Optimal organization of lifting operations at the construction site

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Abstract. The study is dedicated to identifying the influence of the tower crane location and its technical characteristics in panel housing construction for the duration of lifting operations. The organization of the construction site is represented by a triangle, at the tops of which a tower crane, a warehouse of panels and a place of installation are located. It is assumed that the delivery of goods is carried out separately by turning the crane and then moving the crane truck in the right direction. The computer model is described by a nonlinear trigonometric equation, the roots of which were found by the Newton method. As a result of a model study, it was found that to accelerate lifting operations, it is necessary to select a crane with a large boom reach and move it further away from the direct connecting warehouse to the installation site, achieving the isosceles of the triangle formed by the crane, warehouse and installation site, and also the minimum lifting time operation increases with decreasing angular velocity of the tower crane.

Introduction
In the construction industry, in the conditions of the prevailing market economy, the technologies used and the organization of construction must solve the tasks set by the investor. Current trends are aimed at improving the quality and level of security [1]. Which, in turn, including the implementation of complex space-planning decisions, due to the need to use effective building materials, the introduction of safe construction technologies, the use of high-performance machines and mechanisms. This should provide mechanical, fire, environmental safety, safety of use and stay in the building of all groups of the population, as well as the main function of buildings or structures to persevere the impact of the environment [2]. In addition to the need to comply with the requirements of regulatory documents and provide a comfortable, safe and functional conditions for the construction and operation of buildings and structures is the requirement to reduce the construction time. As a result, the economic efficiency of construction depends on the construction technologies adopted in the project and the organization of construction work by the general contractor. An important factor affecting economic efficiency is the reduction of construction time, which in turn reduces the costs and payback period. Reduction of construction time can be achieved in various ways: by increasing the number of working units [3], ensuring multithreading of construction, automating construction processes, using efficient machines and mechanisms. However, without an efficient construction organization, it is impossible to achieve high levels of economic efficiency. Under the effective organization understand the maximization of results at minimum cost [4].
Theory
The most effective technology in construction is the technology of large-sized precast concrete elements. The mass segment of construction is the technology of panel housing. The “leading” machine in such technologies is certainly a tower crane that performs almost all lifting operations. Especially its role in high-rise construction increases [5,6]. Therefore, to increase the efficiency of construction, first of all, it is necessary to optimize its operation. In this case, the question of the choice of criteria is important.

The study of the efficiency of the movement of cargo in the configuration space of the mechanical subsystem of a jib crane has already been carried out [7-9]. At the same time, many criteria were chosen to solve the optimization problem, for example, the cost of 1 ton of lifted load. Of course, financial assessments are the most effective, but it should not be forgotten about the time of operations. It may happen that the entire financial benefit will be lost due to the failure of the construction deadlines.

In other works, the efficiency of the crane work is determined by the amount of cargo (building materials, parts and structures), which it can lift for installation work per unit of time, as well as the degree of its capacity use. This criterion is better than the previous one by taking into account time. But the mode of use of the crane in power, as well as the completeness of the use of other design values - load capacity, speeds provided by the drives, the combination of movements depends largely on the organization of the human factor, which is quite difficult to control. The operation mode of the crane in time to shift depends on the time of useful work and interruptions in work, the shortest ways to move goods, compliance with safety regulations. For example, an excessive lifting of the load over the structures and workers makes the hook path much longer, but increases the safety of carrying out lifting operations. Depending on the specific working conditions and speeds of individual movements of the crane, the driver must choose the most rational schemes for the supply of goods by the crane, ensuring the shortest machine cycle time, reducing it by the greatest possible combination of movements and minimizing idle, shunting movements of the crane to improve its use by capacity. This is achieved by the fullest loading of the boom on a given reach when lifting wall materials, packaging partition walls and window blocks, enlarging architectural details and containerizing small elements and other organizational and technical measures that affect the process predominantly indirectly.

Good enough is the criterion of minimum energy consumption [10]. It reflects an attempt to measure efficiency not in finance, but in energy costs. However, the time estimate is again lost. On the other hand, if we evaluate the effectiveness of the organization through the time of the operations, then such an assessment is easy to translate into almost any other. Based on these considerations, the research in this paper is based on an estimate of time.

Model and method
The first obvious consideration, which can be used to save time, is that the shortest trajectory of cargo delivery in panel housing lies in a vertical plane passing through the warehouse and place of installation. However, in order to ensure the position of the trajectory of the cargo movement in this plane, a crane-robot is necessary with the combination of several strictly time-coordinated movements, and therefore with computer-controlled drives.

Another limitation adopted in normal construction practice is to ensure safe work practices, including limiting the simultaneous performance of crane operations [11] (turning with lifting cargo, moving crane truck with lifting cargo, and finally turning with simultaneous lifting cargo). From this it follows that it is possible to divide the movements and, bringing the vertical ascent into the independently carried out, optimize the trajectory only in the horizontal plane. Since simultaneous movements are not considered here, we take a scheme of two movements: rotation of the boom and final lifting of the load using the movement of the crane truck. We further investigate the following layout of the construction site and the location of the crane on it, shown in Figure 1.
Point A here reflects the position of the warehouse of panels, point B - the place of installation, finally at point C - the tower crane is located, respectively, the AC - the departure of its boom. In this notation, we can formulate the following minimized criterion

\[ t = \min_\alpha \left\{ \varphi + \frac{|BC - AC|}{V} \right\} \]  

(1)

\[ \text{Figure 1. Scheme of the layout of the construction site and the location of the crane} \]

Here \( \omega \) - the angular speed of rotation of the crane, \( V \) - the speed of movement of the crane truck

The first term in the formula (1) reflects the time of boom rotation, the second - the time of movement of the trolley. Moreover, in the latter case, the direction of movement of the trolley is not important, therefore the absolute value of the distance traveled by the trolley is taken in the numerator of the second term.

