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CRANE SELECTION PROBLEM IN ASSEMBLY WORKS PLANNING – CRITERIA RELEVANCE AND METHODS

R. MARCINKOWSKI[1], M. BANACH[2]

Crane selection is an important issue in assembly works planning. Tower and telescopic, stationary and mobile cranes used in construction have essentially different properties. Assembly planning begins in analyzing the possibilities of assembly with a given crane. This is called technical aspect of crane selection. Cranes that meet the technical criteria are then analyzed in terms of other criteria related to the effectiveness of their use on the construction site. The article presents the assessment of the selection criteria and the method of crane selection itself. Surveys conducted among construction managers and planners in Polish companies dealing with assembly works allowed to determine the significance of the selection criteria. For this purpose, an example using SAW (Simple Additive Weighting) and FSAW (Fuzzy Simple Additive Weighting) methods was presented. They also allowed to propose a technique for determining preferences in the use of selected construction cranes. The aim of the research was to increase the usability of computer applications supporting assembly planning by acquiring expert knowledge for the initial selection of organizational solutions.

Keywords: assembly, assembly planning, construction cranes, MCDA (Multi-Criteria Decision Analysis), relevance of criteria

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1. INTRODUCTION

The efficiency of construction performance is the main goal of construction companies. It is focused on the efficiency of works' execution according to company's action plan and the rationality of technological and organizational solutions in terms of their costs. The companies pursue these efforts through effective use of their production potential - machines, construction equipment and staff. This is particularly important in comprehensively mechanized construction processes, in which there is always a problem of selection of cooperating machines. Due to the variety of complex mechanized processes implemented in construction, it is justified to search for individualized methods and techniques of their organization.

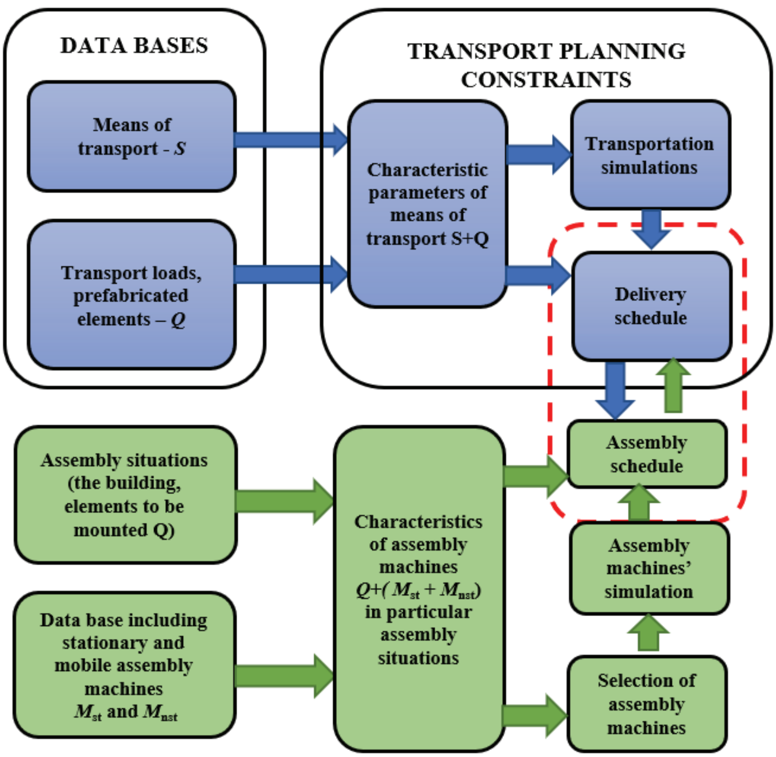

Fig. 1. A general scheme of transportation and assembly planning. Author's elaboration.

