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Effective Use of Tower Cranes over Time in the Selected Construction Process

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Abstract: The quality of preparations carried out before building work commences has a significant impact on the smooth running and overall financial costs of a construction project. The use of construction machinery, which is crucial with regard to the efficiency of the construction process, plays an important role. In building construction, the machines in question are mainly tower cranes. The paper presents a new method for assessing the utilisation of tower cranes over time during the construction of reinforced concrete monolithic structures. The method, which contributes to the efficient utilisation of such cranes, is based on a mathematical simulation model that predicts the work cycles of a tower crane during a work shift when work is being performed on individual construction sub-processes. Construction sub-processes are analysed in detail with regard to the service provided to them by a tower crane. Data can also be obtained from binding construction schedules and boundary conditions, which in every case are for a specific executed construction project. The simulation model of the work of tower cranes has been developed for use in software applications. The created application expands the possibilities of smart construction site design in a digital environment and can also be used directly from an internet browser.

Keywords: pre-construction phase; tower crane; tower crane design; smart construction site

1. Introduction

The quality of preparations carried out before construction work commences is an important precondition for the success of a building project [1]. Ever-increasing emphasis is now being placed on sustainability in construction, both in terms of the final product and in relation to the course of the construction process [2]. Economic and environmental sustainability in the construction industry is connected with construction techniques and spatial requirements at the construction site. These are significantly related to the construction period, which affects the financial costs of the construction process and negatively affects the environment in the vicinity of the building site [3]. Pollution occurs in adjacent areas, as does the increased dustiness, contamination of the soil with oil products, increased noise levels, increased traffic around the building site, and the often unnecessarily large-scale and long-lasting occupation of areas by the construction site, all of which have a negative impact on construction costs. It is, therefore, important to address issues concerning the economical handling of space at the construction site (for example, minimising the areas of construction sites and material storage sites, and the periods for which they are used) and the optimisation of the construction period, these being issues which are particularly important in densely populated areas and city centres [4].

Both of these topics are related to the efficient use of expensive construction machines, which in civil engineering are mainly earthmoving machines and tower cranes. The

efficiency of their use directly affects the environmental and economic sustainability of the built structure. The financial costs of the operation of such machines are (depending on the scope, construction and complexity of the structure) usually 5–10% of the total production costs of the construction project [5]. The specific nature of construction work, and the transportation, lifting and storage of large quantities of building materials, requires the frequent use of tower cranes. As far as the economic management of space at a construction site is concerned, it is necessary to sensitively investigate the necessary number and location of cranes at the site, and the related location of material storage sites and their scope, which affects the size of the area needed for the construction site and the organisation of construction site supply [3]. As regards the construction period, the efficiency of the utilisation of tower cranes is one of the decisive factors for the productivity of construction site work, as it affects the total execution time, the period of occupancy of the needed space, and thus also the total financial costs of the construction project [5].

Many authors deal with these topics [6–9], with work that mainly focuses on the optimisation of spatial design for construction sites and on the location and monitoring of construction materials and machines in the productive area of construction sites in relation to the efficiency of supply.

The research which is presented in this paper focuses on an essential topic from the perspective of site supply efficiency, namely the assessment of the efficiency of the utilisation over time of tower cranes during the construction of reinforced concrete monolithic structures. The vast majority of construction companies do not deal with the accurate assessment of compliance with the binding construction schedule or the utilisation over time of tower cranes in the pre-construction phase, or they use outdated methods [3,4]. This discrepancy often significantly affects the efficiency and economics of the construction project, as well as other criteria in the context of structural sustainability [4]. Today, when advanced computer technology is available, it is necessary to use far more accurate calculation methods as well as input data that are digitally processed in the project [1,3,5]. The newly proposed methodology is based on a binding construction schedule, the real-time requirements for construction sub-processes, and the amount of material moved. It also takes into account the construction system of the building. A deterministic approach was used for the mathematical modelling and the creation of a simulation model, the advantages of which will be described below. The methodology is presented for the construction of a reinforced concrete monolithic structure, but it is also generally applicable to other structural systems and is ready for software use in the "Crane occupancy 0.4" programme.

The next part of the paper presents related research by other authors and their evaluation. An explanation of the procedure for developing the proposed methodology follows. The following chapter clarifies and presents the boundary conditions of the task as well as the preparation of input data for the simulation model, including the design of a model operating cycle of a tower crane, and analyses the operating cycle of construction sub-processes. The next part of the paper presents a simulation model for the work of a tower crane and its software processing and verifies the designed methodology using ongoing construction projects and reinforced concrete multifunctional buildings. A comparison of current approaches with the presented methodology and its evaluation can be found in the Discussion section. The conclusion of the paper emphasises the importance of the task and mentions the further continuation of the research.

