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COMPARATIVE ANALYSIS OF SLAB FORMWORK OF MONOLITHIC REINFORCED CONCRETE BUILDINGS

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paper presents the issue related to the selection of slab formwork taking into account the criteria that are currently the most important The in the process of the construction project execution. The analysis included selected, modern system solutions, which significantly accelerate the tempo of reinforced concrete works and, as a consequence, increase the effectiveness of the construction project execution. The innovative system of drop heads, which the analysed slab formwork is equipped with, is offered by various formwork producers. The offered solutions, however, differ not only in the construction of the drophead itself, but also in the arrangement and variety of other system elements, as well as the scheme of their operation, which may ultimately significantly affect the effectiveness of their application. For that reason, the choice of formwork for specific buildings should be made from among carefully analysed several variants of the wide market offer. The paper presents the results of analysis and evaluation of formwork systems with dropheads according to the proposed methodology, including multi-criteria analysis.

*Keywords***:** slab formwork, drophead, monolithic reinforced concrete technology, multi-criteria analysis

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1. INTRODUCTION

The construction of buildings in monolithic reinforced concrete technology is becoming more common, due to many advantages advantages [1]. Thanks to technical progress, the execution of the component processes of this technology is becoming more and more complex, mainly due to the use of modern system and material solutions with adapted technology, as well as the need to optimize production costs, lead time and other indicators, especially economic and technical ones. At the beginning of the elaboration of a comprehensive works project, the planner has to solve many decision-making problems. The ability to solve them enables rational allocation of resources over time and allows for their efficient use [2, 3].

One of the many decisions taken during the process of planning the organization of works is the choice of an appropriate slab formwork. For a long time, commonly available traditional (single use) formwork and later classic system formwork were used to form the slab surfaces. However, with the development of slab formwork, the importance of competitiveness of enterprises increased, which resulted in the introduction of innovative solutions. A breakthrough system, which began to be used for slab formwork, was the introduction of a drophead. This system gave the possibility to dismantle some of the formwork elements just two days after the formwork, which significantly accelerated the possibility of their reuse on the next work plot. This method of assembly changed the importance of the existing criteria for the selection of slab formwork, which were mainly based on costs - influencing the need to look also at the execution time.

Appropriate planning of works with the use of slab formwork with drop heads enables optimization of execution time and costs of monolithic reinforced concrete structure slabs while maintaining maximum efficiency of formwork work [4].

Nowadays, almost every company specializing in the production of system slab formwork has in its offer formwork with dropheads. These systems differ not only in the construction of the drophead itself, but also in the arrangement and variety of other system elements, as well as the scheme of their operation. Practical experience on the construction market shows that although the formwork supplier provides the formwork design (with a team of assemblers), it is not the most advantageous offer for the construction of a specific building with its specific conditions of construction. The best formwork is not selected from among the many possible to use. Moreover, in choosing a solution it is necessary to be guided by a number of factors, so that the choice is really the most advantageous, taking into account the multitude of requirements and conditions of construction production [5,6,7].

Therefore, in the article the authors present the methodology of selection of slab formwork with dropheads from the systems offered by leading companies. The presented method consists in carrying out a multi-criteria analysis which allows to select the most advantageous solution for a given construction object.

2. RESEARCH METHODOLOGY

The problem taken up for research results from the needs of construction practice. The aim and scope of the research was based on the experience in reinforced concrete works of monolithic site managers and was preceded by interviews with experts in the field of construction and market research of leading formwork manufacturers. Decisions to choose from several solutions require the adoption of one or several criteria. In the analyzed problem there is a need for multi-criteria analysis. The solution to the problem was obtained by conducting research according to the following methodology:

