UDC 621.3.088

Y. S. Biks

PREDESIGN OPTIMISATION OF THERMAL PERFORMANCE FOR MULTILAYERED ENVELOPES

Vinnytsia National Technical University

Abstract

The predesign optimisation of the total energy consumption has been proposed to comprehensively assess the thermal performance of multilayered wall assemblies, using the minimisation of the total embodied and operational energy as the goal function. The proposed model considers physical characteristics, such as internal areal heat capacity, decrement factor, embodied and operational energy, through the 50-year lifespan of the particular multilayered assembly. Current research focuses on defining the best wall performance solely based on the wall material's physical parameters, its dynamic characteristics under ISO 13786 and the total energy consumption value.

The performed numerical research has revealed that, in terms of the total energy figures, the AAC wall configuration was the most energy-efficient, with an energy reduction possibility of 36.76%, while the least energy-efficient in terms of the total energy was the wall from wood-chip cement-bonded block, with an energy reduction possibility of 3.28% only.

Keywords: operational energy, embodied energy, internal area heat capacity, thermal performance, multilayered assemblies, energy efficiency, dynamic characteristic.

Introduction

Modern construction practice employs a variety of building materials and techniques, drawing attention to multicriteria decision analysis (MCDA) methods [1, 2]. Thus, the issue of optimised energy-efficient building envelopes in terms of thermal and mechanical performance remains a significant challenge for engineers and developers who aim to construct dwellings aligned with sustainable development principles, which LCA parameters could evaluate under EN 15978:2011 [3].

The optimisation process inevitably involves trade-offs among alternatives, making selecting an optimal solution inherently complex. The term optimal is used in this context because, as in a multicriteria evaluation of real-world issues, only the alternatives belonging to the Pareto set can be regarded as optimal, which in a particular case is literally equal to the "best" solution [4, 5]. To make a proper choice of a multilayered envelope, a comprehensive analysis is to be performed, where different criteria as physical, mechanical, structural and others, can be optimised with respect to the goal function. It can be quite tricky, often with contradicting competing parameters, even at the predesign stage [5, 6].

The scope of this paper is to perform the wall layer thickness optimisation with respect to the minimising of such physical parameters as total energy *Etot*, MJ/m^{2}year, by limiting the dynamic thermal performance parameters of wall assemblies as internal area heat capacity $k1$, kJ/m²K and decrement factor f under EN ISO 13786 [7] and thermal transmittance u-value, W/m²K, as the main influencer of envelope winter and summer behaviour [6] within the fixed range.

Materials and research methods

The abovementioned specific physical parameters were considered as those which could be easily quantifiable to facilitate the decision-making during the predesign stage of building construction. Five multilayered wall assemblies were assumed for the numerical assessment of dynamic, steady-state, and life cycle assessment characteristics. These characteristics include thermal transmittance (*U-value*, W/m²K) as the steady-state parameter, internal area heat capacity ($k1$, kJ/m²K) and decrement factor f, which are the dynamic thermal performance parameters of wall assemblies under EN ISO 13786 [7] and considered as the main influencer of envelope winter and summer behaviour under [6].

For current research, the embodied energy (*EE*) as LCA criteria [8] of each multilayered wall, MJ/m^2 is limited to the A1-A3 stages of the LCA framework, which was taken from the Baubook Eco2soft online tool [23] as a production of embodied energy of material functional unit, MJ/kg, to its mass in the wall.

The operational energy (*OE*), MJ/m^2 was calculated by the production of the effective exploitation term *Tef* for each multilayered wall (was taken as 50 years =50×24×3600 = 4320000 s), to the Hot Degree Day (HDD) value for the city of Vinnytsia, namely HDD = 3676 and the wall *u*-value. Wall layer's optimisation was performed in Excel Solver.

The internal heat area capacity *k*1 and decrement factor *f,* as the dynamic thermal characteristics, were calculated using a downloadable Excel spreadsheet from HTflux [12].