2. Literature Review

Among those works dealing with the production space and efficient supply of construction sites lies, for example, research by Hawarneh et al., focusing on the automated design of construction site building locations, material storage sites and the placement of construction machinery. A binary integer linear programming model is used for the automated design of deployment locations. It optimises the placement of machines with regard to availability, element overlap, assembly, disassembly, forbidden areas for machine movements and element placement restrictions. The use of dynamic allocation minimises

the area of the construction site and traffic distances and thus reduces the total financial costs of construction site equipment [6].

Spisakova and Kozlovska also describe an innovative approach to increasing the technical, safety and environmental efficiency of building sites with regard to construction site supply and the on-site transport of materials. They refer to the options for using RFID (Radio Frequency Identification) high-frequency identification technology for localisation during the construction process and describe the advantages of its application. The main components of the RFID system are the transmitter (sensor and reader) and a set of chips (tags). On the construction site, the position of materials, workers, construction machinery and equipment can also be monitored. It is thus possible to monitor the course of specific construction sub-processes and react to current developments in supply requirements. This approach can mainly be used to spontaneously manage construction site supply during the construction process [7].

Huang is another author that deals with the topic of optimising the productive area of construction sites with regard to construction site supply. He proposes a method for the optimisation of tower crane placement. The study also considers the calculation of the costs for the crane, but it does not deal with its utilisation over time in greater detail. The result is thus not an exact assessment of the efficiency of the use of tower cranes but of their optimum positioning [8].

Research focusing on calculating the optimum position of a tower crane was also carried out by the authors Funtík and Gašparík. The proposed position of a tower crane is evaluated in terms of the transport distance of materials, the length of the jib needed for the delivery of all elements, and the travel time of the crane hook. The evaluated data are then compared with the permitted workload of the tower crane. The result is a map of the evaluated criteria in a coordinate system related to the tower crane. The map indicates the differences between all possible crane positions. It is used as a basis for evaluating an optimum position for the tower crane with regard to the minimisation of transport distances [9].

The papers mentioned above, and others, deal mainly with the optimisation of the productive space at a construction site [10–12], the localisation of machiner, construction site storage areas [13,14] and the planning and optimisation of the delivery and consumption of materials in relation to construction site supply [15–17]. These factors all influence the efficiency of the work of tower cranes on a construction site, but these studies do not deal with the direct evaluation of the efficient utilisation of tower cranes with regard to the specific requirements of construction sub-processes (CSP) and the binding construction time schedule. If construction companies do take the utilisation of tower cranes over time into account, they only use outdated and insufficiently accurate calculation methods.

Previously known calculation methods used for the design and assessment of tower cranes with regard to their efficient utilisation over time and with respect to construction time are based on the insufficiently accurate input information and calculation procedures that are based largely on empirical data and the intuition of experienced experts [3–5,18]. Consequently, the values obtained from such procedures are only very approximate and inaccurate.

A method using the indicator of the number of employees. The number of required cranes is determined according to the number of construction workers whose activity requires support from a crane. Unfortunately, different authors [3,18] give different values. Most often, 10–20 workers per crane are reported. Some sources specify this information according to the structure of the building. The impact of the type and amount of transported material or the type of crane is not mentioned in the literature.

A method using the indicator of the enclosed area of a constructed building per unit of time. It states how many m^3 of enclosed space can be built per time unit (for example, one month) when supplied by one crane. Most frequently, it is stated as 1000 m^3 per one crane for one month [5]. Moreover, in this case, no distinction is made between the types of material or structural system used for the building.

A very approximate method uses the weight indicator of the transported material per unit of time. This indicates how many tons of building material can be transported per time unit (e.g., one month) when supplied by one crane. Different authors [3–5,18] state different values ranging between 300–660 t/month for one tower crane. Again, no distinction is made between types of material and the specific requirements for their supply. These indicators can be rendered more precise by determining the consumption of construction material in t/m^3 of enclosed space for the individual construction type of the buildings [2]. However, the result is once again only indicative.

In the context of sustainable construction criteria, these methods are currently no longer suitable. This is especially true considering today's construction speeds, the high costs associated with the operation of modern construction cranes and the environmental and other economic requirements for construction. New, more precise procedures are being sought to deal with the design and evaluation of the efficiency of the use of construction machinery (not only tower cranes [2,19,20]), using various mathematical models (stochastic, deterministic, heuristic or genetic algorithms) in the context of sustainable construction [21–23].

All these exact approaches based on mathematical modelling of the task require one to start with the careful preparation of the input data and the determination of the boundary conditions of the solution. A possible approach is proposed by Wu et al. There is a link between the project plan and the building materials to be used. The model is based on the selection of information on the vertical transport of building materials, auxiliary materials for construction sub-processes (formwork, scaffolding, sheeting), the generation of information on the vertical transport of construction workers and the determination of the method of vertical transport. The author deals with the quantity and position of materials in the structure and their connection with the time schedule. This is the most important contribution of the work, as it brings a great deal of refinement to the whole calculation. However, it does not perform a detailed analysis of the specific time requirements of the construction sub-processes for tower crane service, relying only on consumption coefficients for estimating the amount of material. This facilitates the preparation of input data, which can then be used for the stochastic or heuristic solution of tasks [24].