Applying the sine theorem can be written

\[ \frac{AB}{\sin \varphi} = \frac{\sqrt{AC^2 + AB^2 - 2AC \cdot AB \cos \alpha}}{\sin \alpha} \]  

(2)

From here you can express the angle \( \varphi \). Substituting then the resulting expression in (1) we have

\[ t = \frac{\arcsin \frac{AB \sin \alpha}{\omega}}{\frac{\sqrt{AC^2 + AB^2 - 2AC \cdot AB \cos \alpha}}{\sin \alpha} + \frac{\sqrt{AC^2 + AB^2 - 2AC \cdot AB \cos \alpha - AC}}{V}} \]  

(3)

To achieve the minimum time value, it is necessary to differentiate this expression according to \( \alpha \) [9,10], and equating the resulting expression to zero, we obtain the equation for \( \alpha \)

\[ V(AB \cos \alpha (AC^2 + AB^2 - 2AC \cdot AB \cos \alpha) - AB^2AC \sin^2 \alpha + \omega(AC^2 + AB^2 - 2AC \cdot AB \cos \alpha - AB^2 \sin^2 \alpha)AC \cdot AB \sin \alpha = 0 \]  

(4)

Model and method

As follows from the theory, the resulting equation (4) is nonlinear and trigonometric. To solve it for different values of the input parameters, a computer program has been developed that uses the Newton method to find the roots.

The data used for the numerical calculation are summarized in table 1.

| Table 1. Data for calculations |
|-------------------------------|
| Parameter | V | \( \omega \) | AB | AC |
| Dimension | [m/s] | [rad/sec] | [m] | [M] |
The program allows you to build a graph of the minimum movement time of the load on the distance between the warehouse and the installation site for different values of the distance between the crane and the warehouse (∆C) in the same group of experiments and a different ratio between the angular speed of the crane and the linear movement of the crane truck (V/ω) in another group of experiments. For the study, the program organized cycles in increments of 3 meters in the first group of experiments. In the second case, the step is carried out while simultaneously reducing the angular velocity from an initial value of 0.063 rad/sec with a step of 0.005 rad/sec and an increase in the linear velocity from an initial value of 0.1 m/sec with a step of 0.05 m/sec. Changes occur before the linear velocity reaches 0.5 m/s.

### Results and discussion

Figure 2 shows the dependence of the minimum time of movement of cargo on the distance between the warehouse and the installation site. In general, there is a proportional increase in time when moving away from the warehouse. There is a distinct minimum in the middle of the graph (∆C = 17 m). It is due to the fact that the cargo is delivered only by turning the boom (the ABC triangle is isosceles), and there is no movement of the trolley. It follows from the figure that the shortest cargo delivery time is observed at zero distance between the warehouse and the installation site, which was intuitively clear right away. It is not by chance that modern technologies try to place a crane inside a building, and a warehouse as close as possible to its outer wall. But next to the wall, the warehouse can not be arranged because of the need to implement travel on the perimeter of the building.

![Figure 2](image2.png)

**Figure 2.** Dependence of the minimum time on the distance between the warehouse and the installation site

Figure 3 shows the step-by-step dependencies of the minimum delivery time of a cargo on the distance between the warehouse and the place of installation. The results show that as the distance between the crane and the warehouse (∆C) increases, the graphs shift to the right, but it should be noted that the minimum of time due to the lack of movement of the crane’s truck is present on all graphs. In practice, this means that in order to accelerate the lifting operations, it is necessary to choose a crane with a large boom reach and move it further away from the segment AB, achieving the isosceles of the ABC triangle. But it should not be forgotten about the more inertia of the crane with a large boom reach and, accordingly, it leads to high energy costs, as well as restrictions on the size of the construction site.

Figure 4 shows the step-by-step dependencies of the minimum delivery time of a cargo on the distance between the warehouse and the place of installation. The results show that with an increase in this ratio (a decrease in the angular velocity of rotation of the crane and an increase in the linear velocity of the crane truck).

| Fixed value | 0.42 | 0.063 | 20 | 15 |
|-------------|------|-------|----|----|
| Change range | 0.1-0.5 | 0.1-0.087 | 1.5-0 | 10-30 |
velocity of the crane truck) the minimum time increases, reflecting the greater influence of the angular velocity of rotation. It should be noted that at least this time becomes less pronounced due to an increase in the linear speed of the crane truck.

Figure 3. Stepwise dependencies of the minimum time on the distance between the warehouse and the installation site

Figure 4. Step-by-step dependencies of the minimum time on the ratio between the speed of rotation of the crane and the speed of movement of the crane truck.

Summary

Thus, the optimal organization of lifting operations at the construction site leads in the first place to the minimization of the execution time of technological operations, which allows to increase the efficiency of construction work. The study found that to accelerate lifting operations, it is necessary to choose a crane with a large boom reach and move it further away from the line connecting warehouse with the installation site, ensuring that the triangle formed by the crane, warehouse and installation site is equal, and that the minimum lifting time increases with decreasing angular velocity of rotation of the tower crane.

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