Selection of Lifting Mechanism for Small-Scale Construction Project: A Comparative Method Based on Building Volume and an Automated Schedule

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Abstract. The selection of construction machinery for a project is a very important part of the construction process. Rigorous preparation for construction is very often neglected in practice even though three fifths of the construction companies in the Czech Republic operate at prices that lie below the safe pricing threshold. For small-scale buildings this ratio is even more pronounced. This fact can be understood as meaning that the price of construction is undervalued in such a way that it also has a negative impact on construction safety. On the other hand, the selection of a lifting mechanism usually relies on the individual decision-making capabilities of the construction manager, and the decision is mostly based on the options that are locally available. In such cases, the result is often that the total cost is disproportionately high and/or the lifting mechanism is oversized. The proper selection of the main lifting mechanism for a project depends on many factors and criteria, such as crane position, load characteristics, economic criteria and the flexibility of the schedule. Effective lifting mechanism selection fundamentally depends on the definition of the economic and technological criteria for each individual structure at the beginning of the project. This paper presents an approach developed by the authors to assess the suitability of a lifting mechanism for small-scale construction work based on an automated schedule in combination with the volume of the structure. A case study comparing two types of small self-erecting crane and a mobile crane is presented in order to prove the usefulness of this method. The results include a graph from which the suitability or unsuitability of each individual mechanism can be found. A cost curve with a transition point depicted for a range of six small-scale structures with different building volumes is shown for each mechanism. A clear transition point was found at a building volume of 6030 m³.

1. Introduction

The issue of lifting mechanism selection is one of the crucial parts of the construction management section of the technical preparation phase of a construction project, and it should be dealt with before construction begins. The selection of a suitable mechanism depends on many criteria, and on a wide range of boundary conditions. At present, the design and assessment of a small lifting mechanism is usually carried out by the supplier himself, or by the construction manager. The time available to both of these parties to make this assessment is already limited, and therefore the boundary conditions are only taken into account to a limited extent. The supplier’s aim is to sell/rent their products, so they may have reason to deliberately ignore the economic criterion. In practice, the most commonly used method for selecting a lifting mechanism is based on an assessment of the weight of loads, and the
distance they need to reach. The necessary boundary conditions in this method are the geotechnical conditions of the subsoil and the potential of collision with surrounding objects, the plan for transportation and logistics and the options for the erection of the mechanism. When selecting a mechanism for a specific structure, a variety of possibilities can arise when there are several types of lifting mechanism and identical criteria. In these cases, it is advisable to select from options based on multi-criteria methods when evaluating this decision-making problem.

Methods for designing lifting mechanisms can be divided into two groups, namely methods of determining the most suitable position for a crane on a construction site, and methods for the optimal selection of a particular type of lifting mechanism. The authors published paper [1] in which they developed a new algorithm for the selection of a crane position on a construction site. The algorithm took into account the geometric characteristics of the crane, the maximum hook height, technical sheets and other characteristics. The output was a graphically presented model with a mathematical record of the individual steps of the algorithm. Two scenarios were analyzed using an algorithm within software developed by the authors. In the paper [2], the authors presented a methodology for crane placement on a construction site. The methodology was verified via a study where a very heavy weighted crane with 102 tons bearing capacity was assessed. The result was the selection of two necessary lifting mechanisms. Other authors presented the article [3], where they combined an algorithm for selecting the optimal location for a lifting mechanism, as well as selecting a suitable type. A 3D model was created with zones that define the placement of loads and the alternative locations of lifting mechanisms. The loads in the case study weighed between 1.1 and 5.4 tons. The output was demonstrated in a 3D crane selection layout expressing the optimal position and a visualization of time on the vertical axis (2D + time). The second category of methods can include a paper presented by the authors [4], in which data obtained from building managers from seven construction projects were used to identify the factors influencing lifting mechanism deployment times. The authors then utilized two methods, one based on neural networks and the other on genetic algorithms, to model the necessary time. The result was a proven model that showed better results using the genetic algorithm. In the paper [5], the authors presented a predictive model based on nonlinear neural networks and a linear regression model, where they evaluated 15 variables in order to predict the optimal result for crane deployment time. As a result of the method comparison, the neural network method was confirmed to be more accurate (accuracy ± 2%) than the regression model (± 2%; -8%). In the article [6], the authors presented an optimization model which was divided into the categories of the foundation, design and protection against wind effects of the crane, and its cost. The criterion was the minimum total cost. However, this model does not work with specific load weights.