Kozlovská et al. compared stochastic and deterministic approaches to the specification of the performance of construction machines. After comparing the two investigated approaches in the case study, the values gained for the performances of the monitored machines were found to be quite comparable. The investigation shows that when the formulas and relationships between variables are more complicated, it can be assumed that the potential of the stochastic approach will be fully exploited. As a result, this approach can be used in cases with more varied input parameters, while the deterministic approach does not reflect the randomness and probability of an event affecting the performance of construction machines. However, if the boundary conditions of the solution are determined exactly and the input data are relatively unambiguous, a deterministic approach can lead to a more accurate result for an investigated task [25].

One example of a stochastic approach to the solution of tasks is the work of the authors Motyčka et al., which comprehensively deals with the issue of the utilisation of tower cranes over time on construction sites. It is the first time that exact evaluation and real supply requirements with regard to the details of construction sub-processes have been dealt with in the literature. The authors describe the effect on supply requirements of fluctuations in the consumption of construction materials and, for the first time, define what can be termed "decisive materials" for tower crane transportation on a construction site. Queueing theory was used to calculate the time requirements for the transportation of needed materials using tower cranes. As part of the calculation, this method determines the time requirements of all construction sub-processes entering the system and the number of all crane cycles in the monitored shift. However, the statistical approach using queueing theory also considers only the average service time of all construction sub-processes in the monitored shift and the average time outside the service system, i.e., the average time of element circulation. It

does not distinguish more precisely between the differences in the time requirements of the individual construction sub-processes entering the system in one working shift. This leads to a certain distortion of the overall results, which the stochastic approach can generally cause [3].

Wu and García de Soto carried out a study in which they propose the spatio-temporal planning of the work of tower cranes. It involves a meta-heuristic algorithm. Generally, such heuristic algorithms are based on the experimental solution of a task and do not necessarily guarantee sufficiently accurate results. An optimisation model was created that considers the forbidden areas for the movement of the crane jib, as well as alternative solutions for the cases of one or more tower cranes. The model allows the display of task scheduling using a 4D simulation in BIM. This enables the intuitive and efficient display of information about the lifted load and the relationships between lifting tasks. The aim is the optimum design of planned tasks in terms of the minimum total working time of the cranes. However, this minimum time may not reflect the actual operating time required, which must also consider the technical aspect of the construction project and the resulting time requirements for the servicing of construction sub-processes [26].

In another study, the same authors, Wu et al., developed their previous solution and present an adapted mathematical model of the spatio-temporal planning of the work of tower cranes, where the input parameters are the specifications of the designed cranes (type, load capacity, reach, height), their number, position and the duration of their use. The proposal aims to optimise the work of previously defined groups of cranes to ensure that they work efficiently. The optimisation model pays special attention to the calculation of delays caused by the waiting of a crane for new transport tasks and the waiting of workers for service from a busy crane. This is a new element that makes the calculation more precise. The result is, again, the minimisation of the construction period and the total construction costs. As with the previous solution, this heuristic approach does not sufficiently take into account the technical aspect of the construction process (for example, the priority servicing of decisive construction sub-processes), which is more important for the quality of the built structure than the minimisation of the construction time [27]. The same authors develop the topic further in their following work, where they focus on monitoring and the use of current requirements for vertical transport during the construction of high-rise buildings [27,28].

The optimisation of tower cranes on construction sites using a planned series of activities prepared for every crane was the subject of research by Tarhini et al. An integer linear programme was developed to deal with the task. Tasks for the server of construction sub-processes are first divided up between individual cranes, after which each individual problem is solved for each crane. The optimisation also takes certain boundary conditions into account, such as the need to avoid the collision of cranes and the need to prioritise tasks. However, it does not consider the possible cooperation of cranes in jointly served parts of the construction site with regard to the technical priority of the construction sub-processes. This can significantly affect the outcome of the task solution [29].

An interesting approach is the work of Petlíkova from the Czech Technical University in Prague, who proposes in her dissertation a neural network application for the standardisation of work and other models realised during the preparatory stage of construction. Models based on neural networks could increase the efficiency of, and optimise, for example, the calculation of the duration of the performance of specific construction processes and the financial costs of their performance. Provided that a sufficient amount of quality input data is available and that further research in the field of neural network optimisation is simultaneously carried out, the procedures presented in the paper could lead to optimal prediction models also in connection with the solution of the efficiency of construction machines [13].

The contribution of Hosang Hyun et al. [30] focuses on the optimal design of cranes to minimise costs. Specifically, the authors focused on minimising the reach of the tower crane. Ju Yong Kim et al. [31] focused on minimising safety risks when deploying cranes

on a construction site. In this paper, the authors analysed the key factors leading to the minimisation of safety risks in the process of assembly work. Danel et al. [32] analysed key input data related to the optimal design of cranes on site and proposed a methodology for measuring productivity in construction assembly processes.

