DEA Modelling Effectiveness of Building Envelopes

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Abstract. Today, insulated building envelopes must not only meet thermal-technical, mechanical, and economic requirements but must also be environmentally friendly. These requirements are often contradictory, and it is not clear what the effective option is for a particular case. The aim of the paper is to compare twenty different variants of building envelopes, not only in terms of thermal-technical properties but also in terms of environmental parameters and time and financial demands. The result of the paper is the determination of effective variants by a suitable mathematical method with consideration of all the above-mentioned influences.

1. Introduction
Buildings are intended to provide protection against climatic influences and ensure healthy and comfortable use by their users. The buildings sector is responsible for approximately 40% of the energy consumed and for 36% of produced GHS (Greenhouse Gases) emissions. It is clear that the building sector has the potential to protect natural resources as well as the environment. It is the uneconomical operation of buildings using non-renewable energy sources that contributes to the negative impact on the environment and human health. This situation does not go unnoticed and the construction sector is under increasing pressure from the European Union and government regulations that seek to contribute to the development of sustainable construction [1-3].

One of the key possibilities to reduce the energy demand of the building is to minimize heat loss through the building envelope using an additional thermal insulation system (depending on climatic region). The external thermal insulation system (ETICS) is nowadays a widely used technology almost all over the world [4]. Revitalization using ETICS significantly improves the thermal properties of the building envelope. This technology is sufficiently tested from a technical and economic point of view [5, 6]. It is even used in northern Scandinavia, where winter conditions are particularly unfavourable [7]. Although the technology is carefully described and tested, it is still relatively common to encounter poor design, technological indiscipline, or the use of incorrect materials [8-10], which in turn increases energy consumption and reduces efficiency.

2. Materials and methods
Twenty different variants of building envelopes, often used in the Czech Republic and Central Europe, were selected for a comparative study. Input data were taken from [11]. The compositions of the peripheral structures are detailed described in [12]. The prices of materials are related to the year 2018.
and are paid for the territory of the Czech Republic. Environmental aspects of thermal insulation (expanded polystyrene, extruded polystyrene, rock mineral wool, glass mineral wool, and others) are described in [13].

The first three variants are made without additional insulation only using thermal insulation blocks. Variants 4 to 15 represent the use of the ETICS contact thermal insulation system.

For variants 4 to 7, a load-bearing structure made of HELUZ UNI 30 fittings were designed and supplemented with thermal insulation made of white and grey polystyrene and mineral wool from ISOVER and thermal insulation made of phenolic foam from Baumit.

The load-bearing structure of variants 8 to 11 consists of aerated concrete blocks YTONG -400 supplemented with insulation of white and grey polystyrene and mineral wool.

Variants 12 to 15 have a load-bearing structure made of SENDWIX 16 DF-LD sand-lime bricks, supplemented by thermal insulation made of white and grey polystyrene and mineral wool from ISOVER and thermal insulation made of phenolic foam from Baumit.

The load-bearing structure of the perimeter cladding consists of BEST lost formwork fittings filled with concrete and reinforced with reinforcing steel for variants 16 to 18. In these variants, the thermal insulation layer consists of white polystyrene and mineral wool from ISOVER and hemp insulation NAPOROwall.

Variant 19 is designed as a MEDMAX construction system and variant 20 consists of a light perimeter cladding of a wooden building.

| Variant No | L (Sh/m²) | GWP (kg CO₂/a) | AES (g SO₂/a) | Price (EUR/m²) | TR (m² K/W) | Effectiveness |
|------------|-----------|----------------|---------------|----------------|-------------|--------------|
| 1          | 2.00      | 1.00           | 3.05          | 85             | 5.49        | 0.95         |
| 2          | 1.51      | 1.61           | 4.47          | 76             | 5.68        | 1.00         |
| 3          | 1.77      | 1.00           | 3.02          | 97             | 5.75        | 0.87         |
| 4          | 2.64      | 0.80           | 3.34          | 90             | 6.29        | 0.98         |
| 5          | 2.64      | 0.76           | 3.02          | 88             | 6.80        | 1.00         |
| 6          | 2.63      | 1.27           | 4.72          | 97             | 6.17        | 0.78         |
| 7          | 2.61      | 1.74           | 5.30          | 116            | 5.59        | 0.69         |
| 8          | 2.40      | 1.58           | 5.35          | 94             | 7.35        | 0.95         |
| 9          | 2.40      | 1.54           | 5.03          | 94             | 7.87        | 0.75         |
| 10         | 2.39      | 2.04           | 6.73          | 101            | 7.19        | 0.92         |
| 11         | 2.30      | 1.61           | 4.58          | 98             | 6.58        | 0.91         |
| 12         | 2.18      | 1.05           | 3.19          | 90             | 5.92        | 0.88         |
| 13         | 2.18      | 1.00           | 2.79          | 90             | 6.58        | 0.91         |
| 14         | 2.17      | 1.63           | 4.92          | 98             | 5.78        | 0.93         |
| 15         | 2.15      | 2.04           | 6.46          | 134            | 5.95        | 0.86         |
| 16         | 2.59      | 2.36           | 10.41         | 79             | 5.78        | 0.77         |
| 17         | 2.57      | 2.12           | 10.67         | 98             | 5.38        | 0.79         |
| 18         | 2.58      | 2.32           | 12.14         | 89             | 5.62        | 0.81         |
| 19         | 2.39      | 1.92           | 8.56          | 110            | 6.37        | 0.82         |
| 20         | 3.33      | 0.35           | 3.74          | 115            | 5.35        | 0.86         |