1. Defining the problem and setting the purpose of the study: Selection of slab formwork with dropheads.
2. Carrying out an analysis of system slab formwork and determining a set of considered variants based on market research and expert interviews.
3. Establishing a preliminary set of criteria (PSC) for the assessment of considered variants on the basis of literature review and conducted surveys.
4. Determination of the final set of criteria (FSC) in two stages (I stage - application of algorithms from the theory of graphs, and more strictly the properties of layered graphs; II stage – verification of a set of criteria based on expert surveys).
5. Quantification of criteria considered in the assessment and their validity based on direct surveys
6. Selection of the method of solving the problem. Multi-criteria analysis was performed using three appropriately selected methods. The following methods were used: synthetic indicators, AHP and PROMETHEE II. Calculation using the three methods is a kind of verification of the results obtained.
7. Carrying out calculations and analysis of the results obtained.

The use of proper formwork in the monolithic works of a building depends on a number of factors that have a significant influence on the execution of works and decisions taken. Multi-criteria analysis is helpful in this process. Currently, there are many proposals for the analysis and synthesis of the most common discrete multi-criteria problems, which enable the solution of difficult and complex problems [8].

In order to solve the problem of optimal selection of slab formwork with dropheads, a multi-criteria comparative analysis of three methods of calculation, differing in the course of action, was carried out: synthetic indicators method, AHP method and Promethee II method. The methods chosen belong to different schools of multi-criteria decision making. In addition, the analysis was enriched with expert studies including the preparation of a direct questionnaire, as well as consultations and interviews with experts. The options considered in the analysis were formwork systems with drop heads of leading formwork companies. On the basis of interviews and expert opinions, the systems were taken into account in the analysis: SKYDECK, CC-4 i DOKADEK 30. The basis for all three methods, which selected the weight of the awarded, as important evaluation criteria, was an expert survey giving reliability to their results. The group of respondents participating in the survey consisted mainly of people working in managerial positions (i.e. site manager, works manager) and assembly positions (i.e. concrete worker, reinforcement worker, formwork assembler), who deal with system formwork on a daily basis.

The first method, classified as taxonomic methods, consists in the construction of a synthetic indicator. The adjusted index is obtained by encoding the values of the nominated options assessed against the selected criteria, and then aggregating the partial assessments.

Both the choice of synthetic index and coding method can have a small impact on the score. Finally, the authors decided to use two coding methods (Pattern and normalization) and two indicators (Adjusted index of summation and multiplication).

The second method used is the analytical hierarchical process method (AHP), which was developed by Thomas L. Saaty [9]. This method consists in decomposing the decision-making problem into smaller and easier to analyse partial problems and comparing them to subsequent levels.

The PROMETHEE II (Preference Ranking Organization Method for Enrichment Evaluations) is the procedure of the European School of Decision-Making. This method is the last one used by the authors and consists in examining to what extent a given alternative is preferred over the rest of the alternatives (positive preference flow) and to what extent the rest of the alternatives are more preferred than the given one (negative reference flow).

3. SELECTION OF THE FORMWORK SYSTEM

3.1. DESCRIPTION OF THE FACILITY, CONCEPT OF WORKS, PURPOSE

Due to the individual character of construction projects, reference was made to a specific building and the organization of reinforced concrete works adopted by the contractor.

The object for which the analysis was carried out is located in the Silesian region. It is a shopping mall with a total area of 120,000 m^2, with over 42,000 m^2 of retail space. The remaining space will be occupied by the cinema, fitness club, restaurants, clubs, squash and badminton courts. Due to the cubic capacity of the building, a division into working plots was applied. The division of the building into plots took into account, among other things, the height of the feet as well as the arrangement of structural walls and columns. Thanks to this solution, work could be carried out simultaneously on several work plots. The adopted division enabled effective use of slab formwork with dropheads. The contractor decided to use one of the available formwork systems CC-4 from ULMA. This decision was not preceded by any comparative analyses of other formwork systems of this type. The possibility of observing the process of forming slabs with the use of slab formwork with dropheads on the discussed construction site and access to the necessary information prompted the authors to analyze the use of other formwork systems of this type based on the most important (according to the contractor) criteria (Table 1).

