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Research paper

Method for choice of industrial hall walls variants optimization

Maciej Mielcarz[1], Paweł Nowak[2]

Abstract: The current trends in the construction market require developing and completing building projects with balanced costs and the shortest execution time, while maintaining a high quality of works and properties of completed objects. Achieving this goal is difficult, however with the development of new technologies and management techniques, a sustainable project is possible to achieve. The authors' goal was to find a technological solution which would efficiently meet the imposed requirements for optimizing the technology and organization project of the hall. Three technologies were analysed using the multi – criteria analysis based on the 6 aspects – all important from the sustainability point view. Choice and proper check of the criteria for sustainable decision making is crucial, as criteria are usually described by experts in not fully objective and mathematical way. Chosen elements of the Value Engineering (VE) practices were discussed and used. In order to evaluate each construction variant the weight of every criteria was determined using the Simos method and the variants' data was normalized. The practicality of every construction variant as a sustainable solution was established through two evaluation methods – the entropy and the ideal point method. The results of this research prove that project managers can successfully achieve sustainable projects through the described optimization process. Similarly, this type of analysis can also be beneficial in other fields, such as mechanical engineering, finance, transportation, agriculture etc.

Keywords: entropy, ideal point, Simos, optimization, technology, VE

[1]MSc., Eng., Mostostal Warszawa S.A., ul. Konstruktorska 12A, 02-673 Warszawa, Poland, e-mail: m.mielcarz@mostostal.waw.pl, ORCID: 0009-0003-1623-2009

[2]PhD., Eng., Warsaw University of Technology, Faculty of Civil Engineering, Al. Armii Ludowej 16, 00-637 Warsaw, Poland, e-mail: pawel.nowak@pw.edu.pl, ORCID: 0000-0003-4748-0796

1. Introduction

An investment process is a multi-stage and complex undertaking, the course of which is influenced by many factors. A situation on the market as well as investor's budget often verifies the initial assumptions and forces to rationalize the construction project. Therefore, a detailed analysis is conducted in order to adapt the project to new circumstances, which is usually associated with changes in the construction technology of an object. "Each project is limited by six factors: scope, quality, cost, time, resources and risk. A modification of one of these parameters may cause a change of at least one of the others" [1, 19]. Moreover, such changes will significantly influence not only the construction phase of a project, but also a long period of an object maintenance, for example due to a comfort of use, fire resistance conditions etc. That is why a number of building construction concepts is made and then verified. The field which deals with the evaluation of these variants is called Value Engineering, abbreviated as VE. Value engineering is one of the managerial techniques which expands the possibilities of making rational decisions regarding design and construction management [2]. It is a very broad field which not only offers many various tools to reduce costs and shorten a duration of an investment but also improves safety and quality of works. The main goals of Value Engineering analysis can be defined as follows: [3–5]: providing a new perspective on possible technical and organizational solutions, elimination of unnecessary costs, improvement of technical capabilities by considering the implementation of new design solutions, reduction of operating costs [20, 21] by taking into account the impact of maintenance costs and durability in the considered design solutions and scopes of works performed.

When using this type of analysis, one should try to ensure that before selecting the most advantageous solution, all proposals have been thoroughly verified [22]. Every analysis should include not only the actual cost of the investment, but also the factors influencing project sustainability, like execution possibilities, durability, aesthetics, material properties, environmental impacts, etc. [6–9, 26, 28].

Value Management (VM) is about getting the right project, whilst Value Engineering (VE) is done to get the project right [27]. Value Analysis (VA) relates to the improvement of a construction, manufacturing or management process and also to a post project review to establish value achievement. Generic value drivers are presented in Table 1.

Assignment of quantitative measures (also known as setting metrics) to each individual value driver and agreeing performance measure (Fig. 1) will enable the VM team to assess and quantify performance and thus generate the value index of the project. Successive reassessments of the value index after each value study can give the project team a clear indication of how effective their efforts have been and where additional effort is needed to further improve value. It is important to consider potential difficulties in agreeing objective metrics for attributes that may be somewhat subjective. Ideally, a metric should be identified that cannot be influenced by the observer. For example, costs and quantities of materials can be estimated from the market and are therefore objective. Even relatively soft values can be the subject of objective metrics. For example, the level of satisfaction of the end users of a department can be measured by the number of letters of complaints received. Where such objective metrics are not possible, it may be necessary to resort to surveys, ideally undertaken by independent observers [25]. Section 2

Table 1. Generic value drivers for construction projects [24]

Value driver	Key prompt question
Enhance/achieve desired financial performance (of the structure)	Is the structure affordable?
Manage the delivery process effectively (maximise project delivery efficiency, minimise waste)	Are the project management processes efficient? Are the right people engaged at the right time? Is the delivery chain effectively managed? Are the resources used effectively?
Maximise operational efficiency, minimise operational costs	Does the structure work well for the end users?
Attract and retain employees/ occupants/ users	Is it a nice place to live/work/be?
Protect the appropriate image	Does the structure convey the appropriate image?
Minimise maintenance costs	Is the structure easy to maintain?
Enhance the environment	Is the structure environment friendly? Is the structure built using the ethos of environmental sustainability?
Comply with third-party constraints	Does the structure conform to legal and other external stakeholder requirements?
Ensure health and safety during implementation, operation and occupation	Is the structure safe to construct and operate?