The authors took on the task of building a decision support system for planning the process of comprehensive mechanized assembly of prefabricated buildings. It includes optimization of organizational solutions. A generalized scheme of transportation and assembly planning is presented in Fig. 1. The solution to the discussed problem was based on models supporting both the selection of means of transport and lifting devices to perform an assembly task. These models propose the use of the Monte Carlo method and logical algorithms based on observational and survey studies on assembly works. The created planning tool was enriched with expert knowledge that supports the planner in the initial selection of solutions. This allows to bring the computer analysis closer to the building practice. The result of the computer simulation is the assembly plan that includes time-cost characteristics [1]. One of its dilemmas of the developed computer system is the problem of crane selection in the aspect of various decision criteria (which are planner's goals). The solution to this issue is the subject matter of this paper.

The choice of a proper crane to perform assembly works in practice can be carried out in many aspects. Of course, in each case the possibilities of assembly with a given crane should be examined. This is called a technical aspect. The authors presented this issue and considered the optimization of crane location on the construction site in [2].

Tower and telescopic, stationary and mobile cranes used in construction have essentially different properties. The clue problem in assembly planning is the selection of their types (sizes). This issue has been solved by many researchers who indicated the need to aid the decision problem with computer applications.

The problems of crane selection were discussed, for example, in [3] where the fuzzy logic theory is used, in [4] where neural networks are proposed, or in [5], where genetic algorithms are suggested to support crane selection. The importance of soft factors in crane selection problem and proposal of incorporating them into solution procedure is presented in [6]. However, in [7] it is proposed to use the AHP method (Analytic Hierarchy Process) and take into account the impact of both hard and soft factors. In all the papers mentioned above, the decision problem is limited to choosing only one lifting device, which does not meet the needs of today's assembly planning, where different assembly machines are used.

In comparing different organizational solutions, the Multi-Criteria Decision Analysis (MCDA) methods are most often used. They allow for an objective comparison of many organizational [8, 9,10] or technological solutions [11, 12] as well as environmental [13]. The models and solutions presented in the literature, together with their limitations, however, are not sufficient to create advisory systems in planning assembly works in contemporary conditions.

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In order for MCDA methods to be implemented in such systems, they must have solved the problem of evaluating the criteria for assessing technical and organizational variants.

In order to solve it, the authors conducted a research among construction site managers and planners whose knowledge allowed to determine the significance of selection criteria and methods for determining preferences for cranes' selection in assembly works.

2. CRITERIA FOR CRANE SELECTION

In the proposed planning system [14], crane selection is the initial stage of assembly works planning. Its goal is to indicate the decision maker a group of potentially beneficial cranes in a given construction situation. The planner's task is to choose cranes for further analysis from the group of potentially beneficial ones according to established criteria.

The criteria for the assessment of individual decision variants vary and can be differently evaluated by the planners. In order to calculate the utility function according to MCDA methods, it is necessary to determine the significance and weight of criteria. This is neither an easy task nor unanimously solved by construction contractors. However, the decision supporting system requires establishing criteria preferences and their hierarchy.

Whenever cranes are being selected to use in a given situation, it is necessary to investigate their range of work, time and costs of preparing for work, available space at the construction site, reliability, or safety of use. Non-technological aspects may also be relevant, such as: availability of own cranes, contractor's experience in working with specific cranes, or good rental conditions, which cannot be assessed objectively. Nevertheless, these factors can be equally important for the planner, for whom the priority may be to use his own assembly machines. Therefore, the decision-making process for crane selection should be interactive and incorporate the planner, who realistically assesses the requirements of the planned construction project, the possibilities of work of individual cranes, or the availability of own equipment.

With regard to the criteria important for crane selection, Shapira and Goldenberg [6] drew attention to the importance of the so-called soft factors. Dalalah, AL-Oqla and Hayajneh [7] also dealt with such issues, taking into account the impact of both hard and soft factors in their analyses. They distinguished 5 main factors influencing the selection of a crane. These are: building construction, crane technical capabilities, labour costs, safety and construction site restrictions.

