<table>
<thead>
<tr>
<th>Publikacja / Publication</th>
<th>Comprehensive Approach to Efficient Planning of Formwork Utilization on the Construction Site, Krawczyńska-Piechna Anna</th>
</tr>
</thead>
<tbody>
<tr>
<td>DOI wersji wydawcy / Published version DOI</td>
<td><a href="http://dx.doi.org/10.1016/j.proeng.2017.03.114">http://dx.doi.org/10.1016/j.proeng.2017.03.114</a></td>
</tr>
<tr>
<td>Adres publikacji w Repozytorium URL / Publication address in Repository</td>
<td><a href="http://repo.pw.edu.pl/info/article/WUT79d23f9a234c43a8b5f3e14e6d2108c1/">http://repo.pw.edu.pl/info/article/WUT79d23f9a234c43a8b5f3e14e6d2108c1/</a></td>
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<td>Data opublikowania w Repozytorium / Deposited in Repository on</td>
<td>Jun 25, 2020</td>
</tr>
<tr>
<td>Rodzaj licencji / Type of licence</td>
<td>Attribution-NonCommercial-NoDerivs (CC BY-NC-ND)</td>
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Comprehensive Approach to Efficient Planning of Formwork Utilization on the Construction Site

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Abstract

The paper presents a consistent approach to concrete works planning, which begins with formwork selection and ends with project scheduling. To work out the problem of formwork selection, selected MCDA methods are recommended. In order to apply them, the decisive criteria were recognized with a structured survey sent to contractors. The efficiency of formwork utilization is measured with a virtual cost of formwork under utilization, so when the formwork is available on the construction site but remains unused or when it should be struck but remains unremoved from the construction. Such measure was determined, after having analysed various criteria of schedule quality and optimality assessment.

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Keywords: formwork; monolithic concrete works; interactive planning; efficiency of formwork utilization

1. Introduction

Formwork is the largest single cost component of a concrete building’s structural frame and varies averagely between 35 and 45% of a reinforced concrete structure’s unit cost [1, 2]; for civil engineering structures it can reach even 60%. Formwork items are usually rented by the contractor to perform particular concrete works. Therefore, considering their constructability and analyzing efficiency of their utilization at each stage of construction planning, in order to accelerate construction schedule or increase jobsite productivity, seems to be the smartest step to reduce lease costs and in consequence – total building works’ costs.

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This brought about the idea to establish a new, consistent method of project planning which begins with formwork selection and ends with project scheduling, where formwork availability and utilization efficiency is being analyzed at once. The key issue to resolve the decisive and planning dilemmas settled in the research [2] was to identify problems and their constraints, that stem from specifics of the cast-in-place building technology. A thorough investigation on formwork selection problem, as well as project planning and scheduling methods was carried out. Its goal was to decide, whether it would be possible to adapt existing planning techniques to work out the solution for the subject matter. The whole planning method is explained in detail in [2], while the present paper describes a synthetic approach to the subject problem.

2. What influences on formwork utilization efficiency?

It can be easily stated, that having profound knowledge on monolithic concrete works’ technology and formwork systems’ features results in choosing an appropriate system to perform concrete works. This gives rise to: reduction of labor costs, improving the quality and safety of produced concrete, achieving faster work cycles [3]. Formwork selection is, thus, the first problem, that should be considered in order to improve formwork utilization on the construction site.

However, it is not the only one. The second issue is how to schedule works and plan formwork utilization effectively and how to measure such efficiency?

Effective formwork utilization should be understood as condition wherein formwork is being used to its fullest potential. During the building performance, the efficiency of formwork utilization should be measured with a cost of formwork under-utilization, so when the formwork is available on the construction site but remains unused or when it should be struck but remains unremoved from the construction. The rightness of such measure of schedule quality and optimality assessment was proved by Kapliński [4] and was incorporated into author’s planning method in [2].

A combination of solutions to both problems introduced above should foster a growth in efficiency of formwork utilization on the construction site and enhance schedule quality. Such comprehensive approach to the described issue and consecutive steps of its solution are presented in Fig. 1 and are the subject matter of the present elaboration.

3. Formwork selection problem and its solution

3.1. Decisive criteria for the formwork selection problem

Factors that influence on formwork selection had been investigated since early 90’s until now by various researchers in Poland, i.e. by Marcinkowski and Krawczyńska [5], Biruk and Jaśkowski [6] and all over the world, i.e. by: Hanna, Willenbrock and Sanvido [7], Kamarthi et al. [8], Proverbs, Holt and Olomolaiye [9], Elbeltagi et al. [10] or Shin et al. [11] and many others. The literature on the subject matter, both foreign and national, suggests

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Fig. 1. A scheme of a comprehensive approach to formwork planning.
various decisive criteria for formwork selection, but their importance in the selection problem has not been distinctly formulated. Furthermore – it cannot be formulated without investigation on local contractors’ needs, understanding the building culture and work conditions.

To unify the solving method and having assumed that the expert knowledge can strongly influence in technological and organizational solutions in practice, the hierarchy of decisive criteria for the problem of formwork selection was established with a structured survey, described in [2, 3]. Basing on poll’s results, nine decisive criteria were formulated. They are gathered in Table 1.