For the purpose of the presented analysis, one of the sectors (a plot of land) was identified, which included three reinforced concrete slabs of two stores with a height of 5.50 m in the light of the building. The slabs were designed as 26 cm thick column-plated ceilings with locally occurring stiffening beams. For the construction of the ceilings, the following classes of concrete were used C 30/37. The sector slab area was rectangular in size 40/24 m and is covered with a grid of 1.5 /1.5 m columns with a symmetrical spacing of 8 m. Additional slab stiffening is provided by two bracing beams connecting the structural wall with the columns (Fig. 1).

The multi-criteria analysis also used data obtained on the basis of technical specification of formwork manufacturers, standard calculations included in the Eurocodes and drawings of formwork of the consideration work plots (Fig.2).

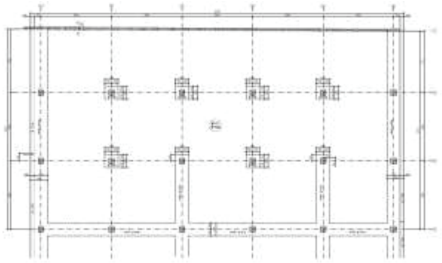

Fig. 1. Plan of one section of the slab in a shopping mall [10]

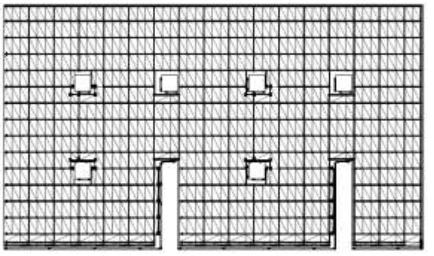

Fig. 2. Projection of a formworked section of the slab in the shopping mall, view from the program PERICad

3.2. CHARACTERISTICS OF THE FORMWORK AND CRITERIA FOR THEIR ASSESSMENT

The development of monolithic construction over the last decades has made it necessary to apply new material and technological solutions. The ever shorter lead times imposed by the investors inspired system formwork manufacturers to improve their products and create completely new ones, with the emphasis on ease of assembly, low weight of components and increased speed of work. The main distinguishing feature of drophead systems from traditional formwork is that there is no need to leave the entire formwork until the concrete mix has reached the appropriate strength. Depending on the weather conditions and the thickness of the slab, the floor can be partially stripped off even after one day. In any drophead system, panels can be completely removed and, depending on the manufacturer, also beams or transverse beams. Until the concrete mix reaches the required strength, the slab is supported point-by-point by props with lowered drop heads or linearly, if the beams are not dismantled in the system together with the slabs. The first company to introduce innovative products to the market in 1992 was PERI, with the introduction of MULTIPROP aluminum supports and the SKYDECK drophead formwork system. In the following years, the dropheads were also included in the formwork offers of DOKA–DOKADEK 30, ULMA–CC-4, ALSINA–ALUMECANO, NOE–NOEdeck, and others.

Based on expert opinions, the four leading manufacturers of drophead slab formwork systems were pre-selected for the tests. The first analyzed formwork was a system that was used on the observed construction site, i.e. CC-4 by ULMA (Fig. 3 and 4). Panel formwork with drop heads is characterized by the possibility of quick and easy assembly and disassembly. Below (Fig. 3, Fig. 4) the diagram of the CC-4 system drop head operation is presented.

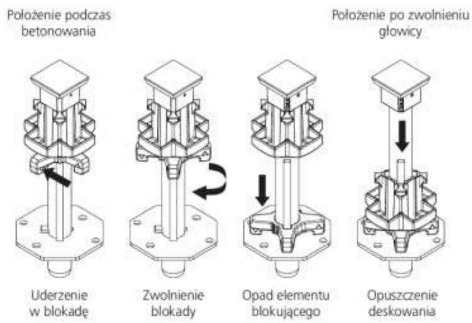

Fig. 3. Operating scheme of the CC-4 drophead [11]

Fig. 4. CC-4 drop head in upper position [10]

With the SKYDECK system it is possible to form slabs with a thickness of up to 109 cm. The system consists of five basic elements, the heaviest of which generally doesn't exceed 15.5 kg. The third formwork under consideration is DOKADEK 30 from DOKA. This formwork is equipped with the XF drop head. In addition, this system has been integrated with the company's maturation control system (in real time), which allows the slab to be formworked at the right time, thus guaranteeing optimisation of the working time of the formwork.