In Polish conditions, in order to determine the preferences in the selection of assembly machines for assembly, a survey was conducted among work managers and planners in enterprises dealing with

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assembly works. Therefore, a survey among 85 construction site managers and planners was conducted. In the survey, the respondents were asked to indicate the decisive criteria important when choosing a crane type and their importance on a scale of 1 to 5. A total of 14 criteria were formulated; 9 of them were technological:

1. crane's working range (K1),
2. complexity of assembly process / time to prepare for work (K2),
3. costs of preparing the crane foundation (K3),
4. possibilities and time of moving the crane (K4),
5. reliability of the crane (K5),
6. safety of crane's operation (K6),
7. assembly productivity (K7),
8. possibility of crane's remote control (K8),
9. visibility conditions for the operator (K9),

and 5 were connected with contractor's preferences, or economical factors:

10. experience in using a given type of crane (K10),
11. availability of own cranes (K11),
12. availability of cranes for rent,
13. good rental terms (the lowest unit cost of rent) (K12),
14. constant cooperation with crane supplier (who has specific types of cranes).

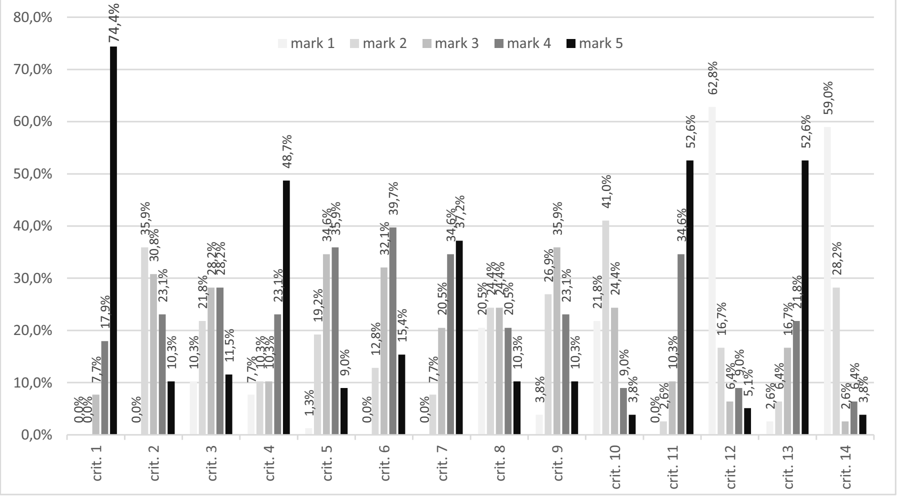

Fig. 2. Crane selection criteria and their marks - survey's results. Author's elaboration.

The goal of the survey was to identify which and how each criteria are important to contractors. The questionnaire enabled the responders (in an open question) to suggest their own criteria, important to them when choosing crane's type and to give their own remarks on the problem. A bar graph showing frequency of marks given to each criterion is presented in Fig. 2.

Criteria ordering pays a key role in the MCD analysis and was a subject matter of research carried out in [15,16,17,18]. Based on mean values of criteria (which were obtained in the survey) criteria ranks were determined. To obtain criteria weights the following criteria ordering methods were investigated:

- Rank-Order Centroid Weight Method (ROC)
- Reciprocal Ranks Method (RR),
- Rank Sum Method (RS),
- Rank Exponent Weight Method (RE).

A comparative analysis of these methods is presented in [1]. Weight determination strongly influences the final result of the decision making. It was noted that the RR method, as well as the ROC, re-evaluate the weights of the higher rank criteria. A good choice would be the RS method, for which the weight values are centred among the weights obtained with other methods. However, a constant difference between the values of weights, assuming constant differences between the rank values, determine a linear approximation, which may not reflect reliable values of the criteria weights.

For the above reasons, the RE method seems to be the most advantageous, as the exponent has a significant impact on the values of weights. The calculation formula for RE method is:

$$w_k(RE) = \frac{(n-r_k+1)^p}{\sum_{j=1}^{n}(n-r_j+1)^p}\,. \tag{2.1}$$

In the RE method, see Eq. (2.1), the variability of weights is related to criterion rank r_k and parameter p. As p increases, the dominance of low-rank criteria increases while the weight of hight-rank criteria decreases. Thus, the decision maker, by influencing in the value of the exponent, can participate in the process of determining the weight values.