The new method for assessing the effective use of tower cranes in the construction of reinforced concrete monolithic structures presented in the next part of the paper follows on from previous solutions and both develops and adds specificity to that body of work in certain aspects. The refinement is based on several factors. The mathematical simulation model is based on a deterministic modelling approach. This allows more accurate results to be achieved, requiring more exact input data. Therefore, a standard tower crane operating cycle was created and a method of calculating the operating cycle duration of the crane, t_c, was determined. A detailed analysis of a CSP was created, first theoretically and then for a specific CSP. Their selection, analysis, classification into groups according to the crane load and the method of crane operation requirements were performed. Due to the use of deterministic mathematical modelling, boundary conditions and simplifying assumptions for solving the problem were defined. With regard to the construction technology, CPS service priorities were set as a fundamental principle of the model. All the source materials necessary to determine more accurate input data are available in the construction technology documentation of the building project and, for example, in the BIM model of the structure.

The proposed method has also been prepared for rapid operational use in the form of a computer (software) application, and it can be used via an internet browser.

3. Procedure for the Development of the Proposed Method

The work on the proposal and development of the method for assessing the utilisation over time of tower cranes according to the priorities of CSP in the construction of monolithic reinforced concrete structures was divided into two basic parts. The work in both areas took place almost simultaneously because, in particular, the monitoring of construction sub-processes at real construction sites is very time-consuming.

In the first part of the task called "the preparation of input data", we concerned ourselves with the creation of the boundary conditions for the investigated task and the process of preparing and creating input data for use in the new simulation model. It was necessary to analyse the course of construction of monolithic reinforced concrete buildings, and so a standard tower crane work cycle was created along with an analysis of CSP used to create the fabric of a monolithic reinforced concrete structure. Simultaneously, the course of construction sub-processes monitored selected reinforced concrete structures, in this case, monolithic reinforced concrete multi-storey buildings. This type of structure was chosen because of the diversity of the construction sub-processes that occur during construction and also due to the frequent use of this type of structure in the construction of buildings in densely built-up large cities. Subsequently, comparison and assessment were performed with regard to the theoretical analysis of individual construction sub-processes and the results of the inspection monitoring of the provision of service to construction sub-processes using tower cranes on specific construction sites.

In the second part of the task—called simulation modelling—we focused on the creation of a simulation model for assessing the utilisation over time of tower cranes, on its incorporation into the method for assessing the utilisation of tower cranes over time, and on the creation of computer support for its practical use in the pre-construction phase. A simulation model was created for the prediction of the work of tower cranes. It is assumed that the construction and thus also its supply proceeds according to a binding schedule [3]. Therefore, at this stage, a construction schedule analysis and a network analysis using the CPM (Critical Path Method) are performed to support the creation of a simulation model [4]. The input data for mathematical modelling during the creation of a simulation model are obtained from this analysis. The mathematical modelling was performed in the MATLAB environment. Subsequently, a computer application was developed for practical use.

4. Boundary Conditions of the Task and the Preparation of the Input Data for the Simulation Model

It is very difficult, or rather impossible, to accurately predict the requirements of the various construction sub-processes served by tower cranes in terms of the amount of material being moved in connection with the time required for tower crane service. We tried to simulate the real work of cranes on a construction site as closely as possible with the simulation model. For mathematical modelling, it is necessary to clearly define the assigned task, determine the preconditions for the investigation, which will help us simplify the whole task, and prepare the input data for the model so that they are mathematically graspable within the model.

The task was thus to create a tool to assess whether a tower crane (or a set of them) can service all the requirements of a construction sub-process in the required time set in the binding work schedule. The following boundary conditions and simplifying preconditions for the investigation of the task were determined:

- We always evaluate a fixed time interval—we assess the degree of construction progress or the technical stage of the construction, where the unit interval most often equals the time of one work shift;
- We assume the course of construction and the collection of material will both occur smoothly;
- We work with the binding work schedule, which is set out at the construction sub-process level;
- We monitor the construction sub-processes which are regularly served by a crane in the monitored time interval;
- There is a finite number of monitored construction sub-processes in this time interval;
- The concurrencies of the monitored construction sub-processes are known;
- Each monitored construction sub-process runs continuously throughout the assessed time interval;
- The crane always transports a unit amount of material corresponding to the construction sub-process served;
- A standard work cycle is produced for every monitored construction sub-process (explained in more detail below);
- The basic version of the simulation model does not consider random effects.