In order to determine the set of evaluation criteria for the set of initial criteria, in the first stage, calculations were carried out using an ordering algorithm [14], which eliminated criteria containing similar information. The second stage consisted of an expert survey to determine whether the set of criteria set out in the first stage met the needs of decision-makers. Twenty experts working on the construction of cubature buildings were asked for their opinions. The respondents evaluated the features presented in the forms, awarding points depending on their relevance according to the principle: 10 - most important 0 - insignificant. The questionnaire submitted for completion also allowed us to determine the weights of individual criteria.

The criteria were sorted according to the points obtained. The most important feature turned out to be: construction time of $1m^2$ of the slab (measured by the labour intensity index [man-hour/m^2]), whose average score was 9.4 points. The least important was the information on the type of materials used and how their production process affected the environment. The set of final criteria included criteria assessed by the experts as no less than 7 (**Błąd! Nieprawidłowy odsyłacz do zakładki: wskazuje na nią samą.**1), while criteria which did not differentiate between the analysed options were rejected.

Table 1. Final set of criteria for the assessment of slab formwork systems with dropheads (FSC)

No.	Criterion	Weight *Ki*
K1	Labour intensity index (Execution time of 1 m^2 of the slab)	0.156
K2	Ergonomics of the construction	0.138
K3	Required puncture resistance of the slab	0.134
K4	Execution cost 1m^2 of the slab	0.136
K5	Weight of the basic formwork elements	0.121
K6	% of slab surface area covered with system elements	0.120
K7	Wear indicator per 1m^2 of the slab	0.117
K8	Maximum permissible slab thickness	0.082

The values of the adopted criteria for the selected formwork systems are in Table 2.

Table 2. A set of criteria considered in the multi-criteria evaluation of slabs formwork selection

No.	SKYDECK	CC-4	DOKADEK 30
K1	0.3 m-h/m^2	0.38 m-h/m^2	0.2 m-h/m^2
K2	4.33	4	3
K3	0.040 MPa	0.044 MPa	0.037 MPa
K4	51.76 zł/m^2	38.00 zł/m^2	33.20 zł/m^2
K5	24 970 kg	22 950 kg	22 500 kg
K6	98 %	98 %	89 %
K7	1.06 piece/m^2	1.35 piece/m^2	1.00 piece/m^2
K8	90 cm	90 cm	50 cm

4. CALCULATION RESULTS AND THEIR ANALYSIS

Partial calculations and results obtained in the multi-criteria analysis carried out with the following methods: synthetic indicators, AHP and PROMETHEE II are presented below.

In the synthetic indicator method, the first step is to encode the titled values to the unchanged values. Coded values were multiplied by the weight vector, then calculated according to the formula for adjusted index of summation and adjusted index of multiplication (Table 3).

Second method used in proposal analysis was AHP. Decomposition of discussed problem into a hierarchy is shown in Fig.5. Calculations for the second level is shown in Table 4.