Various lifting mechanism design methods and procedures have been developed in the past for logistics purposes within the Czech Republic. Paper [7] presented a method using the indicator of the volume of the realized structure per unit of time. In another article, the authors [8] presented a review of the methods used in the design of the lifting mechanism. The number of cranes needed can be determined by a method using the number of workers whose task requires servicing by a crane. However, the authors did not deal with the type of crane. The method using the indicator of building volume per unit of time considers how many m³ of building volume can be built when one crane per time unit is used to supply the construction process. However, this method does not consider the type of crane. Another method, which uses the weight of the transferred material per unit of time, indicates how many kN of material can be transported by one crane per unit of time. This method also does not deal with crane type. The method using the volume indicator, or the weight of crucial materials per unit of time, is based on the volume or weight of the critical transport materials to be transported in a given period of time. Another method of crane design based on the standard duration of crane-serviced processes deals with the determination of standard times for crane-serviced activities, from which the duration of these activities can then be determined. It is a method of determining the number of
mechanisms. The method of estimating the required crane deployment time assumes that 80% of the material on the construction site will be transported by the crane: this method works via the determination of the density of the structure. The method, which utilizes the theory of mass control, is based on the precise modelling of the movements of individual lifting mechanisms in three basic groups. The first group considers activities requiring full crane time capacity, the second contains activities requiring partial crane capacity and the third only has activities with unusual lifting mechanism requirements. The next article [9] took the size of the construction project into account using predefined schedules. The method deals mainly with related processes and the associated duration and technological continuity of subsidiary construction processes. This methodology has not been verified via any case study yet.

2. Methods
From the above-mentioned references it can generally be inferred that the authors focused mainly on relatively large structures. The algorithms are based primarily on neural networks and genetic algorithms, where the large combination of possible solutions plays a key role in the decision problem. Or, on the other hand, they are based on mass and volume characteristics and do not consider a choice of several mechanisms, instead focusing on the assessment of a mechanism that has already been selected. Small buildings are neglected in the context of lifting mechanism deployment, and there is also a gap in the literature.

2.1. A comparative method based on building volume and an automated schedule
The comparative method is already used in practice. This is the most commonly used method on site, and its use is based on the experience of the given manager that’s in charge. The principle of the method is to compare mechanisms in terms of total costs, which depend on the time utilization of the mechanism in relation to the tasks on the schedule. The comparative method becomes problematic if the comparison is limited due to their only being a small range of alternatives. This occurs due to a lack of time required for the calculation or the limited ability of the construction manager to work with analytical data and algorithms. This was the reason for the creation of a range of models for small construction sites featuring structures with different volumes. The prerequisite for using the presented method is its use in small-scale structures under the particular boundary conditions set out below. An important fact is that the presented method does not consider the selection of the optimal location of the lifting mechanism on the construction site. The optimal location should be resolved by another method in the previous step via a suitable engineering design or estimation. The purpose of the method is to determine a reference construction which can be used in combination with volume characteristics to further define a range of other structures of different sizes. These can subsequently be used on an analogous basis for the evaluation of other similar structures.

2.2. Determination of general conditions
General conditions were set for the proposed method. These conditions must be assessed and taken into account before applying the method or, where appropriate, the reasons for not taking the conditions into account should be described. The conditions are:

- time conditions
- the economic criterion
- the maximum possible load capacity of the considered mechanism
- the maximum possible range of the considered mechanism
- the suitable vertical handling space
- the site plan (horizontal) handling space available for the mechanism

2.3. Determination of the boundary conditions for a particular structure (e.g. an apartment building) and the assessed lifting mechanism
The hydraulic arm of the mobile crane being considered serves only as a lifting mechanism. When using a hydraulic arm mounted on a truck, the machine is not used for off-road transportation.

