$$

where α_{int}, α_{ext} – the heat exchange coefficients near the internal and external surfaces of enclosure. According to [16], $\alpha_{int,}$ = 8.7 and α_{ext} = 23.

Substituting the values obtained when calculating the (1) and (3) into a formula (2) allows us to obtain the actual values of enclosures heat transfer resistance that given in Table 2.

The standard values of heat transfer resistance for existing types of enclosure structures are determined with accordance to [16].

Table 2 – Comparison table of standard and actual values of thermal resistance

Type of enclosure	Thermal resistance, $m^2 \cdot K/W$	
	Actual value	Standard value
External walls	4.817	≥ 4
Floor	5.596	≥5
Windows	0.48	≥ 0.9
Combined enclosing bordering the outside air	4.76	≥7

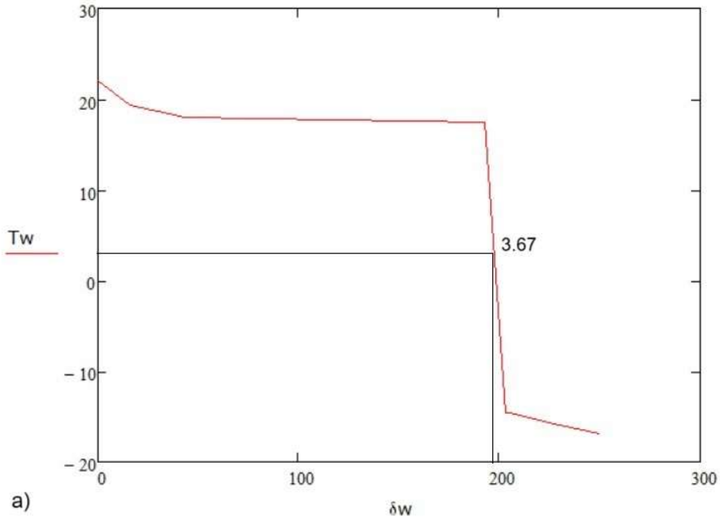
Analyzing of obtained data it can be concluded that the 4-10-4-10-4 type windows doesn`t meet the regulatory requirements at all. That is also correlates with the results obtained after infrared thermography. In order to improve the energy performances of the windows with accordance to a standard value the 4i-10Ar-4-14Ar-4i type windows with five air filled chambers profile system or better should be installed. According to our calculations such windows system provides the thermal resistance at a level of 0.95 $m^2 \cdot K/W$ with the energy loss about 0.178 kW. Additionally, the thickness of the roofing insulation of 150 mm is not enough. Our calculations has revealed that in order to get the regulatory value the roofing insulation thickness should be increased up to 250 mm.

The temperature distribution through the enclosing layers was calculated as follows [17]:

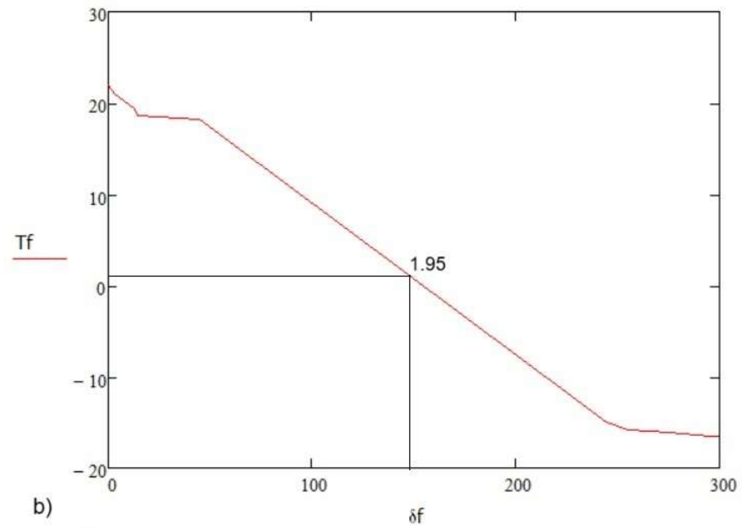
$$\tau_n = t_{in} - \left(\frac{t_{in} - t_{ext}}{R_0}\right) \cdot \left(\frac{1}{\alpha_{\text{int}}} + R_1 + R_2 + R_3 + \ldots + R_n\right); \tag{4}$$

where t_{in} – temperature of internal air, t_{int} = 22 °C; t_{ext} – estimated temperature of external air, (according to [16], t_{ext} = -23 °C); R_0 – overall thermal resistance of enclosure; R_1, R_2, R_3, R_n – thermal resistances of 1_{st}, 2_{nd}, 3_d and n layers of enclosure accordingly.