The *u*-value of the assembly is inversely to the value of the thermal resistance and is calculated under the formula [9]:

$$u = \frac{1}{R_{tot}} = \frac{1}{\frac{1}{\alpha_{int}} + \sum \frac{\delta i}{\lambda_i} + \frac{1}{\alpha_{ext}}} \quad (1)$$

where δ_i – the width of the *i*-th material;

R_{tot} – the total thermal resistance of the assembly;

where α_{int} is the heat transfer coefficient of the internal surface of the wall, α_{int} = 23 (W/m^{2}K) [9];

α_{int} is the heat transfer coefficient of the external surface of the wall, α_{int} = 8.7 (W/m^{2}K) [9];

The multilayered assemblies were taken into the current research:

- Wall A (Hempcrete);
- Wall B (Aerated autoclaved concrete (AAC) D300 + Rockwool as insulation material);
- Wall C (Insulated concrete formwork (ICF) block);
- Wall D (Hollow brickwork masonry (Porotherm 38) + Rockwool as insulation material);
- Wall E (Wood-chip cement-bonded block).

The proposed assemblies and their cross-section dimensions are represented as follows (Fig. 1).

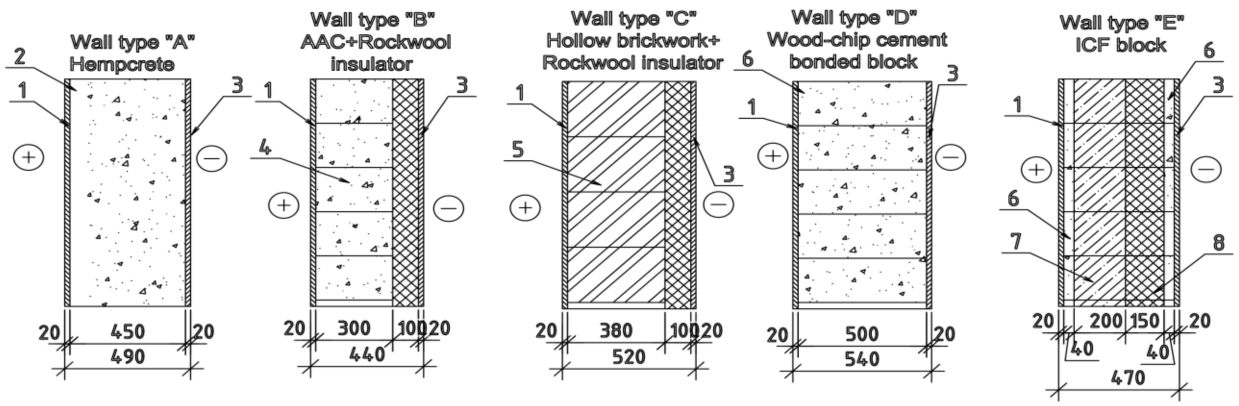

Fig. 1. Cross-sectional scheme of investigated wall assemblies: (1 – internal lime-sand plaster, 2 – hempcrete, 3 - external lime-sand plaster, 4 – aerated autoclaved concrete (AAC), 5 – hollow brickwork, 6 – wood-chip cement bonded block (woodcrete), 7 – reinforced concrete, 8 – BASF Neopor insulator)

The main thermal performance characteristics of the materials are presented in Table 1.

Table 1. Assumed thermal properties of wall materials

Assembly material	The thermophysical parameters of materials		
	Specific heat capacity, *c* (J/kgK)	Density ρ, (kg/m^3)	Thermal conductivity λ, (W/m·K)
Lime-sand plaster	1000	1500	0.67
Hempcrete	1200	450	0.08
Aerated autoclaved concrete (AAC)	100	275	0.09
Hollow brickwork masonry (Porotherm 38 W)	1000	745	0.112
Wood-chip cement-bonded block	1400	475	0.12
Reinforced concrete	1000	2200	1.65
BASF Neopor insulator	1450	16	0.031
Stone wool wall insulator (Rockwool®)	1030	70	0.034

The optimisation of multilayered envelopes was performed according to the following assumption:

1. Minimising the total energy consumption *Etot* = *EE* + *OE*→ *min* with constraints: total mass and width of the wall, u-value and decrement factor (see Table 2).