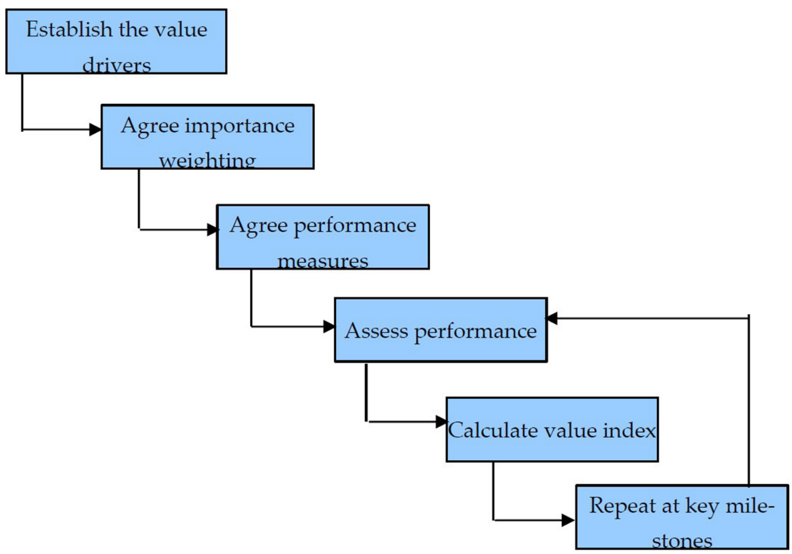

Fig. 1. Value measurement process within construction projects [24]

shows a general overview of the problem, location of the discussed building and optimized walls variants. Section 3 shows descriptions of the chosen criteria and Simos method used for weight calculation. In Section 4 the authors describe calculations and discuss the results. Section 5 contains the conclusions.

2. Description of the optimized variants

The subject of the optimization is a hall with a steel and reinforced concrete structure, located on 34 Marywilska Street in Warsaw. It is an uninhabited, fenced off area intended for office buildings. The hall is adjacent to two other buildings, but it has an independent load-bearing structure, Fig. 2. The analysed building is divided into a production part and a storage part intended for high elements. The hall has one over ground and one underground floor. The height above the ground is measured to the ridge and has 11.90 meters for the higher part and 5.75 meters for the lower part. The building area is 3020.30 m^2 and the cubic capacity is 30291.06 m^3 [10]. Prefabricated reinforced concrete frames are set every 6 meters, with a span of 34.5 meters in the higher part and 12.5 meters in the lower part. They form the load-bearing structure, which is unchanged in all considered technological solutions and will not be rationalized. Only the technology of external and internal walls construction is subject to sustainability [29] optimization.

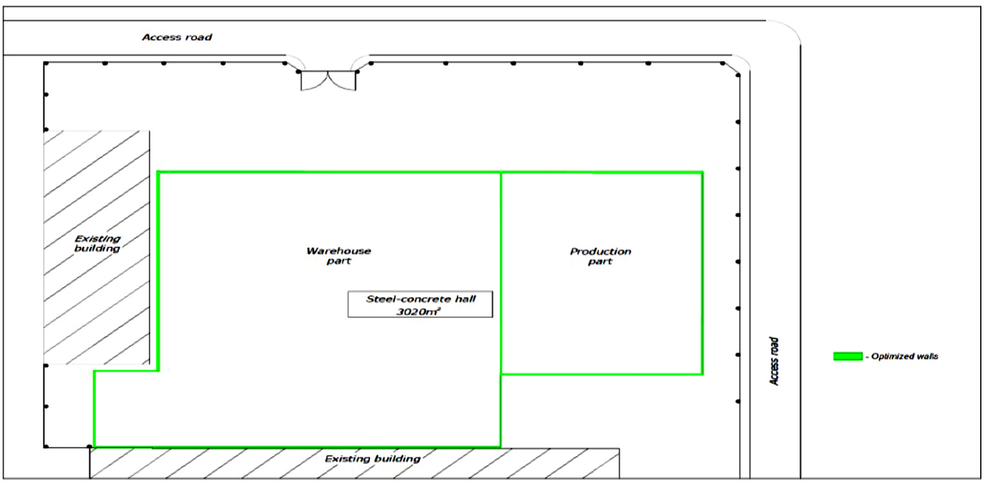

Fig. 2. Plan of the discussed object [own source]

Three construction variants were analysed, each with a distinct quality, durability and dimensions and hence with different times and costs of completion of the building: sandwich panels – the original technological solution presented in the executive project. This technology is widely used for industrial and public purposes due to their low weight and simple and quick assembly. Panels consist of two layers of galvanized trapezoidal sheet between which there is an insulating material i.e. a core that gives properties to panels.