The ranks given to the criteria can be in a different relationship to each other (example in Table 1). By using the RE method and computer simulations for different p values, it is possible to determine criteria weights in correlation with criteria's rating derived from the survey (Fig. 3).

The accepted ranks and rating of individual criteria are gathered in Table 1. (based on the analysis in [1], criteria crit.12 and crit.14 were considered insignificant).

Table 1. Crane selection criteria weights obtained within RE method with p=0,47. Author's elaboration.

Criterion	K1	K11	K12	K7	K4	K6	K5	K3	K9	K2	K8	K10
Crit. rating (the mean value)	4,67	4,37	4,24	4,01	3,95	3,58	3,32	3,09	3,09	3,08	2,76	2,32
Criterion's rank	1	2	3	4	5	6	7	8	8	8	10	11
w_k(RE) p=0,47 fitting accuracy 99,9%	0,109	0,104	0,100	0,095	0,092	0,084	0,078	0,072	0,072	0,072	0,065	0,057

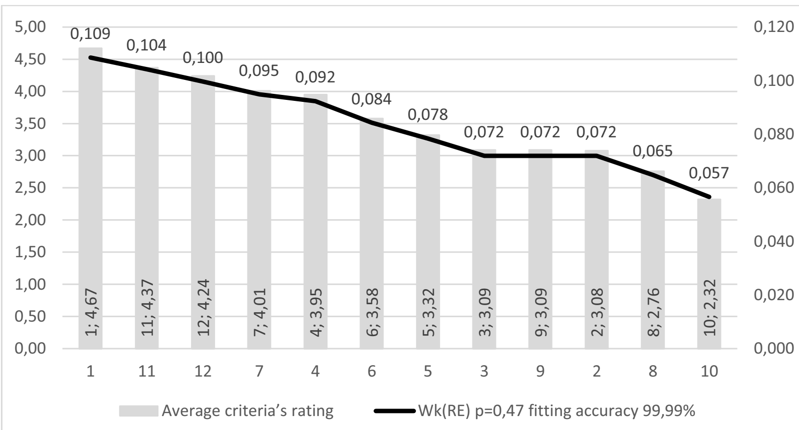

Fig. 3. Crane selection criteria's rating vs criteria weights. Author's elaboration.

Having the criteria weights established, it is possible to apply selected MCDA methods, like SAW or FSAW as below, in order to select potentially the best crane.

3. SOLUTION FOR CRANE SELECTION PROBLEM

According to [1], in the proposed planning system, the final selection of crane to perform assembly works belongs to the planner. The ranking of organizational solutions is determined based on the value of the utility function calculated for all the variants (cranes) considered.

3.1. PROBLEM SOLUTION WITH SAW METHOD

Let us assume that the crane selection takes place from n decision variants $W=\{w^1,\ldots,w^n\}$, which are assessed through the assessment criteria $K=\{k_1,\ldots,k_m\}$. Let the variants' assessments form a decision matrix **D** with d_{ij} elements, where the rows of the matrix correspond to subsequent decision criteria, while columns j – to the decision variants. The d_{ij} values specify the rating made by the planner. They should be set so that they have the character of a stimulant. Thus, the decision matrix **D** should be normalized according to the formula:

(3.1) $$r_{ij} = \frac{d_{ij}-d_{ij}^{min}}{d_{ij}^{max}-d_{ij}^{min}} \; for \; i = 1,2,\ldots,m.$$

As a result of scaling, a new **R** decision matrix is created. It contains r_{ij} elements and the total of ratings for a given variant equal to 1. In the SAW method, by multiplying the **R** matrix by the criteria weights and adding those values, the value of the decision variant's utility is obtained:

(3.2) $$p_j = \sum_{j=1}^{j=m} w_i \cdot \mathrm{r}_{i,j} \qquad \text{for} \quad j=1,2,\ldots,n.$$

Table 2. Cranes' assessment: the mean values (d_{ij}), standard deviations (σ) and normalized values (r_{ij}). Author's elaboration.