Table 2. The considered restriction conditions for research

Characteristic	Restriction
Thermal transmittance (*u*-value), W/m^{2}K	≤0.25
Internal plaster thickness, m	∈[0.01; 0.05]
External plaster thickness, m	∈[0.01; 0.05]
Decrement factor, *f*	∈[0.04; 0.08]

Results of the research

After conducting numerical simulations for all assemblies, the output influence parameters were obtained (see Table 3 - Table 5).

Table 3. Output influence parameters of the assemblies (before optimisation, with respect to dimensions in Fig. 1)

	Wall width *d_wall*, m	Thermal transmittance at steady state, *u-value*, W/m^{2}K	Internal areal heat capacity *k1*, kJ/(m^{2}K)	Decrement factor *f*	Energy consumption, MJ/m^2		
					Embodied, *EE*	Operational, *OE*	Total, *Etot*
Wall A	0.490	0.171	39.955	0.013	1926.30	2718.08	4644.38
Wall B	0.440	0.154	37.369	0.115	1613.03	2446.16	4059.19
Wall C	0.520	0.153	43.742	0.007	2075.68	2423.94	4499.62
Wall D	0.540	0.215	43.551	0.007	2013.88	3420.72	5434.60
Wall E	0.470	0.171	40.073	0.052	2597.28	2717.34	5314.61

Table 4. Output influence parameters of the assemblies (after optimisation)

	Wall width *d_wall*, m	Thermal transmittance at steady state, *u-value*, W/m^{2}K	Internal areal heat capacity *k1*, kJ/(m^{2}K)	Decrement factor *f*	Energy consumption, MJ/m^2		
					Embodied, *EE*	Operational, *OE*	Total, *Etot*
Wall A	0.390	0.208	30.412	0.040	1181.17	3299.18	4480.34
Wall B	0.624	0.080	26.835	0.040	1293.04	1273.93	2566.97
Wall C	0.419	0.147	35.805	0.007	1292.12	2337.42	3629.54
Wall D	0.451	0.250	35.516	0.020*	1283.07	3970.51	5256.57
Wall E	0.389	0.169	33.573	0.080	1561.07	2677.02	42873.09

* the only parameter that wasn't optimised within the recommended range.

Table 5. Relative decrease of the *Etot* parameter of the assemblies

	Energy consumption, MJ/m^2		
	Total, before *Etot*	Total, after *Etot*	Decrease $(Etot_{before} - Etot\_after)/Etot\_before, \%$
Wall A	4644.38	4480.34	3.53
Wall B	4059.19	2566.97	36.76
Wall C	4499.62	3629.54	19.34
Wall D	5434.60	5256.57	3.28
Wall E	5314.61	4287.09	19.33

Analysis of the data represented in Table 5 revealed that the maximum decrease in the *Etot* is shown for Wall B with 36.76%, where the minimum energy saving could be achieved in Wall D, which demonstrates 3.28% only. Wall C and Wall E demonstrate the same energy-saving achievement with 19.34% and 19.33% respectively. It means that walls B, C and D are aimed to be possibly modified at the predesign stage of construction, when walls A and D have no such significant energy-reducing potential.

The comparison between the *u*-value and *Etot* from Table 3 and Table 4 is shown in Fig. 2.