They are installed in a horizontal system by fastening to hall's columns with self-tapping fasteners [11]. Figure 3a shows trapezoidal sheets walls – a variant is proposed in which the external casing is made of a trapezoidal sheet mounted in a vertical system by fastening to the transom structure. Then the insulation material is laid. The next step is to attach trapezoidal sheet on the inside, under which a vapour barrier foil is additionally placed [12]. This solution is used less frequently due to the high degree of labour intensity and rising costs. However, it is much easier to repair [13]; Fig. 3b shows cassette walls – another alternative solution is the technique that uses cassettes i.e. elements with a wide profile and long sides, which are placed on the inside of the building. Assembling in this system is similar to the method described in trapezoidal sheets walls, but it shows less labour consumption. The inner casing is connected with sealing tapes, leaving a 1 cm horizontal gap between the elements so that a free operation of the structure is allowed [13, 14]. Then a mineral wool is placed in the cassettes. The last stage is the assembly of the outer casing made of trapezoidal sheet. The partition made in this system is light, dense and resistant to mechanical damages (Fig. 3c).

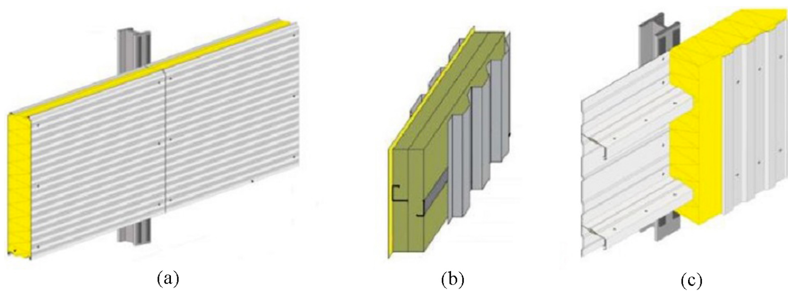

Fig. 3. Diagram of: (a) a sandwich panels solution [32]; (b) a trapezoidal sheets wall solution [33]; (c) a cassette walls solution [32]

All these three technologies are typical for this type of construction i.e. light, non-load bearing and simple to assemble.

3. Theoretical basics of research – choice of the criterion and decision weights

Criteria which have to be taken into consideration are often concurrent. That is why it often becomes impossible to select a variant in which all of them would be rated the highest [35]. The Simos method exhibits a considerably easy system for data collection and implementation; therefore, it has been extensively used in the scientific literature [23]. Assessments of individual variants in the example do not differ significantly from the results obtained using the "classical" and the primary Simos method, yet the formal procedure for weights determination to each criterion makes the decision-making process less random and more objective [37]. The evaluation criteria describe technical solutions that are subject to multi-criteria analysis, which means that the significance of the variants is tested on their basis.