4.1. The Standard Work Cycle of a Tower Crane

To determine the total work cycle time t_c we use the standard work cycle of a tower crane (Figure 1). This involves the determination of a period which includes the transfer of material from the place of storage to the place of deposition or assembly in the building, including the hooking and unhooking of the load and the possible assistance of the crane during construction sub-processes.
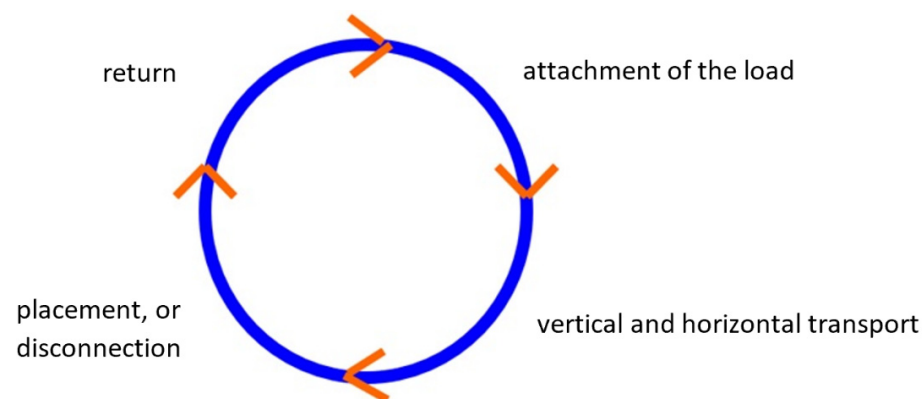

Figure 1. Basic division of the work cycle of a crane.

The binding work schedule, prepared at the CSP level, shows the required speed of construction, material consumption and time in the monitored time interval (e.g., work shift). It is assumed that the crane always transports a unit amount of material corresponding to the CSP served. This determines the work cycle of each specific CSP. We can define it as a time interval in which a unit amount of material is delivered by a crane for this CSP. The duration of one work cycle of a monitored CSP, marked as T, is defined as the sum of time t_c, i.e., the total time required by a tower crane to service a CSP in one work cycle, and time t_p, the time during which work on the CSP takes place without the provision of service by a construction crane. Thus, the large T means the time interval between demands for the delivery of a unit quantity of material for a particular CSP, and it expresses the following relation (Figure 2):
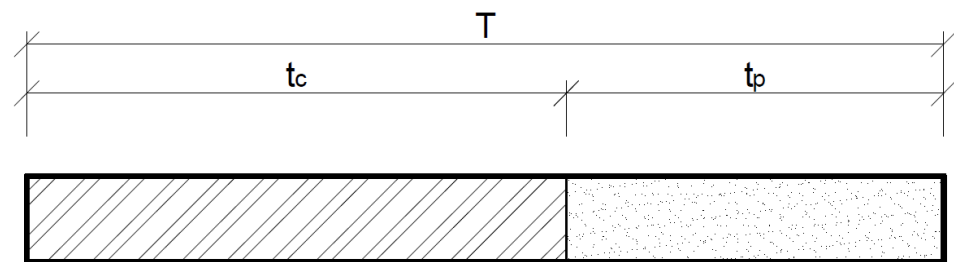
$$T = t_c + t_p \tag{1}$$

Figure 2. The duration of a CSP work cycle designated T is the sum of the total time needed for the CSP to be serviced by a tower crane, t_c, and the time work takes place on a CSP without service from a tower crane, t_p.

T—the duration of the work cycle for a CSP,
t_c—the total time needed for a tower crane to service a CSP in one work cycle,
t_p—the time for which work on a CSP takes place without service from a construction crane.

To determine the values t_c and t_p of the decisive CSP, their theoretical analysis was carried out and subsequently verified during the monitoring of several ongoing construction projects.

The tower crane work cycle time t_n needed for a tower crane to service one work cycle of a CSP has to be divided into a period for the transport of material using the crane, t_j, the time for hooking and unhooking the material t_m and possibly the time during which the crane assists in work on the monitored construction sub-process, t_a (if it takes place during the monitored construction sub-process). It is shown schematically in Figure 3.
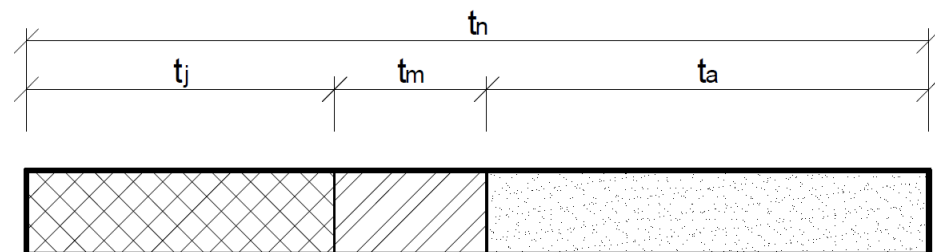

Figure 3. The standard work cycle of a tower crane t_n.

When calculating the total time of a tower crane work cycle, designated as t_c, the objective and subjective influences of working conditions for the given tower crane (e.g., material properties, the technical influence of the serviced process, the spatial structure of the construction site, weather influences, the quality of the machine operator) are taken into account. These influences on work are taken into account via the coefficient k_s and can be considered according to [5,18] in the following chart (Table 1).

Table 1. Values for the coefficient of influences on work k_s.

