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BIM-BASED PROTOTYPE OF A MATHEMATICAL MODEL OF CONSTRUCTION PLANNING

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Abstract. This article tackles the problem of rational and effective planning of the entire construction site, including the planning of mechanisms, equipment, warehouse space, temporary buildings, temporary engineering networks, etc. The authors propose the principles of creating a mathematical model to calculate the needs of construction objects, using the photogrammetry model. The problems raised can be solved with the use of BIM in the preparation for construction planning stage. The prototype mathematical model presented in this article addresses these issues: identify current situation, using photogrammetry model, define optimal number and location of construction site objects, avoid conflicts between cranes, detect possible hoisting problem, avoid overload of cranes, and of course construction site planning. Therefore, it becomes possible to perform a multicriteria decision-making analysis. Extensive analysis in the pre-construction stage is often abandoned due to the lack of data on the current situation, difficult calculations of the need for mechanisms, equipment and simply due to the lack of time to analyze all possible rational solutions. The data received from the created mathematical prototype could also be used in further construction stages for planning human and material resources, the project schedule and cost estimate.

Keywords: BIM, photogrammetry, construction equipment selection, building information modelling, construction site planning.

Introduction

The incomplete analysis of the existing situation and the omission of important obstacles that appear in the construction stage are fundamental problems in construction. The investor needs to realize how construction will proceed and what impact neighbouring plots will have. It is important to show the expected risk associated with one construction technology or another. In the design stage, one should have complete information about the limitations of civil engineering that can affect the implementation of the designed solutions. The contractor who plans to carry out the construction work should have the most information about the existing situation and the construction technology. With well-planned work technology, one can create a reliable work schedule, make a reasonable cost estimate, and complete construction work on time. Also, by using BIM technology in the early stages, we are talking about BLCM (building life cycle management). The life cycle begins with material production, which includes the extraction of raw materials from the earth, transportation to manufacturing sites, the manufacture of intermediate finished materials, the fabrication, packaging and distribution of building products. Therefore, even at an early stage of construction planning, it is necessary to think about the general BLCM, when selecting appropriate materials for construction preparation, implementation of construction technology, etc. Scientific articles also contain methods that will propose a method for estimating the cost of the construction fields using the case-based argumentation method (Leśniak & Zima, 2018). The initial elements of the work include the consideration of environmental factors such as the impact of buildings on the environment and the materials used, and the effects of the installation on the environment affect. From the point of view of its impact on the environment, the type of materials used can be decisive in determining the cost determined during the construction life cycle. The lowest cost of building con-

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struction ensures appropriate quality and environmental sustainability.

In modern building construction, mechanical processes that require various types of specialized mechanical equipment for their implementation are widely used (Sacks et al., 2018; Ilce & Ozkaya, 2018). Usually, construction site planning begins from the analysis of the current situation. The current situation not only provides information about the possibilities and area of the plot, but also determines the limitations. The limitations have a great influence on the further development of the project. After determining the current condition and limitations of the future construction site, it is important to plan the areas of the construction site that will be used during construction. For this purpose, it is necessary to analyze the need for mechanisms and storage areas from the beginning. If there is a need and knowing the location of the mechanisms, it is possible to identify unsafe zones, storage areas and driveways, areas for locating the mechanisms, as well as the servicing transport, the assembly and working zones and the workshops. Although much attention is paid to the basic mechanisms of the construction process, it is very important to predict where it will be installed in an early-stage temporary buildings, equipment, workers, temporary electric power, and other resources used at each stage of construction work. Automated construction site planning is carried out as follows: the 'prohibited' zones (i.e., the location of the new construction and existing buildings and structures, storehouses, industrial buildings, and permanent communication lines) are determined. A scheme is developed, taking into account the existence of permanent equipment, and the transport system scheme is developed, keeping the total transportation expenses in transporting the resources to a minimum, and the technical parameters of the engineering communication lines are determined.

In general, it can be stated that in developing the construction site plan, solutions are evaluated about the sizes and volumes of temporary buildings and structures (including the permanent equipment used for construction purposes) and the costs of building equipment, as well as the compactness of the building plan.

The stages of traditional organization and technological design of the construction work are as follows: the organizational stage, the planning of resources, and spatial planning. Establishing these stages allows for a comprehensive technological process relating to building management when all processes are divided into procedures and operations. The principles of their implementation and the character of all design documents (the results of the projects) are defined, the methods of developing the presented documents are described, etc. On the basis of the analysis of the initial data (requirements) of design, the analysis of similar projects can be performed. If similar projects are found, evaluation and control of the solutions to be performed. Otherwise, the solutions are generated, assessed, and selected. On the basis of the design solutions made, alternatives are formed, as well as the project documentation. In the case of a great variety of objects, their classification is required, taking into account the purpose of their use in performing various construction works as well as the accurate methods of determining the requirements. For this purpose, a mathematical calculation model is given below.

1. Related research studies

The effectiveness of real-time communication within the BIM environment is restricted to some extent due to the limited sense of immersion in virtual environments (Fadoul et al., 2018). Construction safety management has been a popular problem in research and practice in recent years due to the high rates of accidents and deaths in the construction industry. The complexity and variability of construction sites make safety management more difficult to implement in this area than in other branches of industry. As a promising technology, visualization has been extensively explored to aid construction safety management (Guo et al., 2016). MEP (mechanical, electrical, and plumbing) includes a large number of various types of equipment and pipelines in integrated design, which makes coordination of MEP design optimization a major challenge in designing complex buildings. Huang et al. (2019) presents the BIM-based integrated scheduling approach, which facilitates the automatic generation of optimized activity-level construction schedules for construction projects under the condition of resource constraints, by achieving in-depth integration of the BIM product models into the work package information, the process simulations and the optimization algorithms. In the design stage, problems associated with the realization of the project are considered, which can improve the operational characteristics of the structures and help to successfully realize the project and save time and money (Jin et al., 2019; Kulkarni & Padmanabham, 2017; Liu et al., 2015). The properly, effectively and rationally planned construction site produces a positive effect on labour productivity and work safety at the construction site, while those factors, in their turn, positively affect the construction time and cost. Researchers realized the need for early construction site planning tens of years ago. Planning of the building site is closely associated with other processes of building management, such as planning, the development of schedules, the calculation of the invariable and variable expenses (for assessing the required number of structures and the suitability of the construction site, as well as the possible obstacles). The ineffective and improperly developed plan of the construction site results in unexpected additional expenses and lag behind the terms of the schedule (El-Rayes & Khalafallah, 2005).