The number and nature of selected criteria depend on many factors, such as the investor's requirements or the type of the assessed item, but they can also be imposed legally, for example in a public procurement. Criteria can be classified in many ways. The division depending on what numerical values are considered to be better is highly important. We can distinguish the so-called stimulants for which the higher the value the more favourable a given criterion, while the reverse situation applies to destimulants. It should be emphasized that when conducting calculations the two cannot be considered at the same time. That is why criteria are unified by performing the reciprocal of the value of a stimulant or a destimulant. The second division is the distinction between measurable and non-measurable criteria. Values calculated or obtained from manufacturers, designers and contractor are measurable. In other cases there is a need to select a rating scale, for example from 1 to 5 [15]. In this article technological solutions are compared using the multi – criteria analysis and a variant that best meets these criteria (from 1 to 6) will be selected as the optimal result. The following criteria (from 1 to 6) play a key role in the sustainability optimization problem: 1. Execution costs (PLN – Polish Zloty) – it is the total cost of completion of the walls including the purchase of building materials and the cost of labour and equipment. It is also the sum of the cost of internal and external walls. The values for this criterion are obtained on the basis of the cost estimate which was prepared in the Norma Pro (Polish software for costs calculations in construction); 2. Execution time (days) – one of the most important criteria in civil engineering. It is the time measured from the delivery of building materials to the construction site to the completion of walls, expressed in days. It is the sum of all durations of activities needed to construct walls. A 10-hour work shift was assumed with a 5-day work week. The number of entities is selected in a way that employees and equipment performing a given activity have a similar standard of shift performance, however this number must be justified in reality, for example whether a plot of land can accommodate all entities; 3. Thermal insulation of the curtain walls ($W/(m^2 \cdot K)$) – the ability of the finished wall to maintain heat level inside the building. This i san important criterion because of building operating costs and environmental impact. The measure of thermal insulation is the value of the heat transfer coefficient U, expressed in $W/(m^2 \cdot K)$, which describes how much energy per unit of time passes through 1 m^2 of walls' surface with a difference in temperature of 1 K on both sides of the partition with appropriate corrections for leakage of insulation and mechanical fasteners [30]; 4. Acoustic insulation of the curtain walls (dB) – it is required for the walls to effectively reduce noise from inside the building which is emitted by technical equipment. The purpose of the hall cannot lead to a discomfort to the people who are present outside or in adjacent buildings. However, it is not possible to reduce the sound intensity at the source, therefore it should be counteracted by selecting a partition with high-performance acoustic protection. This value is determined by the acoustic insulation index in decibels [30]; 5. Fire resistance rating of the hall's production part – the ability of a component to meet specified requirements under fire conditions, expressed in minutes as time from the start of the fire until the structure or element reaches one of the three limit states: load-bearing (R), integrity (E) or thermal insulation (I). The minimum resistance for the production part must be REI 60 [31]; 6. Fire resistance rating of the halls' storage part – defined in the same way as the production part. The minimum fire resistance for the warehouse part must be REI 120. The criteria for acoustic insulation and fire resistance are stimulants, while the cost, execution time and thermal insulation are destimulants. The next step is to assign them decision weights which must take values from 0 to 1, and their sum should equal one. In this article, to determine the weights of individual criteria, the authors used the Simos method. As stated in [23] the Simos method exhibits a considerably easy system for data collection and implementation". It is a visual method using the ordering a set of cards, which is divided into two types: cards with the names of the criteria and the so-called unassigned cards [23]. The task is to sort the cards from bottom to top, and the higher the card is, the less important it is for the decision-maker. Where the two criteria are equally important, they are placed side by side. Additionally, to emphasize the difference between more and less important criteria, one or more white cards are placed between them, for example two white cards mean that a given criterion is three times less important than the one below [15]. It should be noted however, that the card sorting process is subjective. “The limits of human rationality have to be taken into account to estimate the possible quality of the resulting decision” [34]. Ranking of the criteria in terms of their importance is determined by a decision maker, therefore, project priorities may differ depending on the assigned person. “In addition to having promising capabilities, human decision making is also characterized by bounded rationality. Cognitive resources are limited, and decisions are influenced by biases that result in suboptimal choices through failures of reasoning. Such failures can be made transparent by relating interests of decision makers and the results of decision-making processes: It is therefore assumed that individuals inherently prefer to improve their choices” [34]. The Simos method was also used in the research article [23] with comparable objectives – assigning weights to criteria and then choosing the proper wheat combine. In the optimization of a given building object, due to the intended use, the most important criteria were the thermal and acoustic insulation of the walls constituting the building envelope. With the next criteria, the investor stated that the lower cost of building walls is more important than the time of their construction. The fire resistance criteria of the production and storage part of the hall were considered the least important, because it was assumed that the values in the original technological solution are greater than the minimum resistance classes, and the two proposed variants meet the minimum requirements, i.e. REI 60 and REI 120, respectively fire safety in a building is a prerequisite and sub-standard technologies would not be considered. The ranking criteria, taking into account white cards, are shown in Fig. 4. After arranging the criteria, it is necessary to write down the number of cards in a given row and assign them a position, with the numbering of items starting with the least important criterion. Then the non-normalized weight is recorded – for white cards it is zero, for the criteria the number of their positions is prescribed, and for criteria in one row (equally important), the weight is obtained by dividing the sum of their positions by the number of cards, for example, for the fire resistance of the production part and fire resistance of the warehouse part, the action $(9 + 10)/2 = 9.5$ is performed. The last step of the Simos method is to calculate the normalized weights according to Eq. (3.1). The rule is that the total in the denominator does not include the positions of the blank cards.

$$\overline{w_i} = \frac{w_i}{\sum_{i=1}^{m} p_i} \tag{3.1}$$

where: w_i – non-normalized weight for a given criterion; p_i – item number for a given criterion; $i = 1, \ldots, m$; m – cards number.

Following the above principles, standardized weights were calculated for each of the criteria. $\sum_{i=1}^{m} p_i = 1 + 2 + 4 + 6 + 9 + 10 = 32$, for example: $\overline{w_{9,10}} = \frac{9.5}{32} \approx 0.297$.

The data required for the calculations and the obtained results are summarized in Table 2. It should be emphasized that in Table 2, in the lines with equally important criteria, the calculated normalized weight is not the sum of their weights, but is specified for each of these criteria. The sum of all weights is equal to one, which confirms the correctness of the performed calculations. Thus, in carrying out a multi-criteria analysis, criteria with the following decision weights will be used: Cost of execution – 0.187; Execution time – 0.125; Thermal insulation of curtain walls – 0.297; Curtain wall acoustic insulation – 0.297; Fire resistance of the production part – 0.047; Fire resistance of the warehouse part – 0.047.

Table 2. Calculation of normalized weights for given criteria [own source]

			Card No	**Position**	**Non normalized weight**	**Normalized weight**
The least important	Fire resistance rating of the production part	Fire resistance rating of the storage part	2	1 and 2	1,5	0,047 × 2
	White card		1	3	0	0
	Execution time		1	4	4	0,125
	White card		1	5	0	0
	Execution costs		1	6	6	0,187
	White card		1	7	0	0
	White card		1	8	0	0
The most important	Thermal insulation of the curtain walls	Acoustic insulation of the curtain walls	2	9 and 10	9,5	0,297 × 2
			Sum:	32		1,000

4. Results and discussion – normalization and criteria analysis

A. The purpose of normalization is to obtain the comparability of the values presented by the considered criteria. There are many standardization tools with different data transformation methodologies, but the choice of the appropriate formula depends on the adopted method of assessing variants. The article uses two methods of normalization:

Street normalization (Manhattan), Eq. (4.1) [15]:

$$\overline{p_{i,j}} = \frac{p_{i,j}}{\sum_{i=1}^{m} p_{i,j}} \tag{4.1}$$

where: $\overline{p_{i,j}}$ – element of normalized matrix; $i = 1, \ldots, m$; $j = 1, \ldots, n$; m – variants number; n – criterion number.