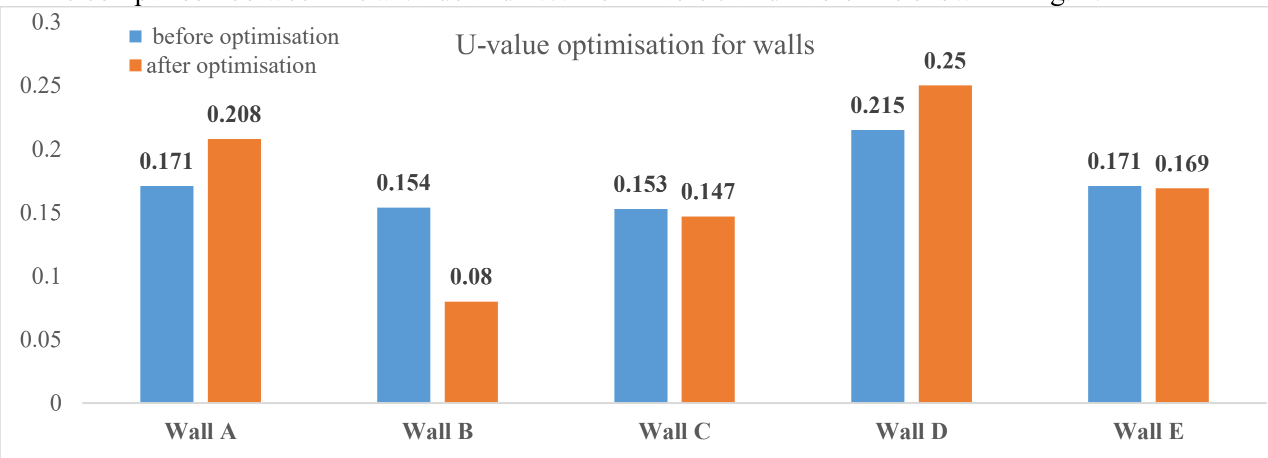

Fig. 2 Thermal transmittance value of the walls before and after optimisation of *Etot*

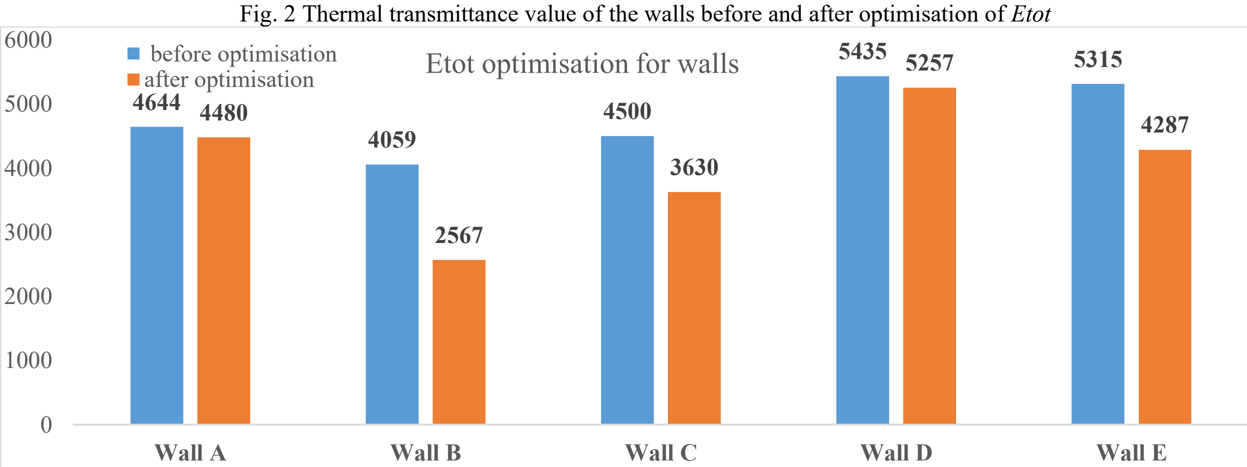

Fig. 3 Total energy *Etot* of the walls before and after optimisation of *Etot*

The general figures of the obtained research are not universal; results need to be clarified regarding the factual values with respect to the embodied energy *EE* figures for a particular country. Thus, further thorough analysis should be conducted to determine an affordable assembly in terms of the optimal thermal performance, dynamic behaviour, and embodied energy for a given LCA framework.

Conclusions

According to the proposed predesign LCA analysis, the research of the five assemblies revealed that the AAC wall could be the most energy-efficient in terms of *u*-value and total energy *Etot*, with great potential to decrease both total energy consumption *Etot by* 36.76% and *u*-value by almost 46%.