The small self-erecting crane will be deployed on the construction site for the entire construction period, while the hydraulic mobile crane will only be at the site for certain important operations requiring items to be moved using machinery.

The comparison of the reference structure and derived structures is performed via percentages. This means that the reference structure corresponds to a building volume of 100%. The derived structures are divided in steps of either 25% or 50% (e.g., 50%, 75%, 125%, 150%, 200% of the building volume), which also corresponds to the number of apartments in the building.

All of the tested buildings have the same construction system, and are built from the same materials and using the same construction technique.

Only carcass structure tasks on the reference and derived structures are compared with each other.

The selected number of flats from \( x_1 \) to \( x_n \) linearly corresponds to the volume of the structure \( V_1 \) to \( V_n \) [m\(^3\)].

The assumption of the cost of renting, transporting and installing the selected lifting mechanisms depends on the location of the construction site and the relevant prices of the nearest possible supplier.

The total cost does not include the costs of materials and their transportation to the site.

The material is ready to be moved on-site by both of the compared mechanisms. The delivery time of the material to the construction site is neglected because the delivery time of the material for the considered mechanisms is identical.

The compared mechanism deployments are only considered for the purpose of transporting materials on-site from the place of deposit to their final position within the structure.

The maximum weight of one load is 1300 kg.

In the schedules for the deployment of the mechanisms, the minimum unit of time is 1 hour, and the work shift is 8 hours.

3. Results and discussions

To verify the suitability of a new comparative method based on structure volume and an automated schedule, data from the construction of a poly functional building in the town of Otrokovice in the Czech Republic was used. This building will serve as a reference structure for the purpose of the following calculations - i.e., its volume of 5200 \( m^3 \) will be considered to be “100%”. The other assessed objects with different volumes are derived and serve only as models for the comparison of the two types of mechanism in order to choose the most suitable variant. There is a general assumption that there is a difference in use between the two compared mechanisms. The self-erecting crane will remain on the construction site throughout the construction phase of the selected stage, while the hydraulic mobile crane (or a small mobile crane) will only be present on site during the execution of key critical processes, such as those related to masonry or formwork, the preparation of reinforcement, etc. In order to calculate the economic advantage of each mechanism for structures with different volumes, it was necessary to first select the mechanisms and determine their costs, which can be seen from Table 1. The cost of electricity was calculated on the basis of the Czech energy supplier’s price list at 0.15EUR per kWh: the self-erecting crane consumes 160 kWh per day of electricity. All amounts are converted from CZK currency to EUR at the exchange rate 1EUR = 26CZK. A Liebherr 35K self-erecting tower crane was selected for the research, along with a TerexDemagAC 25 City hydraulic mobile crane. The specific types of mechanisms can be changed as needed based on local availability.
Table 1. Costs for individual types of mechanisms

| Costs of a self-erecting crane | Rent [EUR / day] | Price of installation [EUR / day] | Cost of operating the machine [EUR / day] | Cost of el. energy [EUR / day] |
|-------------------------------|------------------|-----------------------------------|-------------------------------------------|-----------------------------|
| Costs of a mobile crane       | 42.308           | 769.231                           | 75.385                                    | 24.000                      |
|                               | 215.385          | part of the rental price           | 70.769                                    | part of the rental price    |

Subsequently, after calculating the costs, it is necessary to determine the number of days when the self-erecting crane will be used and when the mobile crane will be present on the construction site. This must be done by a competent engineer or construction manager with experience in organizing such a construction project. The number of working days can be determined from schedules generated from scheduling software. First, a schedule for the reference structure can be created according to the rules for scheduling. To determine the duration of work on the derived structures, multiply the reference duration of the activities by the factor of the building volume. For instance, a structure with a volume of 150% of the original volume would be multiplied by 1.5. All of the derived structures were calculated in this manner. Pauses in construction for technical reasons are the same for all structures. In general, it can be determined that the construction time does not grow linearly with the building volume. The nonlinearity of the relationship between structure volume and the duration of construction is shown in Figure 1, from which the total construction time for each derived construction is visible.