Taking into account the complex character and a large number of variables used in the planning optimization of the building site, computers were used in this process as early as 1980 (Sadeghpour et al., 2004). All the methods used have the same main purpose, i.e., to optimize the construction site (or its arrangement). However, the literature analysis performed has shown that all assumptions made and the application area are very wide in an attempt to optimize the construction site. Studies performed on building site optimization differ not only in the methodologies used in the search for a solution to the problem, but also in the definition of the construction site planning problem. Taking into account that there are many variables in construction site planning and that the studies carried out differ in defining the problem solved and the applied research method, it can be assumed that the optimization problem of the construction site has been thoroughly investigated. It should be noted that it is difficult to compare and evaluate various investigated models and determine their similarities and differences, although they are used to solve the same optimization problem. Scientists also describe about the algorithm uses construction methods to build layout solutions over time, using discrete dynamic searches and heuristic information based on both relocations (Zouein & Kattan, 2022). One of the more important areas of research is the use of construction site planning in creating material delivery schedules. And also, to draw up construction work schedules. A mathematical model based on the analysis of dynamic and interactive constraints, multiphase layout, and dynamic location allocation of the ground is proposed (Zhang & Yu, 2021).

Most of the optimization methods present in the literature are used to solve local optimization problems (Rojek et al., 2021; Cekus et al., 2022), because the analyzed algorithms do not cover all construction processes, i.e., they do not fully cover the selection of machinery, designing temporary roads and storage sites, temporary engineering networks, etc. Due to the fact that BIM modeling usually focuses only on building design, we consider a mathematical algorithm that is used only for the comprehensive optimization of planning and organization of a construction site. The outline of the remaining parts of this article is as follows. The next section presents a solution determining the current situation using virtual reality technology, on the basis of mathematical models, calculation of temporary access roads and temporary buildings. Section 2 discusses the mathematical method to calculate the need for machinery. Crane selection is described in detail as an example of employing the developed mathematical model. After an extensive analysis of the literature, it was established that currently there is no proposed mathematical model that solves the task of planning the construction organization as a whole. That is, the biggest problem is that when different mathematical models are applied to calculate the number of mechanisms and the need, the integrity is not taken into account. Therefore, in this article, a mathematical model is proposed that takes into account all stages of planning the construction organization, that is, the selection of the number of mechanisms and temporary buildings and taking into account the optimal position of the mechanisms as a whole. By creating a construction site model using the photogrammetry method, real obstacles are visible, and precisely defined distances between the elements of the construction site. Therefore,

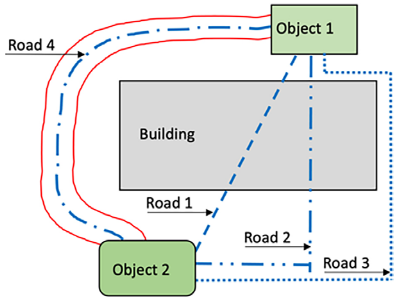

Figure 1. Modeling and measuring the distance of access roads between objects

it becomes possible to perform a multicriteria decision-making analysis (MCDM) (Ustinovichius et al., 2007; Ustinovichius & Simanaviciene, 2008) of possible location points for the main mechanisms of the construction site in a real situation. Optimization (MODM) methods are used to determine the location of other elements of the construction site. This combination, with the previously described construction site model, allows determining an effective option in terms of the indicators analyzed. Multi-criteria decision-making methods using vector optimization based on a decision process model are called multi-criteria optimization methods or multi-objective methods (MODM). These methods are applied to solving a problem involving many objective functions that are optimized simultaneously, and many researchers study in detail multicriteria optimization methods (Zhu et al., 2021). Efficiently planned temporary access roads and parking spaces (later referred to as access roads) not only save time and costs, but also improve the sustainability and safety of construction works. Despite the emphasis in the literature on the importance of effective access road planning (Sanad et al., 2008), this topic has not been adequately discussed in scientific articles. The design and comprehensive assessment of the access roads during the preparation of a construction plan are important because the access roads determine the distances between the facilities. It is crucial to plan rational distances between the relevant facilities on a construction site. In existing models of construction sites, distance is measured in a simplified way, either by the linear distance between objects (Figure 1, Road 1) (Zouein & Kattan, 2002) or by the Euclidean distance between objects (Figure 1, Road 2) (Easa & Hossain, 2008; Osman et al., 2003; Andayesh & Sadeghpour, 2013). However, neither of the two methods takes into account the need to assess existing barriers and bypass them (Figure 1, Roads 2, 3). In fact, the distance between two objects should be measured according to the access roads actually laid out on the construction site (Figure 1, Road 4).

2. Determining the current situation using virtual reality technologies

To calculate the real distance between two objects according to the access roads actually laid out on the construction site, the construction site planning work begins with determining the current situation. In most cases, before starting these works, the transfer of the data from two-dimensional drawings or topography photographs is performed. The assumption is made that the heights are constant, while the topographic features are kept constant.

Data are delivered from topographic photographs, usually stored in the archives of local municipalities. However, modern technologies, such as virtual reality, allow us to fix the situation using. Scanning of existing structures and elements to BIM is widely used, and the accuracy of scanning is described in more than one scientific article (Skrzypczak et al., 2022). Therefore, the accuracy of the photogrammetric model will not be discussed further in this article.

It is based on getting photos from drones or other methods, allowing for combining the obtained graphical information into the unified model. This article examines the use of photogrammetry to assess the current situation of the construction site. The algorithm to recreate the view of the contour of the building that is being built, demolished, or already exists is given in the diagram below (Figure 2).

To immediately represent the algorithm presented with real examples, excerpts from the photogrammetric model are presented below (Figure 3). For educational purposes, the photogrammetric model used is part of the building complex of Vilnius Gediminas Technical University. The accuracy of the photogrammetric model depends on the quantity and quality of the photographs taken. The biggest challenge of virtual reality is that there is no way to accurately convert the resulting photogrammetric model into a parametric model in an automated way. That is, a cloud of points is obtained on the basis of which all the necessary information is mechanically transferred. This problem is currently being solved in several scientific studies, so there is no doubt that a real technical solution will appear.

A more detailed description of the algorithm developed is given below to represent the current situation. First, the data about the group of the current buildings are read from the photogrammetry mode, and the data about the buildings to be demolished, reconstructed, or new constructions. Existing buildings that will not be reconstructed or demolished are drawn in solid and marked

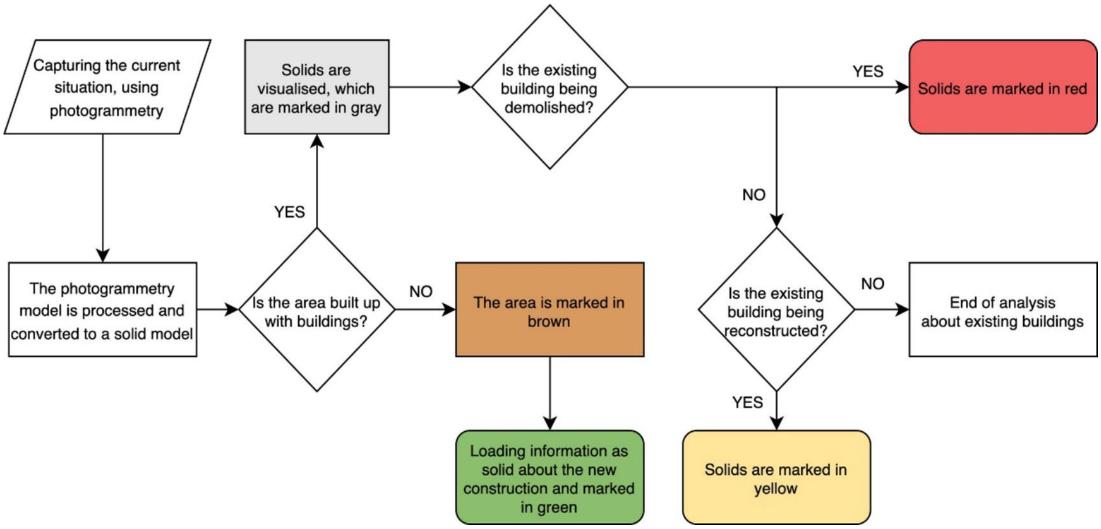

Figure 2. The algorithm to identify the current situation on the construction site