Vector normalization (Euclidean), Eq. (4.2) [15]:

$$\overline{p_{i,j}} = \frac{p_{i,j}}{\sqrt{\sum_{i=1}^{m} p_{i,j}^2}} \tag{4.2}$$

Multi-criteria analysis is used when decision making depends on more than one objective function. In the investment process, by implementing strategic and design assumptions and their verification, many goals must be achieved at the same time, because the aim is to obtain the lowest costs, implementing the investment in the shortest possible time, meeting the standard requirements, etc. Therefore, each construction is an example of the multidimensional decision problem, which involves people's opinion or knowledge, uses natural resources and affects the environment [38]. "Multi-criteria slightly increases the difficulty of constructing a decision model, but it significantly complicates the solution of such models" [6].

This is because in the vast majority of cases the goals will compete with each other, a good example of which is the possibility of using better construction technology, but at a much greater cost. The presented analysis is one of the value engineering tools, the aim of which is to select the optimal solution from a set of variants, when there is more than one decision criterion. All the set requirements are combined by mathematical methods into one common objective function, the final results of which constitute the evaluation of a given variant [9]. The multi-criteria analysis consists of several basic stages, Fig. 4 [16, 17].

First, appropriate evaluation criteria should be selected and decision weights determined for them. For the set requirements, a data matrix is developed, which is normalized in a manner appropriate to the adopted assessment method. After making the appropriate calculations, the decision-maker can choose the optimal solution through assessment methods In this research usefulness of each solution was determined using the entropy and the ideal point method.

B) The Entropy Method is based on the estimation of the validity of the adopted evaluation criteria on the basis of the divergence of each of them. The weights determined earlier cease to be reliable, and as a result, there is a need to modify them.

According to [15], this method was first used in the information processing technique by C. Shannon, and later refined by B. McMillan and L. Breiman. In the literature [9, 15] it is recommended to normalize the data matrix using the relationship described by Eq. (4.1). Then, the entropy E_j of individual criteria determining the degree of disorder (or chaotic nature) of the set is calculated. Eq. (4.3) uses the so-called entropy index k, depending on the number of analysed variants. Based on the value of E_j, the levels of variability of the entropy z_j are calculated, which will be used to modify the weights, Eq. (4.4) and Eq. (4.5).

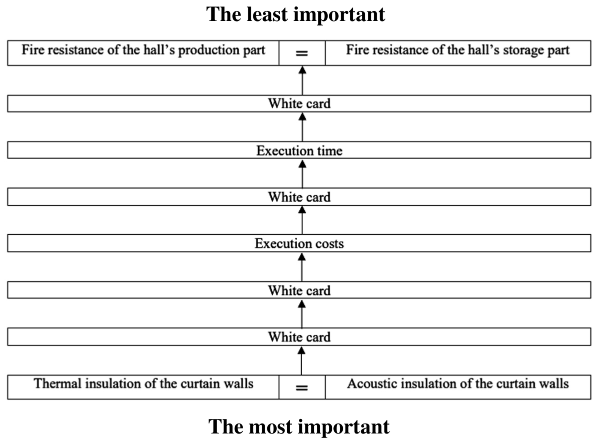

Fig. 4. Evaluation criteria ranking [own source]

According to [18, 40], the lower the entropy value, the more information we obtain about the probability distribution of a random variable, which proves that there is less uncertainty for a given criterion. In a later stage of the method, the weights of the criteria are updated. First, the initial weights w_j are determined as the ratio of the entropy variability level of a given criterion to the sum of all levels, Eq. (4.6). Final weights w_j^0, used in the evaluation of variants are calculated based on the values of w_j and the weights determined previously by the Simos method, Eq. (4.7).

$$k = \frac{1}{\ln n_w} \tag{4.3}$$

$$E_j = -k \sum_{i=1}^{n} \overline{p_{i,j}} \cdot \ln \overline{p_{i,j}} \tag{4.4}$$

$$z_j = 1 - E_j \tag{4.5}$$

where: $\overline{n_w}$ – number of analyzed variants.

$$w_j = \frac{z_j}{\sum\limits_{j=1}^{m} z_j} \tag{4.6}$$

$$w_j^0 = \frac{w_j \cdot \overline{w_j}}{\sum\limits_{j=1}^{m} w_j \cdot \overline{w_j}} \tag{4.7}$$

The disadvantage of the entropy method is the potential inadequate assignment of new weights. The role of more important criteria can be significantly reduced, previously less important criteria become decisive. Moreover, if all variants have the same values in a given criterion, its modified weight will be equal to zero, which completely excludes them from the objective function. For each variant, the take-off and cost estimate was prepared in Norma Pro and then, using the values from the take-off, and Excel used to estimate the times of making the hall walls. Data on thermal and acoustic insulation as well as fire resistance were obtained from the websites of manufacturers who offer such technological solutions. Table 2 summarizes all the values needed to perform the analysis. As mentioned, among the considered criteria are stimulants and destimulants. In order to properly conduct the analysis, the method of describing the considered criteria as the best should be standardized. Therefore, it was assumed that for the entropy method, the variant with the lowest final result would be the determinant of the best technological solution. Therefore, the data from Table 2 regarding acoustic insulation and fire resistance have been transformed according to Eq. (4.8).

$$p_{i,j} = \frac{1}{a_{i,j}} \tag{4.8}$$

where: $p_{i,j}$ – the element of the matrix of data needed for the calculation; $a_{i,j}$ – value from the dataset before conversion.