criterion no.	Fast-erecting crane			Top-slewing crane			Mobile construction crane			Mobile crane		
	d_{ij}	σ	r_{ij}	d_{ij}	σ	r_{ij}	d_{ij}	σ	r_{ij}	d_{ij}	σ	r_{ij}
K1	1,59	0,47	0,00	4,70	0,58	1,00	1,63	0,51	0,01	4,30	0,83	0,75
K2	3,82	0,77	0,74	1,55	0,82	0,00	4,51	0,78	0,96	4,62	0,72	1,00
K3	4,11	0,75	0,29	1,81	0,87	0,00	4,62	0,87	0,99	4,65	0,55	1,00
K4	2,01	0,95	0,16	1,54	0,86	0,00	3,82	0,91	0,77	4,52	0,47	1,00
K5	4,44	0,56	0,82	4,54	0,45	1,00	3,98	0,47	0,00	4,60	0,67	0,41
K6	4,26	0,68	0,75	4,58	0,65	1,00	3,28	0,56	0,00	3,52	0,78	0,18
K7	3,96	1,05	0,29	4,61	0,98	1,00	3,69	0,91	0,00	3,86	0,87	0,18
K8	4,59	0,68	0,92	1,96	0,66	0,03	4,82	0,48	1,00	1,87	0,42	0,00
K9	3,25	0,42	0,15	4,86	0,49	1,00	3,29	0,57	0,17	2,97	0,57	0,00
K10	1,83	1,02	0,10	3,28	1,52	0,54	1,51	0,86	0,00	4,81	0,87	1,00
K11	1,42	0,47	0,15	1,88	0,87	0,34	1,05	0,49	0,00	3,51	1,52	1,00
K12	4,89	0,97	1,00	4,56	1,05	0,84	3,96	1,08	0,54	2,89	0,97	0,00

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The best variant is considered to be the one that achieves the highest value of the utility function.
Let us conduct such an analysis of selection from among 4 types of cranes (indicated in surveys as the most commonly used) - according to Table 2. The assessment will be done on the basis of criteria formulated in the survey. The assessment of individual "W" decision variants through the criteria "K" is presented in Table 2 as average values obtained in surveys. The economic criteria are largely dependent on individual preferences of the planner, so in practice, instead of averaging assessments, in order to run a multi-criteria analysis for crane selection, the decision maker should adopt his assessments here individually.
Average rating for economic criteria have been adopted as examples, just to present the method without favouring selected solutions. The criteria weights were as in Table 1. The results of matrix **D** normalization are presented in Table 2, while the values of utility functions for individual variants - in Table 3.

Table 3. Values of the utility function for each crane calculated according to SAW method. Author's elaboration.

	Fast-erecting crane	**Top-slewing crane**	**Mobile construction crane**	**Mobile crane**
The value of the utility function	**0,43**	**0,58**	**0,34**	**0,60**

The best solutions in the considered decision problem are wheeled mobile cranes and stationary high-speed tower cranes. The utility functions for these cranes are similar but if we change the individually adopted economic criteria or make criteria weights fuzzy, the ranking of these variants may change too.

3.2. PROBLEM SOLUTION WITH FSAW METHOD

One of the most difficult issues of the SAW method is establishing and assigning weights to criteria and assessing the variants. To increase flexibility of the solution, fuzzy weights of criteria can be applied, like in FSAW method [19], where the weight is defined as in Eq. (3.3):

$$\tilde{w}_k = (L_k, M_k, H_k) \text{ for } k = 1, \dots, 12, \tag{3.3}$$

and the membership function is:

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POLSKA AKADEMIA NAUK

(3.4)
$$\mu_{\widetilde{w}_k}(x) = \begin{cases} \frac{x-L_k}{M_k-L_k} \text{ if } L_k \le x \le M_k \\ \frac{H_k-x}{H_k-M_k} \text{ if } M_k \le x \le H_k \\ 0 \text{ if } x \le a \vee x \ge H_k, \end{cases}$$

where:

L_k – the smallest permissible weight of the *k*-th criterion,

M_k – the most probable weight for the *k*-th criterion,

H_k – the largest permissible weight for the *k*-th criterion.