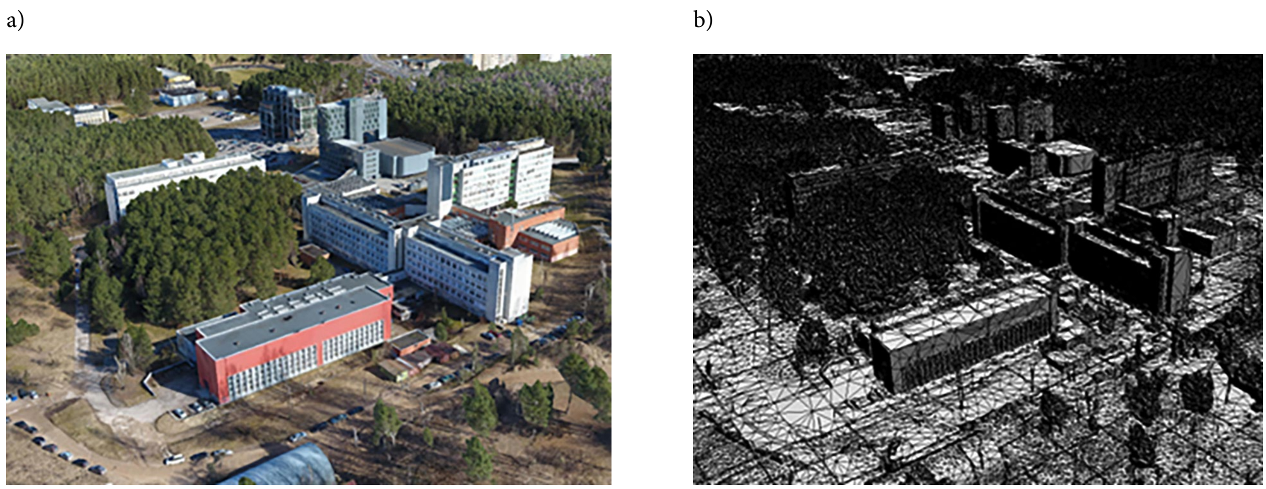

Figure 3. The photogrammetry model and point cloud prototype

in grey color (Figure 4). Reconstructed buildings that will not be demolished are drawn in solid and marked in yellow color (Figure 4). The buildings to be reconstructed, but will not be demolished, are drawn in solid and marked in yellow color (Figure 4). The buildings to be demolished are drawn in solid and marked in red. In addition, information about new construction is loaded from the database and the solids are marked in green.

The drawing of any particular element of the contour depends on the form of the element, which may be straight or in the form of a circular curve. If the element is straight, a straight line section is drawn to the point whose coordinates are shown in the database section. However, if it is the element of the circular curve, the drawing of this element is formalized, and the related calculations are performed. The obtained model is used not only for performing the visual analysis. First, using the model information, a point cloud is produced. It allows digitizing the photographs made and thus identifying the particular areas of the construction site required for ensuring the operation of the platform. The identification of the considered areas includes both built and non-built areas. Built areas include areas with buildings and plants taller than 1.5 m, as well as engineering infrastructure. The non-built territories are areas having plants shorter than 1.5 m. Further identification of areas is continued to determine areas suitable for arranging the construction site, and these areas are marked in brown. It is determined whether the buildings found in the built area can be used to store the materials. It is also necessary to decide whether plants in the considered territory should be preserved or eliminated. If it is decided that the considered site cannot be used to arrange a building site, the platform does not consider this area in further stages. Furthermore, it is identified whether the area can be used to establish objects on the construction site. The platform also determines whether the construction of a new building is planned in the area considered in the future. If that is the case, the platform does not further consider this plot at other stages. Otherwise, the plot is used in the calculations performed by the platform and is referred to as a free space.

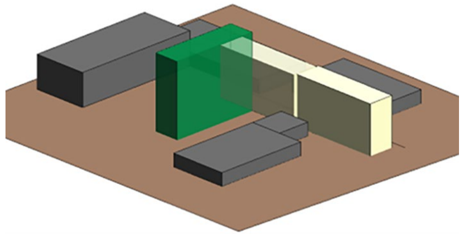

Figure 4. A real example of the use of the algorithm: Converted solid model from photogrammetry model

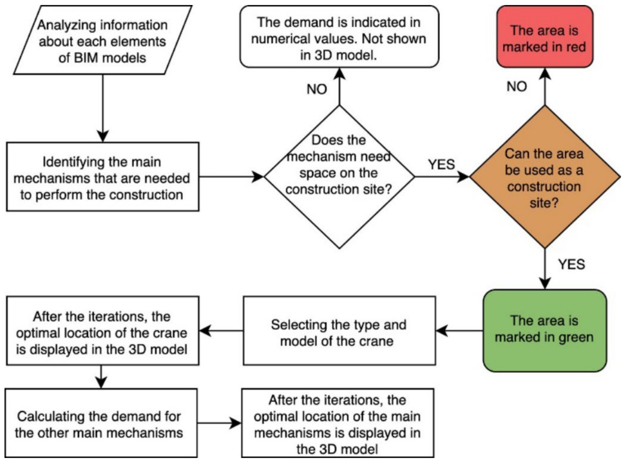

Figure 5. The algorithm to identify possible area for construction site planning and optimal location iteration of main mechanisms

3. The selection of mechanisms and the calculation of the need

To determine what mechanisms will be needed for construction work, the BIM model is first analyzed. The use of the BIM model for construction site planning, optimization, and selection of tower cranes is also studied by other researchers, but using other methods. For example, Riga et al. (2020) describe the use of mixed integer programming, which provides enormous modeling possibilities and rigorous quality guarantees for the solutions obtained. Unlike existing heuristic approaches, the returned solution is likely optimal until the optimality gap is chosen. It is important to emphasize that in this mathematical algorithm, the BIM model is perceived not only as a three-dimensional geometric model, but also as an information model. It is very important that the elements of the BIM model are described correctly to identify the required parameters and attributes of the elements. For example, not specifying the correct slab weight will prevent a tower crane from being selected. One of the consequences of an irresponsible BIM model can be that the tower crane simply will not lift or reach the relevant building element. The second consequence can be that the tower crane will be chosen too powerful and too high, and in this case, you simply pay for a more powerful tower crane, which is not really needed on the construction site. The picture below (Figure 5) shows a mathematical algorithm, based on which the need for mechanisms is determined, the necessary mechanisms are selected, the optimal localization of mechanisms is determined, and the areas of the construction site that can be used for the purposes of the construction site – storage, access roads, temporary infrastructure, etc. are identified. Such areas are marked in green. Also, as mentioned above, it is very important to identify which areas cannot be used for construction site purposes, so these areas are marked in red.