Sample calculations for the acoustic insulation of curtain walls:

$$\frac{1}{31} = 0{,}03226; \quad \frac{1}{44} = 0{,}02273; \quad \frac{1}{43} = 0{,}02326$$

Based on the results and values for the destimulants from Table 3, a matrix of data needed for the calculations was developed. From this stage on, separate calculations are performed with the algorithms described previously, based on the data in Table 4.

Table 3. Summary of data for variants of hall walls with criteria [own source]

	Criterion number 1–6 (same heading for tables 2–6)					
	1	**2**	**3**	**4**	**5**	**6**
Variant I	514 332,17	15	0,34	31	REI 120	REI 240
Variant II	555 284,95	28,5	0,31	44	REI 60	REI 120
Variant III	467 604,31	28,5	0,33	43	REI 60	REI 120

Table 4. Matrix of data needed for calculations [own source]

	1	**2**	**3**	**4**	**5**	**6**
Variant I	514 332,17	15	0,34	0,03226	0,00833	0,00417
Variant II	555 284,95	28,5	0,31	0,02273	0,01667	0,00833
Variant III	467 604,31	28,5	0,33	0,02326	0,01667	0,00833

In the entropy method, the terms of the matrix in Table 4 are normalized using the street method, based on the Eq. (4.2). The results are summarized in Table 5. From the values given in Table 2, the entropy and the entropy variability level of the criteria are calculated according to the formulas provided. With $k = 1/\ln 3$, because three variants are compared. The results are summarized in Table 6. Using the values of the level of entropy variability from Table 6, as well as the original weights and appropriate formulas, the modified weights are determined.

Table 5. Normalized matrix of solutions – street normalization [own source]

	1	**2**	**3**	**4**	**5**	**6**
Variant I	0,33459	0,20833	0,34694	0,41229	0,20000	0,20000
Variant II	0,36123	0,39583	0,31633	0,29048	0,40000	0,40000
Variant III	0,30419	0,39583	0,33673	0,29723	0,40000	0,40000

Table 6. Entropy values and levels of variation for the adopted criteria [own source]

	1	**2**	**3**	**4**	**5**	**6**
Entropy	0,99777	0,96529	0,99933	0,98762	0,96023	0,96023
Entropy variability	0,00223	0,03471	0,00067	0,01238	0,03977	0,03977

Table 7. Set of modified weights for taken criterions [own source]

	1	**2**	**3**	**4**	**5**	**6**
W_j	0,01723	0,26796	0,00515	0,09558	0,30704	0,30704
Former weights	0,187	0,125	0,297	0,297	0,047	0,047
New weights	0,034	0,351	0,016	0,297	0,151	0,151

The results are summarized in Table 8. The calculations below are analogous. The values in Table 6 are multiplied by the corresponding new decision weights. The assessment of variants is performed with the dependence of the weighted sum.

Table 8. Results of the variants assessment of weighted sum for entropy method [own source]

	1	**2**	**3**	**4**	**5**	**6**	**Variant score**
Variant I	0,01138	0,07312	0,00555	0,12245	0,03020	0,03020	0,27290
Variant II	0,01228	0,13894	0,00506	0,08627	0,06040	0,06040	0,36375
Variant III	0,01034	0,13894	0,00539	0,08828	0,06040	0,06040	0,36261

Sample calculations for Variant I are presented below. The corresponding calculation results for variants II–III are shown in Table 8.

$$0{,}33459 \cdot 0{,}034 = 0{,}01138; \quad 0{,}20833 \cdot 0{,}351 = 0{,}07312; \quad 0{,}34694 \cdot 0{,}016 = 0{,}00555;$$
$$0{,}41229 \cdot 0{,}297 = 0{,}12245; \quad 0{,}20000 \cdot 0{,}151 = 0{,}03020;$$
$$\mathrm{P}_1 = 0{,}01138 + 0{,}07312 + 0{,}00555 + 0{,}12245 + 0{,}03020 + 0{,}03020 = 0{,}27290$$

C) the Ideal Point Method is an advanced multi-objective planning technique which distinguishes ideal and anti-ideal solutions and then evaluates analyzed data through determining distance to these solutions [39]. This multi-step process starts with normalization the terms of the matrix in Table 3 which, compared to the entropy method, is done through the vector method based on Eq. (4.2). The terms of the normalized matrix are shown in Table 9. Weighted sums for each variant need to be determined for further analysis. The normalized matrix terms assigned to a given variant are multiplied by their corresponding weights from Table 2 and then summed. Calculations for the variant I are presented below as an example. The weighted sums for the variant II and III are calculated analogously. The results of these calculations are presented in Table 10.