Construction Sub-Process	Values for the Coefficient of Influences on Work k_s
Concreting—solid structures	1.1
Concreting—thin-walled structures	1.4
Reinforcement	1.1
Formwork	1.2
Removal of formwork	1.1
Assembly of elements	1.2

The total time of the work cycle tc can be expressed with the relation:

$$t_c = k_s + t_n \tag{2}$$

t_c—is the total time needed for service from a tower crane in a construction sub-process in one work cycle,

k_s—is the coefficient of influences on work,

t_n—is the time required for the tower crane to service a CSP in one work cycle according to the following relation.

$$t_n = t_j + t_m + t_a \tag{3}$$

t_j—is the time needed to move a unit of material,

t_m—is the time required for hooking and unhooking the material,

t_a—is the crane assistance time in one work cycle.

The value for the transfer of a unit of material "t_j" can be determined with respect to known input values, such as the hoisting speed of the tower crane, the speed of travel of the trolley along the jib and the rotation speed of the tower. The calculation must be based on the available data provided by the manufacturer of the selected crane type and the layout of the construction site, or on the standard work cycles of the tower crane [3].

On the other hand, the time for hooking and unhooking the material "t_m" and the actual value of the crane assistance time "t_a" cannot be determined via calculation. Therefore, it is necessary to use only monitoring of these construction sub-processes on construction sites. The t_m values for the selected CSP were taken from [5].

The evaluated times needed for the hooking and unhooking of selected materials are summarised in the Table 2.

Table 2. Approximate values for the time tm required for the hooking and unhooking of selected materials from the crane hook.

Type of Transported Material	Unit to Be Moved	Time t_m for Hooking (Loading) + Unhooking (Unloading) (min.)
Pallets with masonry material	One pallet	2.0
Formwork	Elements—moved in bulk	3.0
Formwork	Large-format, pre-assembled elements, moved individually	up to 10 min.
Reinforcement	Rods in a package	3.0
Reinforcement	Reinforcement meshes	2.0
Fresh concrete-solid structure	Container holding up to 0.5 m^3	1.5
Fresh concrete—thin-walled structures	Container holding up to 0.5 m^3	2.0
Fresh concrete-solid structure	Container holding up to 1.0 m^3	3.0
Concreting—thin-walled structures	Container holding up to 1.0 m^3	03.V
Ceiling panels	One piece	3.0
Elements—the crane does not ensure stability during installation	One piece	Up to 6 min.
Elements—the crane ensures stability during installation	One piece	10–30 *

* The value depends on the specific type of element and the installation technique.

Calculation of the duration of a tower crane work cycle t_n is performed using the critical path method [5] shown schematically in Figure 4.

Cycle sub-stages [min.]	1	2	3	4	5	6	7	8
Loading of a container	▮	▮						
Lifting of the hook			▮					
Crane travel			▯					
Jib rotation				▮				
Trolley travel				▯				
Lowering at load delivery speed					▮			
Unloading of a container						▮		
Lifting of the hook after unloading							▮	
Jib rotation							▮	
Pulley travel								▯
Crane travel								▯
Lowering of the hook								▮

Figure 4. Schematic representation of the calculation of a tower crane work cycle t_n using the critical path method (red colour), processes out of the critical path (yellow colour).

4.2. Analysis and Determination of the Duration of Construction Sub-Process Work Cycles Serviced by a Tower Crane

To be able to assess the utilisation of a crane over time accurately, it is not possible to rely only on indicative methods and approximate indicators—it is necessary to deal with the construction process in more detail and especially the more detailed requirements for the secondary supply of the construction site at the construction sub-process level.

All construction sub-processes requiring service from a crane, or materials that are transported by tower cranes, are divided into three basic groups according to the nature of their supply requirements.

1. The group of construction sub-processes that require virtually continuous crane use during their execution (e.g., installation work or concreting). The following thus applies to this construction sub-process group:

$$T = t_c \tag{4}$$

T—is the duration of one cycle of the construction sub-process, when a unit quantity of transported material is delivered by a tower crane and used by a work team is the time needed to move a unit of material,

t_c—is the total time needed for a tower crane to provide service to a CSP in one work cycle.

2. The CSP group does not need a crane to be deployed throughout the duration of the work cycle T, but only in a part of the work cycle. It needs cyclic deliveries of unit quantities of materials at certain recurring time intervals. The majority of construction sub-processes during the erection of buildings are serviced in this way. Relation (1) applies to this group of construction sub-processes.

3. The group of construction sub-processes which have irregular and unpredictable crane service requirements (this may include, for example, the supply of machinery or unplanned movements of material).

Therefore, it is important to select the crane-serviced construction sub-processes and sort them into these three groups to prepare the input data for the simulation model. Furthermore, it is necessary to determine the number of work cycles needed for the individual selected construction sub-processes in the monitored interval (work shift) and the resulting values for T, t_c and t_p.

For the construction sub-processes in the 1st group, we will consider the value $t_p = 0$, the value t_c thus being equal to the value T according to relation (1).

The time requirements of the construction sub-processes, which belong to the 3rd group, will be considered in the final calculation of the utilisation of the tower crane over time with the coefficient $k_3 = 0.1$. The value of the coefficient is based on [4] and represents about 10% of the utilisation of the crane over time. For these time requirements, possible crane idle times during the assessed time interval (work shift) can be used.