Data Envelopment analysis (DEA) was selected as a suitable tool for multicriteria comparative analysis of selected variants of building envelopes. Laboriousness (L), Global Warming Potential
(GWP), annual equivalent emissions of SO$_2$, eq (AES), price and thermal resistance (TR) were chosen as input data for DEA, see table 1. DEA was used for statistical evaluation. It is one of the methods of multicriteria evaluation. Specifically, the BCC model [14] was used, which considers a convex data wrapper and thus allows more efficient units. The mathematical notation of the input-oriented BCC model is given below.

$$\max z = u'y_q$$

subject to:

$$v'x_q = 1,$$

$$u'Y - v'X \leq 0,$$

$$u \geq \varepsilon, v \geq \varepsilon,$$

where $X = \{x_{ij}, i = 1, \ldots, m; j = 1, \ldots, n\}$ is matrix of inputs, $Y = \{y_{ij}, i = 1, \ldots, r; j = 1, \ldots, n\}$ is the matrix of outputs, $x_q$ is the $q$th column of matrix $X$ and $y_q$ is the $q$th column of the matrix $Y$, $v$ is the vector of weights for inputs, $u$ is the vector of scales for outputs, $\varepsilon$ is an infinitesimal constant, $\theta_q$ is the relative efficiency of $q$th DMU, $s^+$ and $s^-$ are input and output slacks, respectively, $\lambda$ is a vector of weights and $1'$ is a row vector with all elements equal to 1. This is a special case of linear programming. A dual model is used for computation, the notation of this procedure is given here:

$$\min z = \theta_q - \varepsilon(1's^+ + 1's^-)$$

subject to:

$$X\lambda + s^- = \theta_qx_q,$$

$$Y\lambda - s^+ = y_q,$$

$$1'\lambda = 1,$$

$$\lambda \geq 0, s^+ \geq 0, s^- \geq 0.$$

3. Discussion

A total of 20 variants of the building envelope were designed and compared. They differed not only in the materials used, but also in the construction technology. The load-bearing structure consisted of representatives of classic masonry made of brick blocks, as well as lost formwork systems and a light prefabricated perimeter cladding (wooden building). These constructions were designed with or without the use of additional thermal insulation from various materials (expanded white and grey polystyrene, mineral wool, hemp insulation).

Subsequently, a thermal-technical assessment of such proposed variants was performed. The main criterion was to meet the required value of the thermal resistance.

From the thermal-technical point of view, it seems to be the best variant 9, which almost corresponds to the value of the heat transfer coefficient for passive buildings. In addition to this variant, variants 8 and 10 have also achieved excellent results. In all these variants, the load-bearing structure consists of YTONG P2-400 blocks with additional insulation. The worst results were achieved by variant 20 (wooden building).

The evaluation of the time required to make one square meter for the above-mentioned variants was carried out on the basis of the laboriousness of construction activities in standard hours (Sh) from the
technical sheets of manufacturers and from [8]. In terms of time, variant No. 2, whose workload per 1 m² is 1,505 Nh, appears to be the least laborious, followed by variants 3 and 1. All these variants were designed as masonry from brick blocks without additional insulation. The most demanding version was variant 20 (wooden building).

Furthermore, the financial complexity was assessed. The price of one square meter of building envelope was calculated from the current prices (for 2018) of products used and wages for construction work in the Czech Republic. Variant No. 2 made of uninsulated masonry YTONG Lambda YQ came out as the cheapest version, when the price of 1 m² reached CZK 1,972.00, variant 16 (CZK 2,050.00 per 1 m²) was placed second and variant 1 (2,201.00 CZK per 1 m²). On the contrary, the most expensive is the implementation of variant 15, the price of which is CZK 3,493.00 per 1 m², mainly due to the high price of BAUMIT Resolution thermal insulation.

The environmental assessment was performed using the SbToolCZ assessment methodology [15] throughout the life-cycle assessment (LCA). The current construction of buildings focuses mainly on minimizing costs and speed of construction. To determine the amount of annual equivalent emissions of CO₂eq and SO₂eq, parts E.01 - Coupled production of CO₂ emissions and E.02 - Coupled production of SO₂ emissions were used. The smallest amount of bound emissions is contained in variant 5 - HELUZ UNI 30 ground with additional thermal insulation from grey polystyrene ISOVER EPS GreyWall. Just behind it are variant 13 made of sand-lime bricks and additional insulation from ISOVER EPS GreyWall and variant 3 made of POROTHERM 38T Profi brick blocks. On the contrary, variant 18 showed the largest amount of bound emissions (lost BEST formwork + thermal insulation from mineral wool ISOVER TF Profi).

A comprehensive view was provided by the multi-criteria analysis of all considered parameters by the DEA method. DEA found (see table 1) the following variants as the effective ones (effectiveness equal to one): variant 2 - masonry from YTONG Lambda YQ blocks, variant 5 from HELUZ UNI 30 blocks ground with additional thermal insulation from grey polystyrene ISOVER EPS GreyWall and variant 13 - sand-lime bricks SENDWIX 16 DF - LD + thermal insulation made of grey polystyrene ISOVER EPS GreyWall.

Variant No. 7 consisting of HELUZ UNI 30 fittings with contact insulation with Baumit Resolution insulation came out as the least effective (effectiveness equal to 0.69), which received a very weak evaluation of all evaluated criteria.

4. Conclusions
With the ever-increasing requirements for energy savings and thermal-technical properties of buildings, the development of building materials will be very fast. Manufacturers will strive to constantly develop new building materials that will offer better properties. It can be assumed that environmental aspects will play an increasingly important role in the future. The outlined DEA multicriteria comparative analysis of selected variants of building envelopes could be a good evaluation criterion for the overall effectiveness of the selected variant.

Acknowledgment(s)
This work is supported by the project IGS201809 Multi-criteria optimization of the building envelope design.

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