For such fuzzy weighting criteria, similarly to the SAW method, fuzzy assessments are calculated according to Eq. (3.5). These are the estimators of the utility function for the *j*-th decision variant:

(3.5)
$$p_{ij} = \sum_{i=1}^{i=12} \widetilde{w}_i \cdot \mathrm{r}_{i,j} \qquad \text{for } i=1,2,\ldots,12.$$

The defuzzification of the fuzzy value of the utility function, which is necessary to compare variants, is a process of obtaining a single number from the output of the aggregated fuzzy set. The paper proposes to use the Centre of Gravity method (COG) to obtain crisp values.
Making criteria weights fuzzy can significantly affect the assessment of decision variants, which can be seen in the case of a mobile crane and a stationary high-speed tower crane. For both of them the fuzzy utility functions are equal. Thus, under certain construction conditions, high-speed stationary tower cranes can be equally beneficial or even more advantageous than mobile ones. In practice, this may apply to medium-high and high facilities, where cranes often cover a significant part of the building (and construction site), so there is no need to remove them.

Table 4. Fuzzy criteria weights. Author's elaboration.

Criteria no.	**Fuzzy values of criteria weights $\widetilde{w}_k$**			**Criteria no.**	**Fuzzy values of criteria weights $\widetilde{w}_k$**		
	L_k	M_k	H_k		L_k	M_k	H_k
K1	0,094	0,109	0,123	K7	0,073	0,095	0,117
K2	0,049	0,072	0,095	K8	0,035	0,065	0,095
K3	0,045	0,072	0,099	K9	0,048	0,072	0,096
K4	0,062	0,092	0,123	K10	0,031	0,057	0,1
K5	0,057	0,078	0,1	K11	0,086	0,104	0,25
K6	0,063	0,084	0,106	K12	0,041	0,1	0,35

In our example, fuzzy values of decision criteria weights were adopted in accordance with Table 4. The smallest and largest permissible values of fuzzy criteria weights were assumed based on the standard deviations according to Table 2 of survey described in previous chapter.

Table 5. Fuzzy and crisp values of the utility function for different cranes. Author's elaboration.

Variant	Fast-erecting crane	Top-slewing crane	Mobile construction crane	Mobile crane
Fuzzy utility function	(0,27;0,43;0,81)	(0,41;0,58;0,97)	(0,20;0,34;0,58)	(0,44;0,60;0,92)
Defuzzificated utility function	**0,50**	**0,65**	**0,38**	**0,65**

For the standardized assessments of decision variants, given in Table 2, fuzzy values of the utility function of the criteria weights $\{L_k, M_k, H_k\}$ were calculated. These values were used to calculate the defuzzificated values of the utility function according to the COG method. The results are presented in Table 5.

4. CONCLUSIONS

The selection of the most appropriate cranes is the first step to effective assembly works planning. The results of the assessment of decision variants using MCDA methods (e.g. SAW and FSAW) should not prejudge the choice of only one type of a crane to perform assembly works. They should rank the solutions, so the decision-maker can employ different types of cranes to perform different construction works in proportion to the value of their utility functions. The final decision to choose assembly machines in work planning support systems should be left to the planner. This is especially important in case of large buildings' assembly, where it is necessary to use many assembly machines that can complement each other during assembly works.

The example calculations concerned selecting a crane from a set of four cranes available and involved expert assessments of criteria significance. The described decision analysis methodology can be easily used with other problems of machine selection or with other sets of criteria.

Observations at construction sites and analysis of results obtained using the SAW and FSAW methods lead to the convergent conclusions, which proves that the tests of criterion preferences were carried out correctly and reliably. However, one should be aware that in each particular situation the final assessment of organizational solutions may be different - depending on their individual assessments through economic criteria. It should also be noted that the values of the utility function for individual

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POLSKA AKADEMIA NAUK

types of cranes considered in the example do not differ significantly. In extreme cases, personalized values of the economic criteria, as well as fuzzy criteria weights, may result in different results than in the examples presented.