Because of the great variety of mechanisms, a classification of the need for them in the particular construction works as well as an accurate calculation of the needs are required. The classification of the main mechanisms used in construction: lifting mechanisms, mechanisms for earthworks, mechanisms for transportation, as well as loading and unloading, mechanisms for drilling, mechanisms for driving poles, mechanisms for stonemasonry, mechanisms and equipment to work with concrete and reinforced concrete, mechanisms for finishing works, the equipment for laying floors: the equipment for laying cement floors and cutting tools, mechanized tools – tools for manual work. The mechanisms, machines, and tools given in the groups of the classification differ in their structural features and the types of the main engine.

The sets of mechanisms depend on the particular construction technology used. In earthworks, a set of the mechanisms used consists of excavators, bulldozers, heavy-duty trucks, compacting equipment, etc. However, in laying roll covering or performing hydro-insulation works, a set of mechanisms includes a crane, a device for making or mixing the required mastic, devices for surface covering and transportation of the required materials, as well as the devices for sticking the covering material to the surface, etc. A set of required mechanisms usually includes one major device, performing the main technological operation, while other mechanisms perform less important operations. The operational characteristics of both types of mechanism should be in agreement with each other. The major mechanism of the set can work linearly, in parallel, or in a combined manner. In the linear mode of work, any changes in the mechanisms cause an interruption of the operation of the set. The productivity of the entire set of mechanisms depends on the mechanism of the lowest power. Therefore, to ensure the highest productivity of the sets, any additional mechanisms should be selected, taking into account the parameters of the main mechanism. In the parallel mode of operation, all the mechanisms in the set operate independently. The productivity of the set of mechanisms is equal to the sum of the productivities of the individual mechanisms of the set. Therefore, the device can stop operating only when all the mechanisms in the set stop working simultaneously. In both cases, secondary mechanisms can be used to create linear and parallel modes of work and used continuously or periodically (Briskorn & Dienstknecht, 2019, 2020; Lucarelli et al., 2019).

Three additional productivity (output) definitions of the mechanisms are provided below.

1. Theoretical productivity assesses the amount of products obtained per technological cycle of the mechanism operation. For example, filling the excavator bucket with soil and carrying it to another place:

$$N_o = \frac{Q}{t_c}; \tag{1}$$

$$N_t = \vartheta F, \tag{2}$$

where: N_o is the theoretical productivity of the mechanism; Q is the output of the mechanism per technological cycle (for the excavating machine – m^3); t_c is the duration of the technological cycle, min; ϑ is the speed of movement of the mechanism, m/min; N_t is the technical productivity of the mechanism; F is the amount of the lifted material.

2. Technical productivity, determining the technical maintenance of the mechanism:

$$N_t = N_o K_t, \tag{3}$$

where: N is the technical production (output) of the mechanism; K_t is the coefficient of technical productivity of the mechanism, assessing the variation in technical maintenance of its equipment.

3. Operating capacity, determining the organisation of work and the technology used:

$$N_e = N_t K_p, \tag{4}$$

where: N_e is the operating productivity of the mechanism; K_p is the coefficient of the operating productivity of the mechanism, determining the loss of time during the shift change and the instructional or rest periods.

Planning of the tower crane in the preconstruction phase has long-lasting impacts on the cost and schedule of the project. Current approaches and tools used by the industry to facilitate tower crane planning can be time-consuming, ineffective in determining all constraints, and challenging to visualize and understand alternatives (Ji & Leite, 2018; Ji et al., 2017). The number of mechanisms can be calculated as follows:

$$M = \frac{V_b y}{100\, N_t K_p T_{dv} T_d}, \tag{5}$$

where: M – need for mechanisms, units / shift; V_b is the general amount of the operations expressed in units used to measure the performed work; y is the proportion of operations performed by the considered mechanism, %; T_{dv} is the working time of the mechanism in the shift; T_d is the period of performing the operations.

When a set of mechanisms is formed, the relationship between the productivity of additional mechanisms and that of the major mechanism is established as follows:

$$M_{pp} = \frac{N_{pk}}{N_{ppk}}, \tag{6}$$

where: M_{pp} is the number of additional mechanisms; N_{pk} is the output of the main mechanism in the shift; N_{ppk} is the output of the additional mechanism in the shift.

The technical characteristics of the mechanism are determined. An example of this calculation stage is the choice of crane parameters. The calculated tower crane parameters include the height of the hook (the height of the mounted crane), the accessibility of the crane boom, and the lifting capacity and stability of the crane (Figure 6).

$$H_m = h_o + h_e + h_z + h_c; \tag{7}$$

$$H_m = h_o + h_e + h_z + h_c, \tag{8}$$

where: H_m is the mounting height of the crane (the height of the boom's lift), m; h_o is the height of the constructed building, m; h_e is the maximum height of the building element, m; h_z is the height between the construction element and the constructed object, m; h_c is the height of the sling connection, m; L_s is the length of the crane's boom, m; a is the width of the tower crane, m; b is the distance between the tower crane and the most prominent part of the constructed object, m; c is the width of the constructed object, m; Q_{kp} is the lifting capacity of the tower crane, t; $g_{\max}$ is the largest mass of the constructed object compared to that of other elements of the constructed object, t; g_{str} is the largest mass of the sling equipment, t; $M_{g_{\max}}$ is the maximum moment of force; M_{pr} is the balance moment; $Q_{\max}$ is the maximum mass of the mounted element (structure); Q_{pr} is the balance mass; r is the balance arm, m; K is the power reserve coefficient.

Organisation of the construction site requires a lot of effort and respective planning, taking into account a particular construction site. The problem of the organization of the construction site is complex, and therefore, generative programming is required, allowing the effective use of BIM technologies at the stage of organisation and planning of the construction site.

It is very important to identify not only the need for the main and auxiliary mechanisms for the construction process, but also to establish at an early stage which areas of the construction site have the possibility of installing the main mechanisms, temporary construction site objects, and temporary infrastructure. For that purpose, as mentioned earlier, the analyzed photogrammetric model of virtual reality allows us to determine not only the existing buildings, but also the area. The area where it is possible to use the construction site for purposes is marked in green (Figure 7). A plot is marked in red if it cannot be used for the purpose of building a construction site due to relevant restrictions, such as the location of the plot, the surrounding buildings or plants (Figure 7).

Therefore, in later stages, both the mechanisms and other objects and infrastructure of the construction site are planned only in green areas. A classical method of selecting a tower crane is based on the use of 2D documents and tools based on a pair of compasses. Using this method can lead to a mistake in choosing the respective tower crane. The final method selected can also be irrational. A perfect example of choosing the location of a tower crane and its optimisation for a particular construction site, based on the use of virtual reality technology, is given below.