$$0{,}57811 \cdot 0{,}187 = 0,10811; \quad 0{,}34879 \cdot 0{,}125 = 0{,}04360; \quad 0{,}60048 \cdot 0{,}297 = 0{,}17834;$$
$$0{,}70427 \cdot 0{,}297 = 0{,}20917; \quad 0{,}33333 \cdot 0{,}047 = 0{,}01567; \quad 0{,}33333 \cdot 0{,}047 = 0{,}01567;$$

Table 9. Normalized matrix of solutions – vector normalization [own source]

	1	**2**	**3**	**4**	**5**	**6**
Variant I	0,57811	0,34879	0,60048	0,70427	0,33333	0,33333
Variant II	0,62414	0,66270	0,54749	0,49619	0,66667	0,66667
Variant III	0,52559	0,66270	0,58282	0,50773	0,66667	0,66667

Table 10. The weighted sums for each criteria [own source]

	1	**2**	**3**	**4**	**5**	**6**
Variant I	0,10811	0,04360	0,17834	0,20917	0,01567	0,01567
Variant II	0,11671	0,08284	0,16261	0,14737	0,03133	0,03133
Variant III	0,09828	0,08284	0,17310	0,15080	0,03133	0,03133

The next step is to distinguish the ideal and anti-ideal values from Table 10 for each criteria using Eq. (4.9) and Eq. (4.10):

$$\text{Ideal } p_{i,j} \cdot w_j = \max_i (p_{i,j} \cdot w_j) \quad \text{for stimulants } \min_i (p_i \cdot w) \tag{4.9}$$

$$\text{Ideal } \overline{p_{i,j}} \cdot \overline{w_j} = \begin{cases} \max_i (\overline{p_{i,j}} \cdot \overline{w_j}) & \text{for stimulants} \\ \min_i (\overline{p_{i,j}} \cdot \overline{w_j}) & \text{for destimulants} \end{cases} \ ?$$

$$\text{Antideal } p_{i,j} \cdot w_j = \min_i (p_{i,j} \cdot w_j) \quad \text{for stimulants } \max_i (p_i \cdot w) \tag{4.10}$$

$$\text{Ideal } \overline{p_{i,j}} \cdot \overline{w_j} = \begin{cases} \max_i (\overline{p_{i,j}} \cdot \overline{w_j}) & \text{for stimulants} \\ \min_i (\overline{p_{i,j}} \cdot \overline{w_j}) & \text{for destimulants} \end{cases} \ ?$$

where: w_j – weight of a given criteria calculated through Simos method.

Then, the distances from ideal and anti-ideal values are determined respectively through Eq. (4.11) and Eq. (4.12):

$$L_i^+ = \sqrt{\sum_{j=1}^{n} (\overline{p_{i,j}} - \text{Ideal}\,\overline{p_{i,j}})^2} \tag{4.11}$$

$$L_i^- = \sqrt{\sum_{j=1}^{n} (\overline{p_{i,j}} - \text{Antiideal}\,\overline{p_{i,j}})^2} \tag{4.12}$$

At this stage the preliminary information about the suitability of each construction variant is obtained, because the shorter the distance from the ideal solution or the greater the distance from the anti-ideal solution, the better evaluation criteria are met. The final step is the calculation of the relative distance to the ideal point Eq. (4.13).The results of this method are presented in the Table 11. Variants are then ranked according to their distance to the ideal point as shown in the Table 12. Regardless of whether the criteria are stimulants or destimulants, the optimal solution is the one closest to ideal point, i.e. its distance P_i is of the lowest value.

$$P_i = \begin{cases} \dfrac{L_i^-}{L_i^+ + L_i^-} & \text{for stimulants} \\ \dfrac{L_i^+}{L_i^+ + L_i^-} & \text{for destimulants} \end{cases} \tag{4.13}$$

Table 11. Set of distances of variants to the ideal, anti-ideal solutions and to the ideal point [own source]

	Distance to the ideal solution	**Distance to the anti-ideal solution**	**Distance to the ideal point**
Variant I	0,06452	0,04588	0,58445
Variant II	0,04868	0,06377	0,43292
Variant III	0,04639	0,06144	0,43024

D) The Comparison of the Methods

Table 12. Comparison between the entropy method and the ideal point method [own source]

	The most favourable				**The least favourable**
Entropy method	Variant I	>	Variant III	>	Variant II
Ideal point method	Variant III	>	Variant II	>	Variant I

In both methods a variant with the lowest final result is the most advantageous and hence the most sustainable solution. Nevertheless, each method indicates a different variant as the most favourable. According to the entropy method sandwich panels are considered to be the most optimal solution, whereas this particular variant is shown as the least favourable in the ideal point method which shows cassette walls solution as the most favourable. However, both methods show that the trapezoidal sheets is not the most optimal solution. Moreover, in all used methods, the evaluation results for variant II and variant III are close to each other.