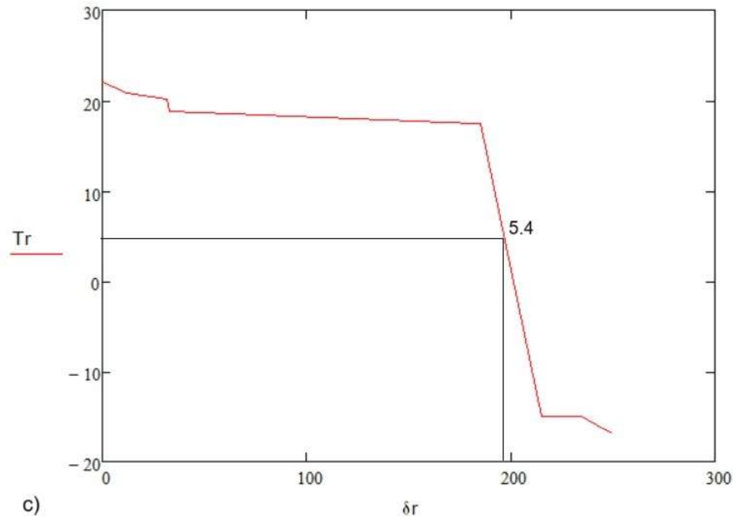
The estimated temperature distribution among the enclosing layers are given in Fig. 5.



a)



b)



c)

Fig. 5. The calculated temperature distribution among the building`s enclosure layers: a – walls; b – floor; c – roof

Analyzing of obtained results it should be noticed, that the temperature distribution between the walls and the roof layers has similar feature mainly because of similarity in their construction. The average temperatures of the building`s enclosures in the period of the coldest month of the year revolve around the positive values, particularly + 3.67 °C for walls, + 1.95 °C for the floor and +5.4 °C for the roof. Thus, building`s envelope provides the positive temperatures inside enclosures without any considerable deviation even though the significant daily and seasonal outside air temperature fluctuations. Theoretically, this should exclude the probability of condensation formation and as a result the possibility of thermal bridges development in the future.

Heat loss through the enclosing structures was determined as follows [17]:

$$Q_{en} = \frac{F}{R_0}\left(t_{in} - t_{ext}\right)\cdot n \cdot \left(1 + \sum \beta\right); \tag{4}$$

where F − calculated area of enclosing structures, m^2; R_0 – thermal resistance of enclosure structure, (m^2·K)/W; t_{in}, t_{ext} – internal and external temperatures, °C; n – the coefficient taking into account the dependence of the position of the outer surface of the fence with respect to the outside air, ($n = 1$) [17]; $\Sigma\beta$ – the sum of additional heat loss as a share of the main losses, ($\Sigma\beta = 1$) [17].

External walls area as well as their spatial orientation are given in Table 3.

Table 3 – External walls area

Type	Area by side orientation, m²								Total
	South	South-West	West	North-West	North	North-East	East	South-East	
Walls	31.18	–	12.76	–	34.78	–	12.6	–	91.32

The heat loss for heating of ventilation air is determined by the formula [18]:

$$Q_{va} = 0.28 \cdot L \cdot \rho \cdot c \cdot (t_{in} - t_{ext}); \tag{5}$$

where L - air flow rate, m³/h (for residential buildings, the specific normalized flow rate is can be taken as 3 m³/h per 1 m² of residential area); ρ - indoor air density, kg/m³; c - specific heat capacity of indoor air, c = 1.005 kJ/(kg ·°C) [18].

$$\rho = \frac{353}{273 \cdot t_{in}}; \tag{6}$$

The calculation results obtained by calculating of (4) and (5) are shown in the Table 4.