Analysis of the length and lifting capacity of the boom of the tower crane can be carried out using various methods and techniques. In this section, the algorithm for choosing the location of the crane is described and given in Figure 8. Using this method, the location of the crane is chosen, taking into account the lifting capacity of the crane with a particular reach of its boom and the location of the object, that is, evaluating the distance from the crane to the element. To use the above algorithm for choosing the crane, the initial data as follows should be known:

1. The elements of the BIM model. These are the structural elements of the information model of the building that should be lifted, transferred, mounted, etc.;
2. The table to determine the lifting capacity of the crane. The lifting capacity is determined, depending on the boom's reach;
3. The storage area. In this area, the storage of elements is planned. The unloading area is also known as this area when particular elements should be unloaded by the crane from the arriving transport facility.

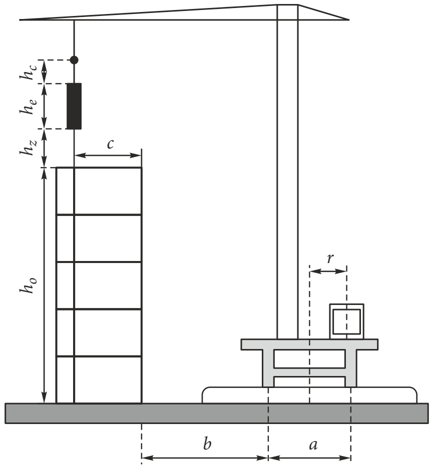

Figure 6. A schematic view of determining the parameters of the tower cranes

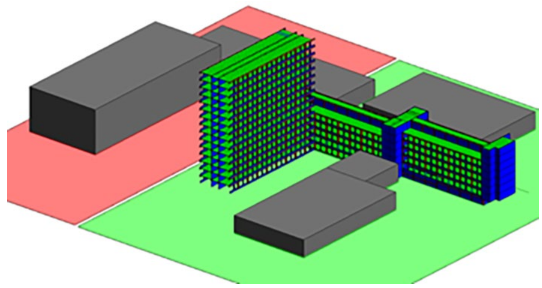

Figure 7. A real example of the use of the algorithm: possible use of the territory for the construction site

The result of each iteration is given in the particular color (Figure 9):

1. The element in the building information model is shown graphically in green. This means that a particular element that is some distance away from the crane is reached and lifted, taking into consideration its weight and the reach of the boom, as well as the lifting capacity of the crane with the particular reach of the boom;
2. The element given in the yellow (orange) colour is lifted, but is still inaccessible due to the arrangement of the storage area. This means that, if the location of the element storage changes, it could be reached and lifted, as well as mounted on the particular plane of the model;
3. The yellow element (orange) is too heavy and cannot be lifted, taking into consideration the lifting capacity of the crane with the boom of a particular reach;

4. The red-painted element is too close to the crane and therefore the crane boom cannot reach the element.

A database for selecting construction machinery, in this case a tower crane, is used based on the types of machinery offered by the local market. It is not possible to create a universal database that is suitable for all types of mechanism. In order to verify the created mathematical model, a partial database was also created. Table 1 shows an extract from the created database, which is intended for the selection of a tower crane.

However, determining the parameters of mobile cranes is more difficult because the boom of the crane is inclined at the angle α to the horizontal plane. Therefore, in calculating the protrusion (L_{mkr}) of the automobile crane's boom, a reserve of the distance of the boom from the transferred element d^1 and the mounted structure d^2 is considered, and the equations given below are used:

$$L_{mkr} = c + \left(f + d^1\right)\frac{\left(H_{str} - h_l\right)}{\left(h_{po} + h_c\right)}; \tag{9}$$

$$L_{mkr} = c + \left(k + d^2\right)\frac{\left(H_{str} - h_l\right)}{\left(h_{po} + h_c + h_z + h_e\right)}, \tag{10}$$

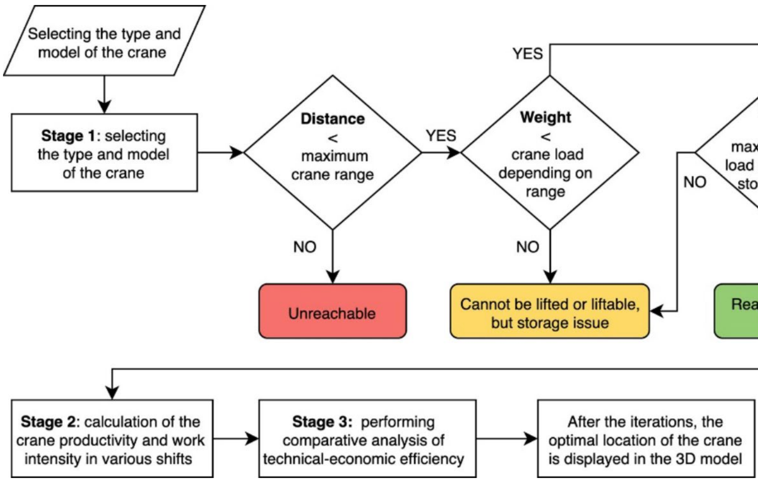

Figure 8. The algorithm for selecting the crane

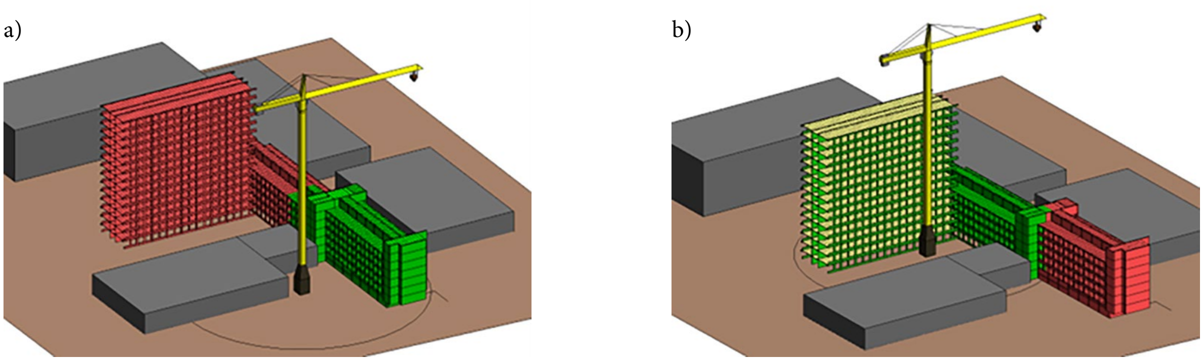

Figure 9. A real example of the use of the algorithm: iterations of tower crane selection

Table 1. Mechanism work characteristic

Boom length	Reach (m) and lifting capacity (t)												
	m	18.0	20.0	22.0	…	26.0	28.0	30.0	32.0	34.0	35.0	36.0	…	45.0
45 m	t	4.34	3.86	3.46	…	2.86	2.63	2.43	2.25	2.10	2.03	1.96	…	1.50
40 m	t	4.96	4.41	3.96	…	3.28	3.02	2.79	2.59	2.42	2.34	2.26	…	
35 m	t		4.70	4.23	…	3.50	3.22	2.98	2.77	2.59	2.50			
30 m	t			4.53	…	3.76	3.46	3.20						