Table 1. The decisive criteria for the formwork selection problem.

<table>
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<tr>
<th>Criterion no</th>
<th>Criterion description</th>
<th>Criterion type</th>
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<tbody>
<tr>
<td>1</td>
<td>Formwork system ergonomics</td>
<td>objective &amp; technological</td>
</tr>
<tr>
<td>2</td>
<td>Support from the formwork supplier</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Formwork system versatility</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Quality of concrete surface and concrete works performance</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Safety provided by formwork system components</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Durability of formwork elements</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Formwork system known to workers</td>
<td>economical &amp; organizational</td>
</tr>
<tr>
<td>8</td>
<td>Compatibility with the yet owned formwork system</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>Attractive formwork rental terms</td>
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The decisive criteria were ordered using the Rank Exponent method. The relevance of such approach is explained in [2]. The suggested weight values are collected in Table 2.

Table 2. Values of criteria weights for the formwork selection problem.

<table>
<thead>
<tr>
<th>Criterion no</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
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<tbody>
<tr>
<td></td>
<td>0.125</td>
<td>0.096</td>
<td>0.108</td>
<td>0.125</td>
<td>0.125</td>
<td>0.096</td>
<td>0.115</td>
<td>0.076</td>
<td>0.134</td>
</tr>
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3.2. Solution for formwork selection problem

The range of methods that can be applied to solve a multi-criteria selection problem is wide: from classical MCDA methods to artificial intelligence. While the AI methods predict the solution more or less accurately, which basically depends on the quality and size of training data, and are scientifically valuable, they require dedicated computer applications and might not be applied by an ordinary construction manager, who is not an expert, as they are too advanced. This is why classical MCDA methods remain valuable for the formwork selection problem. Thus, the most appropriate method should have the following advantages to make the discussed issue easy to solve [3]:

- It should not require any extra parameters such as veto or acceptance level, which might confuse the planner
- The best alternative should be determined clearly by a scalar value – not a hierarchy, where two incomparable solutions are possible to obtain
- The alternatives should be ordered within the algorithm
- The algorithm should be easy to compute.

The study [2] emerged several methods that can be easily applied to solve the problem of formwork selection. One of them is the TOPSIS algorithm, which is clear to understand and easy to compute regardless the number of solutions (alternatives) or decisive criteria. This is its main advantage over other readily used methods, like i.e. AHP, where the number of 9 criteria or alternatives to compare can be a ceiling value. The same straightforward technique of a multi-criteria decision analysis is SAW. Both of those methods have fuzzy extensions, which appears invaluable for the
planner who cannot assess alternatives precisely (FUZZY TOPSIS method) or is not sure to their weights (F – SAW method). Apart from TOPSIS and SAW, ELECTRE method was investigated in [5]. Although it has many virtues, the method has such drawback, that equivalent, pairwise incomparable solutions are possible to obtain. This can hamper decision-making process for an inexperienced planner.

The case study conducted in [2] and [3] proved how handy TOPSIS and SAW methods are. The study considered 5 most often used formwork systems and 9 decisive criteria. All the calculations were made using Excel spreadsheet, which means that the methods are available for an ordinary construction site manager. Please keep in mind, that according to the survey carried out among contractors, there are over 20 different formwork systems commonly used on Polish construction sites. This number can only grow, as formwork producers still improve their solutions and introduce new products on the market. The method to solve formwork selection problem should be then lucid and flexible, which confirms selection of the above mentioned MCDA methods.

3.3. Formwork design

Having formwork system selected, it is the right time to prepare formwork design and bill of quantities. Modern 4D or 5D applications import construction components and extract bill of quantities directly from a model created in an independent application. While BIM modeling is thought to be the best way to check constructability of the structure and automatic quantity take-off (QTO) seems to be the best way to eliminate negative aspects of the manual-based (human-based) measurement process, there are still application gaps, which may have impact on an effective project planning. It should be remembered that even if BIM system creates formwork construction for basic elements like beams or slabs, it is often incomplete – props, alignment couplers etc. may be missing. This affects the basic QTO. Moreover, where elements intersect, taken-off quantities can be overestimated, what disturbs the bill of quantities and therefore total labor and material demand.

This is why the best solution is to aid formwork design with separate software delivered by the formwork supplier (according to the selected formwork system). Precisely done design will authenticate QTO and simplify structure modeling, which is a part of the interactive planning method.

4. The problem of effective utilization of formwork on the construction site and its solution

4.1. The idea of a planning method that allows for formwork utilization efficiency control

Nowadays, advanced and scientifically developed methods are being applied willingly to solve organizational problems on the construction site and plan building works effectively and reliably. Although available are numerous ERP and planning applications, i.e. incorporating LBS technique, network scheduling, 5D planning or BIM models, none of them supports the planner in analyzing efficiency of utilization of falsework. Thus, a simple interactive simulator was developed in [2]. The algorithm bases on an interaction between the planner and computer simulator.