5. Conclusions

This particular study presents the importance of weights determination with use of the Simos method, which minimizes the risk of subjective choice of a variant based on roughly selected weights. Ideally, decision-makers, for example participants of the investment process, individually arrange the criteria in order to compare the results and verify the weights in a joint agreement. Civil engineering is a field in which many of criteria and data can be obtained from official standards, for example properties of materials, final elements (walls) and buildings, hence it can be assumed that reaching a consensus is relatively easy. There are other fields however with too many factors involved where agreeing on output data may be challenging, especially when public opinion is involved. This issue has been extensively described in the articles [23, 37], according to which several individual opinions may lead to a greater complexity of a given problem with the need of creating a mathematical consensus model.

Due to their nature, which may lead to different final results, assessment methods also affect optimization process. The entropy method indicates the variant with sandwich panels as optimal because its weighted sum is minimal. In the entropy method, variant I has the lowest final score – about 0.1 lower than the similar scores for variants II and III, thus it is the best solution. Execution times in particular have become important criteria. As mentioned, the modification of the weights is not always justified and in this case the decision maker assumptions clearly changed. Making a choice between variants depends on the selected criteria and the decision weights assigned to them. For example, a cheaper, but time-consuming construction technology, will probably not get a good rating if the performance time criterion is much more important than the costs incurred in a given optimization. However, the ideal point method determines that the variant with cassette walls is the most optimal, as its distance to the ideal point is the shortest. The evaluation result for the sandwich panels shows a distance to the ideal point which is significantly greater than the distances of variant II and variant II, hence it is considered to be the least favourable solution. Both methods indicate different variants as the most favourable. This is slightly caused by the use of diverse normalization techniques, but more importantly the new ordering of variants in the entropy method from the most to the least important led to creation of new decision weights, which instinctively generates different results.

The fact that the final results for variant II and II are similar leads to a conclusion that their levels of sustainability are almost the same.

Based on the above analysis it is possible to select the most optimal solution through the following conclusions: firstly, variant II is rejected because neither of the methods identified it as the most optimal solution; depending on the method variant I is classified as the most and the least optimal solution. However, none of the methods indicated variant III as the least optimal, it is either the best or second best solution, hence cassette wall is selected as the most sustainable technological solution.

Benefits of the VE method [24], enhanced by presented in this article mathematical optimization methods could be named as follows: the process, when used, allowed the client to feel part of the project and also involved the end users, enabling both client and user needs to be met in a resourceful and value-adding manner; The workshops helped the team to push the boundaries of many factors, including cost, time and quality; Overall, the process improved the definition and articulation of value in the context of the project; contributed to improvement of clearer brief and decision taking and enhanced the value and benefits for the end users, as important element of life cycle of the project; the process, by reducing cost and offering savings, improved affordability and value for money; the process helped to improve productivity, efficiency, collaboration and trust; helped to reduce waste and defects; also facilitated earlier management involvement thus helping in potential issue identification and resolution.

The technologies and materials solutions discussed in the paper influencing significantly sustainable aspects of the construction project not only from cost and time point of view during object construction, but also the longest period of the life cycle – the object maintenance due to the comfort of use – energy use related to internal temperature and acoustic issues and important safety factor – fire resistance conditions. Further research will address other criteria, proper (objective and mathematical) weight calculations and optimization methods leading to sustainable construction, minimizing cost, materials use, waste production etc.

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Metoda optymalizacji wyboru ścian osłonowych obiektów przemysłowych

Słowa kluczowe: entropia, inżynieria wartości, materiały metoda punktu idealnego, metoda Simosa, optymalizacja, technologie zrównoważone

Streszczenie:

Obecne trendy na rynku budowlanym wymagają opracowania i realizacji projektów budowlanych o zrównoważonych kosztach i jak najkrótszym czasie realizacji, przy jednoczesnym zachowaniu wysokiej jakości robót i właściwości realizowanych obiektów. Osiągnięcie tego celu jest trudne, jednak wraz z rozwojem nowych technologii i technik zarządzania możliwe jest osiągnięcie zrównoważonego projektu. Celem autorów było znalezienie rozwiązania technologicznego, które skutecznie spełniłoby narzucone wymagania dotyczące optymalizacji projektu technologiczno-organizacyjnego hali. Trzy technologie zostały przeanalizowane za pomocą analizy wielokryterialnej opartej na 6 kryteriach – wszystkich ważnych z punktu widzenia zrównoważonego rozwoju. Wybór i właściwe sprawdzenie kryteriów zrównoważonego podejmowania decyzji jest kluczowe, gdyż kryteria są zwykle opisywane przez ekspertów w sposób nie do końca obiektywny i matematyczny. Omówiono. i wykorzystano wybrane elementy praktyk Inżynierii Wartości. W celu oceny każdego wariantu konstrukcji wyznaczono. wagę każdego kryterium metodą Simosa i znormalizowano dane wariantów. Praktyczność każdego wariantu konstrukcji jako rozwiązania zrównoważonego została ustalona za pomocą dwóch metod oceny – metody entropii i metody punktu idealnego. Wyniki tych badań dowodzą, że kierownicy projektów mogą z sukcesem realizować zrównoważone projekty poprzez opisany proces optymalizacji. Podobnie tego typu analizy mogą być również korzystne w innych dziedzinach, takich jak inżynieria mechaniczna, finanse, transport, rolnictwo itp.

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