Notes: Color values in the table:

Lifting capacity (t), when quadruple protection ();

Lifting capacity (t), when double protection ().

$$H_{str} = H_m + h_{po}; \tag{11}$$

$$H_{str} = L \sin \alpha + h_l; \tag{12}$$

$$L = \sqrt{\left(H_{str} - h_l\right)^2 + \left(L_{mkr} - c\right)^2}; \tag{13}$$

$$\alpha = arctg \frac{H_{str} - h_l}{L_{mkr} - c}, \tag{14}$$

where: H_m is the mounting height of the crane (the rise of the boom), m; H_{str} is the total height of the mounting height of the crane and the crane's height in the stressed state, m; h_o is the height of the constructed object, m; h_e is the maximum height of the building element, m; h_z is the height from the building element to the construction object, m; h_c is the height of the sling connection, m; h_l is the height of the boom with respect to the level of the crane's platform, m; h_{po} is the crane's height in the stressed state, m; f is the distance from the centre of the slings' application to the element to the point nearest to the crane's boom, m; k is the distance from the centre of attaching the slings of the mounted part of the building to the point of the building, which is the nearest to the crane's boom, m; d^1 is the distance of the crane's boom to the mounted element, m; d^2 is the distance from the crane's boom to the mounted part of the building, m.

If a mobile crane is intended for installation work at the bottom of the pit, then the parameter d_K^2 – the distance from the crane parking lot to the axis of the center of the slinging of the underground part of the building being installed – depends on the depth of the pit and on the angle of repose of the soil (Figure 10):

$$d_K^2 = H_k tg\varphi + 1, \tag{15}$$

where: H_k is the depth of the foundation pit or the basement, m; φ is the angle of the ground inclination, degrees; d_K^2 is the distance from the crane's location to the axis of the centre of attaching the slings to the underground part of the mounted building, m.

In calculating the crane parameters, the criterion of connection of 'the height of the slings' is used. This connection is the element made of slings and is aimed at the lifted elements and suspended on the hook of the lifting mechanism. Allows one to increase the reliability and safety of the structural element fixed to the hook of the mechanism. Sling connections are classified according to the lifting capacity, the length, and the cross section of the rope (Figure 11).

The productivity of the erection crane is assessed by calculating the technological cycles completed per shift of work. A technological cycle is equal to the sum of attaching the slings to the element, its lifting, the movement of the crane, the lowering of the hook, and the mounting to fix another element. Taking into account that the crane cannot work without breaks, the time use coefficient is introduced, which is equal to 0.3–0.5.

Estimation of work intensity requires information about work volume. When mounting operations are performed, the work volume is considered equal to the number of structures. However, the amount of work increases to 20%, taking into account the additional lifts associated with the major structural mounting works.

$$N_{mkr} = \frac{60 t_{cm} K_{pm}}{t_{cmk}}; \tag{16}$$

$$t_{cmk} = T_{strop} + T_p + T_{mont} + T_c + T_{per}; \tag{17}$$

$$T_p = \frac{H_m}{v_p},\ \ T_c = \frac{H_m}{v_c},\ \ T_{per} = \frac{L}{v_{per}}; \tag{18}$$

$$V = \sum_i n_i; \tag{19}$$

$$I_{mc} = \frac{K_{sl} V}{N_{mkr}}; \tag{20}$$

$$M_{kp} = \frac{I_{mc}}{s_{cm} T_{pl}}, \tag{21}$$

where: N_{mkr} is the erection crane's productivity, lifts/shift; t_{cm} is the duration of the work shift, hours; K_{pm} is the coefficient of the time used by the mechanism; t_{cmk} is the time of the erection crane's technological cycle, min; T_{strop} is the time of attaching the slings to the mounted element, min; T_p is the time of lifting the mounted element, min; T_{mont}

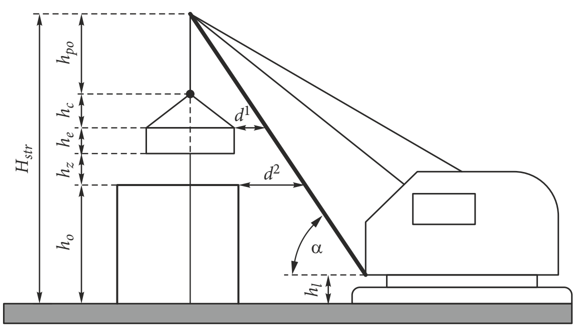

Figure 10. A schematic view of determining the parameters of automobile cranes

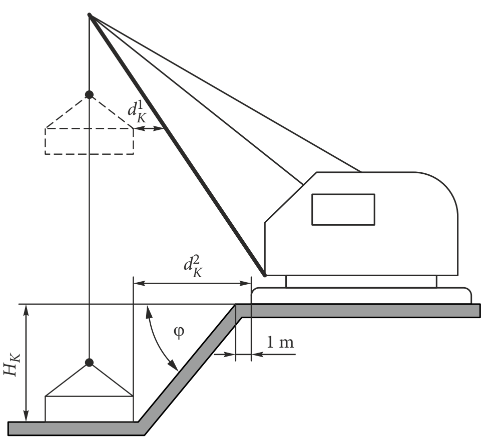

Figure 11. A schematic view of determining the parameters of the automobile cranes located at the edges of the foundation pit

is the time of the mounting works, min; T_c is the time of the crane's hook descending, min; T_{per} is the time of the crane's movement, min; H_m is the mounting height of the crane mounting, m; L is the length of crane movement, m; v_p is the rate of lifting the mounted elements by the crane, m/min; v_c is the rate of lowering the crane's hook, m/min.; v_{per} is the rate of the crane's movement, m/min; V denotes the volume of the mounting works, lifted by a crane; n_i is the number of the construction elements i, units; I_{mc} is the intensity of the mounting operations in the shift; K_{sl} is the coefficient determining the additional lifts by a crane; M_{kp} is the number of the erection cranes, units; s_{cm} is the number of the shifts during the workday; T_{pl} is the time planned for the mounting operations in shifts.

If the mounting operation time is planned, the required number of cranes that work in parallel can be determined. The development of the technological work cycle of the excavating machine is required to develop a technological project of construction work. It should be emphasized that before using the algorithm for automated calculation, the creation of the catalogue of technical specifications and the parameters of the mechanisms should be performed to avoid the restriction of possible solutions by some mechanisms, which would prevent a best and most rational solution. Since there was the possibility of using models of various construction mechanisms, a comparative analysis of their technical and economic efficiency was performed. This allowed the selection of the alternative, ensuring the minimal expenses ($P_i \to \min$). The expenses mean the estimated value of the construction products, whose values are determined by the cost and depreciation of the products. The algorithm to calculate the expenses for each selected mechanism (or a set of mechanisms) is given below:

$$P_i = C_{sav} + A, \tag{22}$$

where: P_i denotes the costs of the mounting works; C_{sav} is the estimated cost of the performed works; A is depreciation.