REFERENCES

1. Basińska M. The use of multicriteria optimisation to choose solutions for energy-efficient buildings. *Bulletin of the Polish Academy of Sciences. Technical Sciences*. 2017. Vol. 65, №. 6. P. 815-826. DOI: 10.1515/bpasts-2017-0084.
2. Wang J. J., Jing Y. Y., Zhang C. F., Zhao J. H. Review on multicriteria decision analysis aid in sustainable energy decision-making. *Renewable and sustainable energy reviews*. 2009. Vol. 13. №9. P. 2263-2278. DOI: 10.1016/j.rser.2009.06.021.
3. EN 15978:2011. Sustainability of construction works - Assessment of environmental performance of buildings - Calculation method. URL: https://standards.iteh.ai/catalog/standards/cen/62c22cef-5666-4719-91f9-c21cb6aa0ab3/en-15978-2011 (Last accessed: 25.02.2023).
4. Thakkar J. J. Multicriteria Decision Making. Springer, 2021. Vol. 336. P. 1-365.
5. Biks Y., Ratushnyak G., Ratushnyak, O. Energy performance assessment of envelopes from organic materials. Architecture Civil Engineering Environment. 2019. № 3: P. 55-67. DOI: 0.21307/ACEE-2019-036.
6. Stazi F. Thermal Inertia in Energy Efficient Building Envelopes. Butterworth-Heinemann, 2017. DOI: 10.1016/B978-0-12-813970-7.00001-7.
7. ISO 13786:2017. Thermal performance of building components – Dynamic thermal characteristics – Calculation methods. URL: https://www.iso.org/ru/standard/65711.html (Last accessed: 10.10.2020).
8. Carabaño R. et al. Life Cycle Assessment (LCA) of building materials for the evaluation of building sustainability: the case of thermal insulation materials. *Revista de la Construcción. Journal of Construction*. 2017. Vol. 16. №. 1. P. 22-33.

9. DSTU-N. B. V. 2.6-189:2013. Methods for the selection of heat-insulating material for the insulation of buildings. [Valid from 2014-01-01]. Official issue Kyiv: Ministry of Region of Ukraine, 2014. 40 p. (in Ukrainian).
10. DBN V. 2.6-31:2021. Thermal insulation of buildings. [Valid from 2022-09-01]. Official issue Kyiv: Ministry of Region of Ukraine, 2022. 27 p. (in Ukrainian).
11. Vilaboa Díaz A., Francisco López A., Bello Bugallo P. M. Analysis of biowaste-based materials in the construction sector: evaluation of thermal behaviour and life cycle assessment (LCA) .*Waste and Biomass Valorization*. – 2022. Vol. 13. №. 12. p. 4983-5004.
12. ISO SPAN Expert 43/15**.** URL: https://www.baubook.at/m/PHP/EinreichungI/Infoauswahl/index.php?Minibox=I_PRW_S_EIKON&iSS=0&SI=2142730302&SG=&Balken=n&SW=5&LU=1823785713&qJ=54&LP=7wFvl&lng=2&SBT_open=738424&SKg=2 (Last accessed: 20.03.2025);
13. Cement-bonded boards made of wood chips (550 kg/m³). URL: https://www.baubook.at/m/PHP/EinreichungI/Infoauswahl/index.php?Minibox=I_PRW_S_EIKON&iSS=0&SI=&SG=2142715868&Balken=n&SW=5&LU=1823785713&qJ=63&LP=7wFvl&lng=2&SBT_open=738546&SKg=2 (Last accessed: 20.03.2025);
14. EPS W15 silver. URL: https://www.baubook.at/m/PHP/Info.php?SI=2142708381&SW=5&LU=1823785713&qJ=70&LP=7wFvl&Minibox=I_PRW_S_EIKON&SBT_open=738424&lng=2&SKg=2&win=y (Last accessed: 20.03.2025);
15. Florentin Y. et al. A life-cycle energy and carbon analysis of hemp-lime bio-composite building materials. *Energy and Buildings*. 2017, Vol. 156. P. 293-305.
16. A brief guide and free tool for the calculation of the thermal mass of building components. URL: https://www.htflux.com/en/free-calculation-tool-for-thermal-mass-of-building-components-iso-13786/ (Last accessed: 18.11.2023)
17. Porotherm. Wall solutions. URL: https://porotherm.com.ua/pdf/Porotherm_Klima.pdf (Last accessed: 22.03.2024) (in Ukrainian).

Biks Yuriy S. — PhD, Associate Professor, Department of Construction, Urban Economy and Architecture, Vinnytsia National Technical University, Vinnytsia, email: biks@vntu.edu.ua