The application informs about formwork utilization efficiency and generates queries to the decision-maker, who is able then to accept or withdraw his decision, if the efficiency is unsatisfactory. The efficiency of formwork utilization is measured with a cost of formwork under-utilization, as it was introduced in chapter 2.
4.2. Model of works and labor estimation

The model of concrete works in the proposed method is defined by a multi-layered network. The first layer refers to separate construction elements \( e_i \) (i.e. slabs, beams, walls, etc.), in which bill of quantities and information on labor and material demand are encoded. For each construction element 4 different technological operations are thought to be performed. These are: initial works, which cover reinforcement preparation, reinforcement placement and formwork setting, concrete casting, partial formwork striking (removal of formwork elements such as working platforms, slab panels etc.) and complete formwork striking (removal of wall panels, props, girders, etc.). Between the operations finish-start relations are defined, see Fig. 2. They include appropriate technological delays that result from a type of formwork used to complete the structure element and a type of the element itself.

![Fig. 2. A sequence of operations for each construction element.](image)

The second layer that is defined by the planner on the beginning of the simulation describes a required technological order between singular elements of the concrete structure.

The third layer is a dynamic network of relations between locations. Locations are created by the planner during the simulation and consist of selected \( e_i \) elements that can be performed together. Locations may differ in each simulation, as only two constraints are put upon the simulation: a proper technological order defined in the second layer and labor and formwork availability.

![Fig. 3. Application window view – an excerpt.](image)
Resources availability is defined on the beginning of the simulation. It can be modified in the middle of it and can be previewed in an application window (see Fig. 3 on the right). This allows for rational management of resources (formwork in particular) during the simulation.

For each construction element, to perform technological operations required are: the minimum crew and particular formwork items. Their amounts arise from formwork design and are assigned to each element. The labor demand is calculated separately for each construction element and each operation basing on unit labor demands.

When location is being created from particular construction elements, labor and formwork demands add up. This allows determining the duration of each of 4 technological operations performed within the location. The duration of technological operation results from labor allocation, which is done individually by the planner, every time the decision on staring this operation is made.

4.3. Decision making and solution assessment

The simulation algorithm generates decision-making situations; see Fig. 3 (the left side of the application window). The user of the application is being asked, if he or she wants to:

- Create a new location and assign particular construction elements to the location
- Begin concrete casting in location (or locations) indicated by the simulator
- Remove formwork (partially or completely) in locations indicated by the simulator
- Modify the number of resources available – rent new or return yet rented formwork.

Decisions made by the planner affect construction costs, formwork utilization efficiency and finally – the schedule quality. This is why they should be rationally made and evaluated using an appropriate measure.

As every formwork item generates rental costs, the best way to assess how efficiently the rented items are being utilized, is to determine a cost of formwork under-utilization. Such cost is virtual – it is generated when formwork is available on the construction site but remains unused or when it should be removed but remains unstruck from the construction. The decision-maker is being informed about this cost during the whole simulation. The accumulated and daily cost of under-utilization is displayed in the application window, see Fig. 3. If it is too high, the decision can be withdrawn.

Obviously the under-utilization cost grows in time, same as total construction cost, but the lower it is compared to the total cost, the better the solution is. Figure 4 presents an excerpt of an application window with two different results of simulations run for the same concrete structure.

![Fig. 4. Comparison of two different simulation’s results – under-utilization and total rental cost growth in time – an excerpt of an application window view.](image)

For both simulations, the ratio of loss cost to total cost remains at the same level (c.a. 52%), however the values of
both costs are lower in the second simulation. Moreover, works are completed earlier (within 177 days). Therefore, this solution should be considered as a better one, where formwork is being utilized more rationally.

5. Conclusion

Nowadays, not only the knowledge about singular building processes but also scientifically developed methods are being applied in order to solve organizational decision-making problems and plan building works effectively and reliably. This in particular refers to monolithic construction works, where rented formwork items are used, as they make a significant cost component of the overall cost of construction works.

The problem of formwork utilization efficiency should be then considered comprehensively – from formwork selection and design to concrete works planning and schedule's quality assessment. In the proposed approach straightforward methods (i.e. Topsis or SAW) are recommended, as they are accessible for site managers and planners without scientific experience. In turn, a developed interactive planning simulator is suggested to be applied to schedule concrete works, as it enables the planner to analyze formwork efficiency. The presented simulation algorithm does not provide the planner with an optimal solution, as the idea of interactive planning does not allow for it. However, the simulator itself, as there is no such tool available on the market, is hoped to be useful in aiding construction site engineers in efficient planning and formwork utilization analysis.

The developed method and proposed wide-ranging approach should help the planner to manage resources rationally in order to reduce total construction costs.

Acknowledgements

7th International Conference on Engineering, Project, and Production Management (EPPM2016) was financed in the framework of the contract no. 712/P-DUN/2016 by the Ministry of Science and Higher Education from the funds earmarked for the public understanding of science initiatives.

7th International Conference on Engineering, Project, and Production Management (EPPM2016) finansowana w ramach umowy 712/P-DUN/2016 ze środków Ministra Nauki i Szkolnictwa Wyższego przeznaczonych na działalność upowszechniającą naukę.

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