Table 3. The adjusted index of summation and multiplication for two coding methods

No.	**Normalization**			**Pattern**		
	SKYDECK	**CC-4**	**DOKADEK 30**	**SKYDECK**	**CC-4**	**DOKADEK 30**
K1	0.1037	0.0819	0.1556	0.0473	0.0373	0.071
K2	0.1382	0.1277	0.0958	0.0528	0.0488	0.0366
K3	0.1274	0.1158	0.1341	0.0453	0.0412	0.0477
K4	0,.85	0.1158	0.1325	0.0338	0.046	0.0527
K5	0.1089	0.1185	0.1209	0.0378	0.0411	0.042
K6	0.12	0.12	0.109	0.0413	0.0413	0.0375
K7	0.1101	0.0864	0.1167	0.041	0.0322	0.0435
K8	0.082	0.082	0.0456	0.0321	0.0321	0.0178
A. i. of summation	**0.88**	**0.85**	**0.91**	**0.33**	**0.32**	**0.35**
A. i. of multiplication	**1.83 E-08**	**1.41 E-08**	**1.85 E-08**	**7.85 E-12**	**6.05 E-12**	**7.94 E-12**

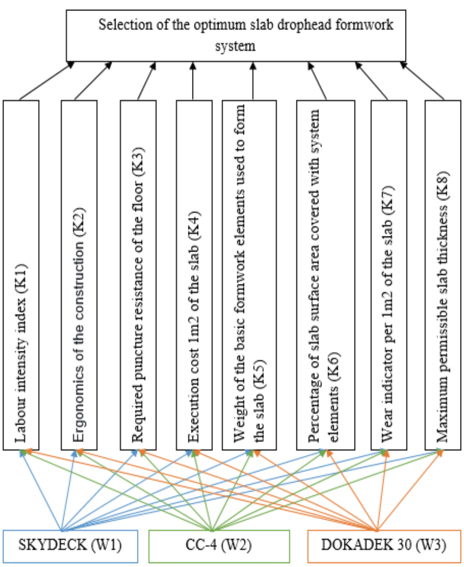

Fig. 5. Decomposition for formwork systems

Table 4. Eigenvectors calculation for second level in AHP method

No.	**Criterion**	Vector w_i
K1	Labour intensity index (Execution time of 1 m^2 of the slab)	0.3077
K2	Ergonomics of the construction	0.2059
K3	Required puncture resistance of the slab	0.1529
K4	Execution cost 1m^2 of the slab	0.1162
K5	Weight of the basic formwork elements	0.0828
K6	% of slab surface area covered with system elements	0.0629
K7	Wear indicator per 1m^2 of the slab	0.0478
K8	Maximum permissible slab thickness	0.0237
Λmax		8.8606
C.I.		0.1229
C.R.		**0.09**

And the third level (Table 5). Finally we obtain the overall priority (Table 6).

Table 5. Calculation of eigenvectors and compliance indexes

No.	SKYDECK	CC-4	DOKADEK 30	λ_{max}	C.I.	C.R.
K1	0.583	0.1047	0.6370	3.0385	0.0193	**0.03**
K2	0.6491	0.2790	0.0719	3.0649	0.0324	**0.06**
K3	0.2583	0.1047	0.6370	0.0385	0.0193	**0.03**
K4	0.0719	0.2790	0.6491	3.0649	0.0324	**0.06**
K5	0.0780	0.2872	0.6348	3.0940	0.0470	**0.08**
K6	0.4545	0.4545	0.0909	3.0000	0.0000	**0.00**
K7	0.2797	0.0936	0.6267	3.0858	0.0429	**0.07**
K8	0.4667	0.4667	0.0667	3.0000	0.0000	**0.00**

Table 6. Overall priority for AHP

No.	Variant	
A	SKYDECK	**0.32**
B	CC-4	**0.21**
C	DOKADEK 30	**0.47**

In the PROMETHEE the intermediate results are presented below. Subsequently for each pair of decision variants x and y is calculated aggregated indexes of preferences is shown in Table 7. The final stage is to calculate net flows for each of the considered variants by using equations (Table 8).