Table 4 – Calculation of heat loss through the enclosures and for heating of ventilation air

Type of enclosures	Characteristics of enclosing structures				Heat loss, kW	%, from the overall losses
	Orientation	Dimensions		Area F, m²		
		a, m	b, m			
Walls	South	8.62	3.7	31.9	0.582	13
	West	3.45	3.7	12.76	0.238	5
	North	9.4	3.7	34.78	0.649	14.6
	East	3.45	3.65	12.6	0.235	5.3
Total:		24.92	14.75	91.32	1.3	31.9
Floor	–	8.99	3.04	27.3	0.404	9.9
Roof	–	8.99	3.04	27.3	0.515	12.6
Windows	Left	1.2	1.2	1.44	0.343	7.245
	Right	1.2	1.2	1.44	0.343	7.245
Total:		1.44	1.44	2.88	0.686	16.8
Total loss through enclosures:				148.8	2.9	71.3
Heat loss for heating of ventilation air:					1.165	26.3
Overall heat loss:					**4.43**	

Conclusions. It can be concluded that the walls are the main source of the heat loss with the overall balance of 31.9 % from the building`s total heat loss. Increasing the thickness of the wall insulation up to 200 mm leads to a reduction in the percentage of heat loss to 27 % of the total amount.

Heat loss for heating of ventilation air is the second source of the building`s heat loss that is 28.6 % from the total heat loss.

With the existing characteristics of translucent structures with the thermal resistance within 0.48 – 0.52 $\frac{m^2 \cdot K}{W}$, heat loss through the windows is 16.8 %. It should be noted that the 4-10-4-10-4 type windows doesn`t meet the regulatory requirements and must be replaced with more energy efficient ones. Therefore, to meet regulatory requirements for thermal insulation properties, windows must have at least a 4i-10Ar-4-10Ar-4i design, i.e. they must have a soft selective coating on the outer and inner glass, and the air gaps must be filled with an inert gas, particularly argon. Bringing the thermal resistance of windows to the standard values of 0.95 $\frac{m^2 \cdot K}{W}$ reduces the heat loss through the windows up to 4.39 %.

The floor and ceiling have almost the same heat loss ratios of 9.9 % and 12.6 %, respectively.

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ОЦІНКА ТЕПЛОВОЇ ЕФЕКТИВНОСТІ ЕКОЛОГІЧНО ОРІЄНТОВАНИХ ЗБІРНО-МОДУЛЬНИХ БУДІВЕЛЬ: РОЗБІР ПРАКТИЧНОГО КЕЙСУ

Актуальність екологічно орієнтованого модульного будівництва постійно зростає через загострення житлово-екологічних проблем, пов'язаних з військовими діями на території України. В свою чергу, екологічний підхід та мінімізація споживання природних ресурсів вимагають зміни звичних будівельних практик у бік більш стійких та енергоефективних. У цьому контексті модульність у будівництві стає однією з сучасних тенденцій. Широке впровадження модульних збірних конструкцій безпосередньо зосереджене на екологічних та енергозберігаючих практиках у будівництві, що дозволяє зменшити небезпечний вплив на навколишнє середовище, споживання ресурсів та енергії, а також будівельні відходи. Водночас існують певні виклики, що обмежують широке використання модульних будівель в Україні, які головним чином пов'язані з високим рівнем скептицизму споживачів щодо якості та енергоефективності модульних будівель порівняно з традиційними будівельними практиками. У зв'язку з цим, метою даного дослідження є глибше розуміння теплових характеристик екологічно орієнтованого збірного модульного житла на основі реального прикладу. На прикладі каркасного модульного одноквартирного будинку "QHome-26", розташованого на околиці міста Чернігів, було досліджено теплові характеристики збірно-модульного будівництва. За допомогою інфрачервоної термографії було проведено моніторинг існуючих містків холоду та основних тепловтрат в огороджувальній конструкції будівлі. Експериментально встановлено, що потенційним джерелом тепловтрат будівлі є світлопрозорі конструктивні елементи, що не відповідають сучасним стандартам, а також фундамент будівлі. Водночас результати теплового розрахунку огороджувальних конструкцій будівлі показали, що основним джерелом тепловтрат на рівні 38,5 % від загальних втрат є стіни. Тепловтрати на нагрівання вентильованого повітря становлять 26,3 %. У той час як через вікна втрачається до 14,5 % тепла, втрати тепла через дах та підлогу становлять 12,6 та 9,9 % відповідно.

Ключові слова: *сталий розвиток; модульні будівлі; екобудівництво; теплова ефективність.*
Табл.: 5. Рис.: 4. Бібл.: 18.

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