A substantial part of all construction sub-processes occurring at construction sites belongs to the 2nd group. This also applies to the decisive construction sub-processes taking place when building the fabric of a monolithic reinforced concrete structure. This involves construction sub-processes that are supplied in regular time intervals, i.e., cyclically. An important task is thus to determine the values t_c and t_p for the 2nd group of CSP.

The decisive CSP during the erection of the fabric of a monolithic reinforced concrete structure which are dependent on the supply of material by tower cranes, are

- Execution of formwork;
- Reinforcement of structures;
- Concreting;
- Removal of formwork;
- Masonry.

The CSP work cycle, which is marked with T, is defined by the time required for the movement t_c and processing t_p of a unit quantity of material or any structural component that is transported by the tower crane to the installation site in one crane work cycle.

For a theoretical analysis of the requirements of decisive CSP for the supply of materials, data and standard values related to time consumption for individual CSP are used, and a binding construction schedule is created according to them.

Based on the standard time consumption for performing a unit quantity of a CSP and based on specified unit quantities of material to be moved by a tower crane for individual CSP, the number of required work cycles can be derived for a given time interval (e.g., in one work shift). We assume that the work proceeds smoothly according to the schedule.

The construction schedule is a binding document for the building contractor. It shows the required speed of construction and, at the CSP level, the consumption of material over time in the monitored time interval. If this document is not prepared for the construction project to the required level of detail for construction sub-processes, it must be prepared using network analysis and suitable computer software.

It is assumed that the crane always transports a unit amount of material corresponding to the construction sub-process served. This determines the work cycle of each specific construction sub-process. We can define it as a time interval in which a unit amount of material is delivered by crane for this construction sub-process. Thus, the large *T* represents the time interval between the individual requirements for the delivery of a unit quantity of material of a particular CSP. Relation (1), which was mentioned earlier, applies.

The analysed data for the individual CSP include:

- The amount of work, or the amount of material being moved in the evaluated unit time interval (e.g., one work shift);
- The unit quantity of material transferred by crane;
- The number of CSP work cycles in the evaluated time interval;
- Time T, i.e., the duration of one work cycle of the monitored CSP;
- Time t_c, which is required for the tower crane to serve the CSP in one work cycle;
- Time t_p, for which work on the CSP takes place in one work cycle, without service from a construction crane;
- The priorities of the individual CSP (determination of the priorities of the individual construction sub-processes will be described below).

The amount of work and thus also the total amount of material transferred for each construction sub-process in the assessed unit time interval (work shift) is clear from the

schedule and material consumption for the decisive CSP. The method and unit amount of the material transfer for each CSP is usually given by the manufacturer of the material, so it is a known value. This also shows the number of work cycles for each CSP in the assessed unit time interval (e.g., in one work shift).

To refine the input data of the simulation model, a distinction is made between construction sub-processes that require crane assistance in addition to the transfer of materials (i.e., it is a matter of determining the time t_a) and construction sub-processes which do not require crane assistance in addition to the transfer of materials.

To decide whether a construction sub-process is without crane assistance or with crane assistance, a detailed analysis of the work tasks (processes) of the construction sub-processes needs to be carried out and the option of crane assistance then assigned where needed.

Vertical and horizontal structures were analysed in more detail for the decisive CSP during the erection of the fabric of a monolithic reinforced concrete structure with regard to the time requirements for tower cranes. Calculations of the values T, t_c and t_p were carried out (Table 3). The calculation is performed with an accuracy of ± 1 min.

Table 3. Calculated values of the construction sub-process work cycles during the building of the fabric of a monolithic reinforced concrete structure (calculated for a 12-h work shift).

Construction Sub-Process	T (Min)	t_c (Min)	t_p (Min)	C (Number of Cycles)
Wall formwork (frame)	48	7	41	15
Disassembly of wall formwork	29	9	20	25
Reinforcement of walls	180	6	174	4
Concreting of vertical walls using concrete buckets	28	28	0	26
Ceiling formwork (beam)	144	6	138	5
Disassembly of ceiling formwork	90	6	84	8
Reinforcement of the ceiling structure	240	6	234	3
Concreting of ceiling using concrete buckets (concrete bucket 1 m^3)	55	55	0	13
Masonry of load-bearing walls	65	6	59	11
Installation of a flight of stairs	90	90	0	8

4.3. Monitoring the Course of Decisive Construction Sub-Processes at Ongoing Construction Projects

To verify the real behaviour of tower cranes when supplying CSP and to compare the time consumed by the servicing of real CSP with theoretically determined values, the work of tower cranes has been monitored continuously since 2017 during the construction of the monolithic reinforced concrete structures of buildings (residential and multifunctional buildings).

So far, over 100 work shifts (or parts of them) have been monitored and evaluated. The monitoring is performed using time-lapse cameras (BRINO Construction Camera Pro BCC200) installed on construction sites. The time-lapse images are recorded at 1.0 s intervals.