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LIST OF FIGURES AND TABLES:

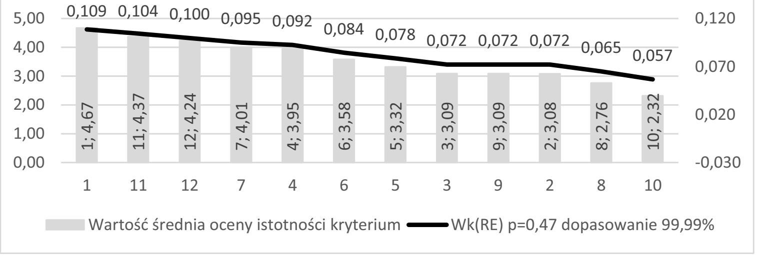
KRYTERIA I METODY WYBORU RODZAJU ŻURAWI BUDOWALNYCH W PLANOWANIU ROBÓT MONTAŻOWYCH

Słowa kluczowe: *montaż, planowanie montażu, MCDA (ang. Multi-Criteria Decision Analysis), kryteria wyboru maszyn*

STRESZCZENIE:

Przedmiotem artykułu jest problem wyboru maszyn do wykonania robót montażowych. Wybór ten realizowany jest metodami MCDA, do których stosowania wykorzystuje się oceny rozwiązań przez pryzmat istotnych kryteriów z określeniem ich wag. W pracy przedstawiono wyniki badań ankietowych i ich analizę ustalające istotność i wagi kryteriów. Przeprowadzono badania wśród kierowników robót oraz planistów w polskich przedsiębiorstwach zajmujących się prowadzeniem robót montażowych, ustalając istotność 14 kryteriów – 9 technologicznych i 5 związanych z preferencjami wykonawców lub czynnikami ekonomiczno-rynkowymi.

Celem badań ankietowych było ustalenie miar istotności kryteriów decydujących o wyborze rodzaju żurawi budowlanych, oraz ocena żurawi względem tych kryteriów. W ankiecie respondenci zostali zapytani o kryteria decydujące o wyborze rodzaju żurawia oraz o ich ważność w skali od 1 do 5. oraz o ocenę wybranych rodzajów żurawi na tle zdefiniowanych kryteriów – również w 5 stopniowej skali (od 1 do 5). Po przeprowadzeniu badań ankietowych uszeregowano kryteria z wykorzystaniem metody wykładniczej RE (ang. Rank Exponent Weigt Method). Średnie wartości oceny istotności kryterium oraz wagi kryteriów ustalone tą metodą przedstawiono na Rys. 1.



Rys. 1. Wykres porównawczy średnich ocen istotności kryterium w stosunku do dobranych wag kryteriów wyboru rodzaju żurawia. Opracowanie autorskie

Ustalone wagi kryteriów poleca się wykorzystywać do oceny wariantów organizacyjnych wykonania montażu metodami MCDA. W pracy przedstawiono też przykłady oceny wariantów organizacyjnych przy wykorzystaniu metod SAW i FSAW, analizując problem wyboru żurawia do robót montażowych spośród 4 rodzajów żurawi (żurawi samojezdnych kołowych, wieżowych stacjonarnych górnoobrotowych oraz stacjonarnych i samojezdnych szybkomontujących). Dla metody FSAW wagi kryteriów przedstawiono za pomocą tradycyjnych trójkątnych wypukłych liczb rozmytych, CFNs (ang. Convex Fuzzy Numbers). Natomiast defuzyfikację rozmytej wartości funkcji użyteczności przeprowadzono z wykorzystaniem metody środka ciężkości CoG (ang. Center of Gravity).

Przedstawione zagadnienia są głównym elementem systemu wspomagania decyzji planowania procesu montażu budynków prefabrykowanych z elementami optymalizacji rozwiązań organizacyjnych. Całościowo, metoda planowania została przedstawiona w [1,14].

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