The calculated cost of the work performed is the sum of direct and indirect expenses of the work performed. Direct expenses include:

1. Costs of materials, constructions, parts, electricity, heat, and water supply during mounting works;
2. Costs associated with the workers' payment;
3. Maintenance (operating) costs of building equipment.

Assuming that the first component of direct expenses should not change in the case of changing a construction mechanism, this value is eliminated from the calculation of the expenses:

$$C_{sav} = E + D_u, \tag{23}$$

where: E denotes the maintenance costs of the building equipment; D_u denotes the costs of the workers' payment.

$$A = \frac{K_{kr}}{T_t} = K_{kr} E_n, \tag{24}$$

where: K_{kr} denotes the actual investments in the work performance; T_t is the calculated period of using the main funds.

$$E_n = \frac{1}{T_t}, \tag{25}$$

where: E_n is the coefficient of the effectiveness of work performance investments ($1/T_{am} = 0.12$); T_{am} is the standard value of the mechanism's depreciation.

The amount of actual investments in the performance of work makes a part of the major funds proportional to the time of performing the analysed work as follows:

$$K_{kr} = \frac{C_r R_t}{T_n}, \tag{26}$$

where: C_r is the inventory value of the machine that performs the work, thousand euros; R_t is the working period (work expense), machines per shift; T_n is the standard number of working shifts of a building machine per year.

If a set of mechanisms working in consecutive order is required to perform the work, the total inventory value of all the mechanisms used should be determined:

$$K_{kr} = \frac{1.07 \sum C_r^j R_t}{T_n}. \tag{27}$$

The costs of maintaining and servicing the construction mechanisms (E) and the costs of the workers' payment (D_u) are calculated by the equations as follows:

$$E = 1.08 C_{ekslp} R_t; \tag{28}$$

$$D_u = 1.5 \sum D_{ui} R_t / 24, \tag{29}$$

where: C_{ekslp} denotes the costs of using the construction mechanisms, Eur/shift; D_{ui} is the monthly work payment of the i-th worker, the member of the brigade, servicing the mechanism.

To perform automated calculations, it is necessary to first create a database of technical and economic characteristics of construction machines (C_r, C_{ekslp}). Since the values of the cost indicators of the database can become outdated over time, it is advisable to use a constantly updated investment price index I_p. Then:

$$C_{ekslp} = C_{ekslp}{}^T I_p; \tag{30}$$

$$C_r = C_r{}^T I_p, \tag{31}$$

where: $C_{ekslp}{}^T$ is the value of the operational costs of the mechanisms given in the reference books or the database, Eur/shift; $C_r{}^T$ is the inventory value of the j-th construction mechanism given in reference books or the database, thousand Eur.

Based on the detailed mathematical model and classification provided, the information system should be developed to determine the technical characteristics of the

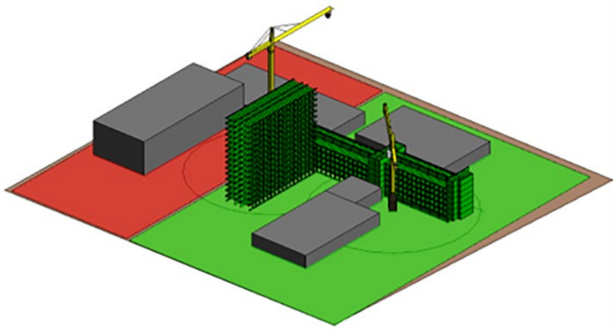

Figure 12. A real example of the use of the algorithm: iteration of tower crane selection

construction mechanism or equipment, to calculate the intensity of work and the productivity of the mechanism and to perform a comparative analysis of the technical-economic effectiveness to find the alternative, which could ensure minimal costs and the appropriate selection of the construction site (Figure 12).

4. Selection of areas for construction site objects and infrastructure

The supply of materials to various construction sites may be different. The case of transporting materials by motor vehicles is analysed below. In this case, the storage areas for the materials should first be planned, followed by the means of their delivery. As mentioned above, free spaces are determined using virtual reality technologies. The selection of the location of the storage areas and mechanisms (e.g., for making concrete and mortar) aimed at servicing several objects on the construction site (Figure 13) is performed, taking into account the cost of transporting building materials, and is calculated as follows (Gbadamosi et al., 2019):

$$C = \sum_{i=1}^{n} c' Q_i L_i, \tag{32}$$

where: c' denotes the costs of transporting one tonne of materials over a distance of one km; Q_i is the amount of materials needed for each object; L_i is the distance from the storage area or the location of the mechanisms to the object; n is the number of objects.

If the position of the points of consumption of products in the system of rectangular coordinates is considered, we can express the distance from the production facility to the place of consumption of products and the cost of transportation as follows:

$$L_i = \sqrt{\left(x - x_i\right)^2 + \left(y - y_i\right)^2}; \tag{33}$$

$$C = \sum_{i=1}^{n} c' Q_i \sqrt{\left(x - x_i\right)^2 + \left(y - y_i\right)^2}, \tag{34}$$

where x and y are the coordinates of the location of each object, for which the distance from the storage area or the location of the mechanism, as well as the transport expenses, are the smallest.

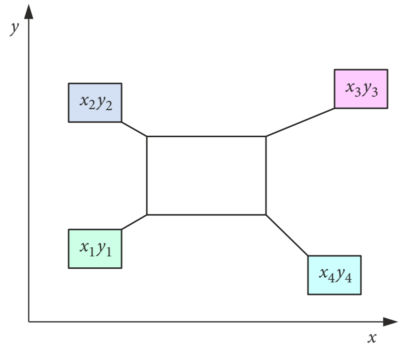

Figure 13. The plan for selecting the locations of the objects

The suggested classification of the objects based on their use is as follows:

1. Production areas for reinforcement, mechanical elements, plumbing fixtures, concrete mortar production equipment, and technological equipment for asphalt concrete production, plastering and painting, etc.;
2. Storage spaces;
3. Administration premises, including the premises for the managers of mounting operations, control rooms, guard posts, etc.;
4. Sanitary spaces (rooms for changing clothes and their drying, shower rooms, dining halls, first aid rooms, toilet rooms, etc.);
5. Living spaces.

The suggested classification of the objects based on the time of their use:

1. Non-inventory objects used only once;
2. Inventory objects used repeatedly.
3. The suggested classification of the objects based on design solutions:
4. Pre-fabricated objects made of one or several blocks (containers). The most widely used and popular containers are $6 \times 3 \times 2.7$ m in size. The blocks can be interconnected or structures of several floors high are made;
5. The objects are 24 m wide and about 60 m long and made of fabric or other material.
6. The calculation of the temporary objects areas is carried out according to the technical standards presented in Table 2.

The need for administrative buildings:

1. The areas for construction managers: 3.0–3.5 m^2/person (5–24 people);
2. The control room: 7 m^2/person.

The need for sanitary rooms:

1. Changing rooms: 0.9 m^2/person (7–10 persons in the room);
2. Drying rooms: 0.2 m^2/person;
3. Heating rooms, eating rooms: 1 m^2/person;
4. Shower rooms: 0.43 m^2/person (5.4 m^2/10 persons);
5. Toilet room: 1 room/20 persons.