Table 7. Substitute criterion for partial criteria

$P_j[\delta_i(x, y)]$	(a, b)	(b, a)	(a, c)	(c, a)	(b, c)	(c, b)
K1	0.4	0.0	0.0	0.5	0.0	0.9
K2	0.5	0.0	0.5	0.0	0.5	0.0
K3	0.5	0.0	0.0	0.5	0.0	0.5
K4	0.0	0.65	0.0	0.92	0.0	0.16
K5	0.0	0.4	0.0	0.49	0.0	0.09
K6	0.0	0.0	0.42	0.0	0.42	0.0
K7	0.002	0.0	0.0	0.0	0.0	0.002
K8	0.0	0.0	1.0	0.0	0.0	0.0

Table 8. Positive and negative flow preferences and net flows for each variants

Variant	SKYDECK	CC-4	DOKADEK
Positive flow	0.200	0.169	0.284
Negative flow	0.233	0.219	0.201
NET FLOW	-0.03	-0.05	**0.08**

The ranking received in each of the methods was the same, classifying the DOKADEK 30 system in the first place, the SKYDECK system in the second place, thus placing the CC-4 system in the last place. The high, achieved result for the DOKADEK 30 system was influenced by as many as four out of eight considered criteria, i.e. *labour intensity index, required puncture resistance of the slab, execution cost 1m^2 of the slab and weight of the basic formwork elements.* The DOKA formwork was distinguished by, among others, the lowest execution cost and labour intensity index, as shown in Table 8. This means both cost savings and an impact on the reduction of the time of reinforced concrete works.

The presented analysis showed that it is worthwhile to carry out an earlier comparative analysis of formwork systems (products) available on the market. A contractor carrying out an exemplary construction project could achieve additional savings through low planning costs. The calculations showed that the applied formwork system is the least advantageous of the options considered.

5. Conclusions

On the construction market there are many manufacturers offering a wide range of products: construction products, construction machines and equipment, including formwork. Although the standard of e.g. formwork systems offered is basically the same, it is possible to choose the most advantageous offer from a wide range of offers for given conditions of project implementation. Selection of a product and related additional services in the offer is often a difficult decision making process requiring consideration of many factors - criteria.

Therefore, the presented example of a method which is not very labour-intensive and easy to apply in practice proves that it is worth making choices from several analysed offers, taking into account the specific conditions of the implemented construction project. This guarantees the best choice, which was lacking in the observed construction of the gallery.

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LIST OF FIGURES AND TABLES:

DOBÓR DESKOWAŃ STROPOWYCH DO REALIZACJI BUDYNKÓW MONOLITYCZNYCH

Słowa kluczowe**:** *deskowania stropowe, głowice opadowe, decyzja*.

STRESZCZENIE

Podjęty problem wynika z potrzeb praktyki budowlanej. Dotyczy wyboru systemów deskowań do wykonywania budynków w technologii żelbetowej monolitycznej. Praktyka wskazuje, że jakkolwiek dostawca deskowań zapewnia projekt deskowania (często i zespół montażystów) to nie zawsze jest to najkorzystniejsza oferta dla realizacji obiektu z jego specyficznymi uwarunkowaniami realizacyjnymi. W artykule przedstawiono metodykę wyboru deskowań stropowych z głowicami opadowymi spośród oferowanych systemów przez producentów.

Materiały i metody

Na podstawie analizy krytycznej literatury przedmiotu badań oraz analizy rynku budowlanego i wyników badań kwestionariuszowych ekspertów i specjalistów ds. realizacji konstrukcji monolitycznych przyjęto do wyboru najkorzystniejszego systemu analizę wielokryterialną. Zastosowano trzy metody oceny: wskaźników syntetycznych, AHP oraz PROMETHEE II (mając na względzie weryfikację wyników). Rozwiązanie podjętego problemu otrzymano prowadząc badania według następującej metodyki:

1. Zdefiniowanie problemu i ustalenie celu badań: Dobór deskowań stropowych z głowicami opadowymi.
2. Przeprowadzenie analizy systemowych deskowań stropowych i ustalenie zbioru rozpatrywanych wariantów w oparciu o badania rynku oraz wywiady eksperckie.
3. Ustalenie wstępnego zbioru kryteriów (WZK) oceny rozpatrywanych wariantów w oparciu o przegląd literatury oraz przeprowadzone badania ankietowe.
4. Dwuetapowe wyznaczenie ostatecznego zbioru kryteriów (OZK) (I etap - zastosowanie algorytmów z teorii grafów, a dokładniej własności grafów warstwowych; II etap – weryfikacja wyznaczonego zbioru kryteriów w oparciu o opinie ekspertów.
5. Kwantyfikacja uwzględnianych w ocenie kryteriów i ustalenie ich ważności w oparciu przeprowadzone badania ankietowe.
6. Wybór metody rozwiązania problemu. Zastosowano analizę wielokryterialną wykonana za pomocą trzech odpowiednio dobranych metod. Zastosowano metody: wskaźników syntetycznych, AHP oraz Promethee II. Wykonanie obliczeń za pomocą trzech metod stanowi swoistą weryfikację otrzymanych wyników.
7. Przeprowadzenie obliczeń oraz analiza uzyskanych wyników.

Wyniki

Z uwagi na indywidualny charakter przedsięwzięć budowlanych odniesiono się do konkretnego obiektu budowlanego i przyjętej przez wykonawcę organizacji robót żelbetowych. Na podstawie opinii eksperckich w analizie uwzględniono systemy: SKYDECK, CC-4 (system, który został wybrany przez wykonawcę) i DOKADEK 30. W tabeli 1 i 2 zawarto zbiór kryteriów oceny deskowań, ich wagi i miary, wybrany w dwóch etapach badań. W wyniku obliczeń uzyskano następujący ranking analizowanych systemów deskowań, dla przyjętych w przykładowej budowie uwarunkowań: 1- DOKADEK 30, 2- SKYDECK i 3-CC-4.

Tabela 1. Kryteria oceny systemów deskowań i ich wagi

Kryterium K_i	**Waga**
Czas wykonania 1m^2 stropu	0,156
Ergonomiczność systemu deskowań	0,138
Czas od montażu do rozdeskowania	0,134
Koszt wykonania 1m^2 stropu	0,136
Masa deskowania (całości stropu)	0,121
Udział % pokrycia powierzchni stropu	0,120
Wskaźnik zużycia elementów na 1m^2 stropu	0,117
Nośność deskowania (maksymalna grubość stropu)	0,082

Tablica 2. Wartości zbioru kryterów do oceny deskowań

Nr	**SKYDECK**	**CC-4**	**DOKADEK 30**
K1	0,3 m-h/m^2	0,38 m-h/m^2	0,2 m-h/m^2
K2	4,33	4	3
K3	0,040 MPa	0,044 MPa	0,037 MPa
K4	5,.76 zł/m^2	38, 00 zł/m^2	33, 20 zł/m^2
K5	24 970 kg	22 95 0 kg	22 500 kg
K6	98 %	98 %	89 %
K7	1, 06 piece/m^2	1, 35 piece/m^2	1, 00 piece/m^2
K8	90 cm	90 cm	50 cm

Wnioski

Na rynku budowlanym działa wielu producentów oferujących szeroką gamę produktów: wyrobów budowlanych, maszyn budowlanych oraz urządzeń w tym deskowań. Jakkolwiek standard oferowanych np. systemów deskowań jest w zasadzie jednakowy to jednak można z szerokiej oferty wybrać dla danych warunków realizacji przedsięwzięcia ofertę najkorzystniejszą. Wybór produktu i związanych dodatkowych usług w ofercie jest często trudnym procesem decyzyjnym wymagającym uwzględnienia wielu czynników – kryteriów.

Dlatego też przedstawiony przykład niezbyt pracochłonnej metody i łatwej do praktycznego zastosowania świadczy o tym, że warto dokonywać wyborów z kilku przeanalizowanych ofert, uwzględniając specyficzne uwarunkowania realizowanego obiektu budowlanego przedsięwzięcia. Daje to gwarancję najkorzystniejszego wyboru, czego zabrakło w obserwowanej budowie galerii.

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