Figure 1. Non-linearity of the relationship between building volume and construction time

The number of working days was determined for the self-erected crane for each structure. The number of working days was determined for the hydraulic mobile crane by selecting the specific tasks in the construction schedule in which the mobile crane participates. These include masonry processes, lintel assembly, formwork processes, reinforcement preparation, etc. Regarding the use of a crane, it is considered that operating and energy costs will only be incurred on working days. The costs for each structure are summarized in the comparative Figure 2 and Table 2. The number of the reference structure is marked with a circle in the bar chart in Figure 2. Table 2 shows the difference in costs between the crane and the mobile crane: from 50% to 100% of the reference volume it is economically more advantageous to use the mobile crane, while the opposite is true for a volume that is 125% to
200% of the reference volume – in this case the economic advantage of the self-erected crane is shown. For a better understanding of the calculations and results, another type of chart was chosen, from which it is possible to read the volume at which one may theoretically consider the two types of mechanism to have the same cost. From Figure 3 the differences between the two mechanisms can be derived from the course of their cost curves.

**Figure 2.** Cost comparison of lifting mechanisms for different structures

**Figure 3.** Cost curves for lifting mechanisms for each structure, with the transition point marked in red
Table 2. Working days and costs of the compared mechanisms for different structures

| Building volume | No. of total working days according to automated schedule | Self-erected crane No. of working days | Self-erected crane Costs [EUR] | Self-erected crane el. energy consumption [kWh] | Hydraulic mobile crane No. of working days | Hydraulic mobile crane Costs [EUR] | Cost Difference [crane Minus mobile crane] |
|-----------------|----------------------------------------------------------|----------------------------------------|--------------------------------|-----------------------------------------------|------------------------------------------|-------------------------------------|---------------------------------------------|
| 50%             | 64                                                       | 45                                     | 7949.231                      | 7200                                          | 22                                       | 6295.385                            | 1653.846                                    |
| 75%             | 76                                                       | 54                                     | 9351.385                      | 8640                                          | 28                                       | 8012.308                            | 1339.077                                    |
| 100%            | 87                                                       | 61                                     | 10512.462                     | 9760                                          | 32                                       | 9156.923                            | 1355.538                                    |
| 125%            | 101                                                      | 71                                     | 12098.615                     | 11360                                         | 44                                       | 12590.769                           | -492.154                                    |
| 150%            | 116                                                      | 82                                     | 13826.462                     | 13120                                         | 52                                       | 14880.000                           | -1053.538                                   |
| 200%            | 149                                                      | 105                                    | 17508.462                     | 16800                                         | 79                                       | 22606.154                           | -5097.692                                   |

4. Conclusions
A new comparative method for crane type selection based on structure volume and an automated schedule was presented in this paper. The presented study has shown that in this particular case, a hydraulic mobile crane, which will only be present on the construction site on some days, is the optimal choice for the reference construction. For an object that is twice as large as the volume of the reference construction it is advantageous to use a self-erecting crane, which will be present on the construction site throughout the construction phase. The calculation serves as a calculation model of this method that can be applied to different types of structures under identical or other boundary conditions. By selecting other boundary conditions (cost of mechanisms, construction technique, etc.) a different mechanism can be selected. In practice, this calculation model can be used by the contractor to decide which type of mechanism will be economically beneficial for him. The contractor simply enters his own input data into the calculation. Future research options include the algorithm for selecting the optimum position of the lifting device within the construction site, for instance through methods such as neural networks or genetic algorithms. This would be combined with a digital 3D model of the building and construction site using Building Information Modelling (BIM) and with the aid of what are termed "Active BIM" systems [10] where, using the 3D model and the information contained therein, an "active" computational algorithm can be added, based on either mathematical or heuristic optimization methods.

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