Table 2. Areas of industrial buildings

The designated purpose of the object	Units of measurement	Container type objects	Pre-fabricated objects
Workshops for tools and instruments	tools, units / m^2	up to 100 / 15–32	200–400 / 46–34
Joiner's shops	thousand m^2 per shift / m^2	up to 0.5 / 15−32	2–5 / 2000–500
Reinforcement shops	t per shift / m^2	up to 200 / 24–32	1500–2000 /2000–1500
Painting plants	t per shift / m^2	up to 4 / 16–32	–
Plastering plants	m^3 per how / m^2	up to 8 / 16–32	–

The need for administration and sanitary rooms is determined taking into account the maximum number of builders to be planned to work simultaneously on the construction site. The temporary objects on the construction site are used with standard dimensions according to the objects used in the market of the respective country. Currently using the prototype developed, it is assumed that the construction site wagons are 2.40 meters wide and 6.0 meters long, which can be shaped according to needs. These are connected to each other and equipped with rooms for various purposes.

The appropriate area for permanent objects is determined taking into consideration the location x_1, y_1 ... x_n, y_n of each object and minimizing the total expenses of the temporary electric power systems and the time of the workers' movement on the construction site. Therefore,

$$L = \min\left(\sum L_{IV}C_{IV} + \sum L_{lN}C_{lN} + \sum L_{lS}C_{lS} + \sum L_{dJ}C_{dJ}\right), \quad (35)$$

where: L_{IV} is the length of the temporary water supply, sewage, and heating systems and the movement of workers on the construction site; $L_{IV,\, lN,\, lS,\, dJ}$ are the coefficients of expenses.

It is assumed that the temporary building areas planned are on the construction site and cannot be planned in the building area constructed. The distance between the objects should not be smaller than the approved one, K_{ij}:

$$K_{ij} \le \sqrt{\left(X_{ij} - X_{(i+1),j}\right)^2 + \left(Y_{ij} - Y_{(i+1),j}\right)^2}, \quad (36)$$

where K_{ij} is the admitted distance between the temporary buildings. X and Y are the coordinates of the location of each object, for which the distance from the storage area or the location of the mechanism, as well as the transport expenses, are the smallest. A real example of the use of the algorithm for selecting the locations for the temporary objects needed is presented in Figure 14.

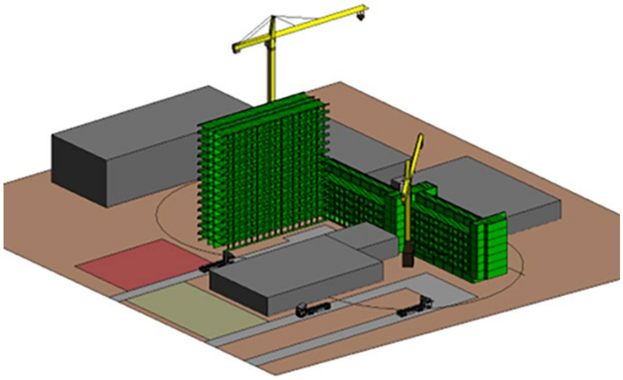

Figure 14. A real example of the use of the algorithm: selecting the locations for the temporary objects needed

Conclusions

A mathematical algorithm considered in this article differs from others in that it presents a complex solution to choose all the mechanisms used on the construction site, such as a tower crane, temporary buildings, and machinery.

The mathematical model described and developed in this article consistently selects each mechanism. Selection and optimization are done using mathematical justification. Therefore, the created mathematical model is easily adapted to the unique parameters of the company or the performance and efficiency of the mechanisms, because the performance and efficiency of the mechanisms are included in the calculations of the needs of the mechanisms. For a more accurate determination of the real situation, virtual reality technology is used. Currently, methods that combine virtual reality technology and the organization of a complex building site are lacking. The use of the photogrammetry model presented in this article to determine the current situation is an important step in the preparation of a construction plan effectively. The completed digitization of existing buildings allows us not only to identify the two-dimensional coordinates of the building on the plot, but also to display the layout of the existing buildings in three-dimensional space. Other existing elements, such as trees and other vegetation, ground engineering networks, etc., are particularly important for building organization planning. All identified constraints are used in the created mathematical model and marked on the construction site plan. The practical application of the developed mathematical model will help avoid the most frequently made mistakes in designing a construction site, such as the excessive amount of mechanisms and poorly organized movement at the construction site, as well as the frequent transfer of temporary buildings during construction due to the absence of their preliminarily planned location. The article describes the organization of the planned building site, while virtual reality technology fully describes the real situation.

The optimal amount of mechanisms required and the need for them are calculated automatically using a mathematical algorithm. Due to the existence of a large number of variables associated with the construction site model, assumptions and possibilities differ considerably, though the research aspects of the analysed methods, defining a general plan used to form the construction site, are determined. The main principles for developing a mathematical model of the need for construction objects and the methods for selecting construction sites and their classification are developed. The article presents the calculation of the mathematical method, which is continuous because the optimized information system prototype of the construction site plan is general and aims to achieve the performance of the main stage of the construction work, that is, the mounting of the part of the structure on the above surface. It has been shown that to maximize and automatically model construction site planning and the selection of mechanisms, equipment, and other temporary objects, other stages of the construction works, i.e., earthworks, zero cycle construction, engineering network development and communication, grounds maintenance, etc., should be integrated into the created information system prototype. Although this article is of a continuing nature, this article has analyzed the following:

1. The principle of forming a mathematical model of the needs of construction site objects has been formed and the methodology for the selection of the main construction site objects has been developed.
2. An algorithm for an optimized construction site plan has been developed, and the final graphical result to be achieved is shown, an optimized construction site plan using virtual reality technologies.
3. It has been established that the research work performed is continuous, as the optimized prototype developed of the construction site plan information system is general and intended for the main stage of construction works, and it means for the installation phase of the above-ground structures. To maximally optimize and automatically model site planning, selection of mechanisms, equipment, and other temporary objects, it is necessary to integrate into the existing prototype of the information system and other stages of construction - earthworks, zero cycle construction, engineering networks and communications, environmental management, etc.

The created mathematical model and calculations are currently used in the planning stage, when the future territory of the construction site is analyzed and the organization and planning of the construction site is designed. The limitations of the created mathematical model are applied when the principles of building site organization and planning in the country are fundamentally different. The proposed methodology corresponds fully to the methods used on the European markets. We will not avoid small corrections of mathematical models when additional coefficients are introduced due to relevant environmental factors.

Although this article analyzes the selection and optimization of the main mechanisms used on the construction site, there are still other construction mechanisms that are not combined into a common mathematical algorithm. Such as interior work machinery which is for fitting, painting, flooring, etc. or machinery for field work. Therefore, future work will be related to the integration of other mechanisms into this mathematical model. After creating a general mathematical model that would integrate all the mechanisms used in construction, a construction work organization model would also be created, which would help not only plan, but also monitor and control the work in progress.

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