Primarily the construction sub-processes considered to be decisive (see the previous chapter) are monitored in connection with the values t_c, t_p and T, which are then transferred from the time-lapse recording to what is known as the two-level form.

The individual monitored time-lapse images and recorded files are progressively saved on a server from where the recordings can be viewed and evaluated. Evaluated forms are also stored on the server.

From the data measured and evaluated so far and their comparison with the calculated values, it can be stated that the calculated and measured values for the crane work cycles t_c show only very small differences with regard to the service of the monitored construction sub-processes, while the construction sub-process work cycle time marked T differed quite

significantly. This difference between the theoretical and measured values for T is mainly due to the smaller amount of transported material within one work cycle of the crane than is considered for the unit amount of material transfer.

5. Simulation Model for the Work of a Tower Crane and Its Software Processing

The task of the simulation model is to predict the actual work of tower cranes on a construction site based on input data and determining boundary conditions (Section 4). The output is an evaluation of whether the assessed tower crane can meet all the service requirements of the served construction sub-processes with the required time, set by a binding work schedule.

The evaluation is therefore based mainly on the binding construction schedule. Other input information for the calculation of the simulation model is given in Table 4.

Table 4. Other input information for the calculation of the simulation model.

The specified evaluated part of the structure or building (degree of progress on the construction, technical stage)
The assessed unit time interval (most frequently one work shift)
The specification of construction sub-processes that require tower crane service in the evaluated unit interval
The concurrencies of individual construction sub-processes in the assessed unit time intervals (e.g., in one work shift)
The analysed data for the individual construction sub-processes

The mathematical simulation model of the servicing of construction sub-processes by tower cranes on a construction site was created based on assumptions and predictions concerning the decisions which an employee in charge (the construction manager or the coordinator for the secondary supply of construction material) would make when coordinating the work of cranes on a construction site.

Priorities for servicing individual construction sub-processes with a tower crane are given in Table 5.

Table 5. Priorities for servicing individual construction sub-processes with a tower crane.

1.	Technical justification for the first construction sub-process priority (e.g., concreting using concrete buckets, installation of prefabricated elements)
2.	Construction sub-processes which are on a critical path in the schedule (network graph)

If it is necessary to decide between multiple construction sub-processes which are on a critical path, the next order of priorities is determined as follows:

(1) The construction sub-process cannot be pre-stocked
(2) The construction sub-process is a controlling process (decision between construction sub-processes in the same work engagement)
(3) The construction sub-process takes place in a work engagement with an earlier completion date (the assessed construction sub-processes are in a different work engagement)
(4) The construction sub-process can be pre-stocked

3.	Construction sub-processes that are not on a critical path in the schedule

If it is necessary to decide between multiple construction sub-processes which are not on a critical path, the next order of priorities is determined as follows:

(1) The construction sub-process has a shorter time reserve in the schedule
(2) The construction sub-process has a longer time reserve in the schedule

The stated order of priorities for the individual construction sub-processes served by tower cranes is recommended to calculate the simulation model and thus newly selectable

for each calculation. It can be entered during the pre-construction phase to calculate the assessment of the utilisation of the tower crane over time as input information [3].

The assessed unit time interval is most frequently one work shift. For this one work shift, construction sub-processes, which are served by the tower crane, are specified. There is a finite number of these construction sub-processes, which are analysed and prepared for the simulation model as stated in Section 4. The result is an evaluation of each construction sub-process with three time intervals, which we label T, t_c and t_p, where the smallest unit of time is one minute. Their priority for providing tower crane service is set (see above). At the beginning of the shift (in the first "starting step" of tower crane service), all construction sub-processes which require service are served in the order of the pre-set priorities (i.e., without the option of servicing a certain construction sub-process again before servicing all of the other construction sub-processes first). In the second and subsequent steps, the construction sub-processes are served only according to the specified priorities. This means that at the moment when a construction sub-process with a higher priority requires service, it is served preferentially, providing the tower crane has "free capacity". This occurs during the evaluated work shift until all requests for tower crane service in all construction sub-processes in the given shift have been carried out. The result is the total time needed to service all construction sub-processes (CSP) that require tower crane service. It is evaluated and compared with the length of the work shift.

A computational mechanism (algorithm) was developed, which allows the described task to be solved mathematically and implemented within the MATLAB environment.

This algorithm was subsequently transferred to the PHP environment and a web application with the title Crane Occupancy 0.4 was created for simple, practical use in a web browser during the preparation of construction projects. The following figure shows the user interface of this computer application.

The computer program can be used by construction contractors to quickly assess the utilisation of a tower crane over time in connection with the contractual binding schedule. This utilisation over time of a tower crane can be assessed spontaneously both for individual work shifts and also for individual technical stages or the entire course of construction.

The length of the work shift is entered into the Crane Occupancy 0.4 application and also the parameters of the individual CSP which are served by the tower crane are entered in the prepared table, see Figure 5. These basic parameters include the order in which the CSP are served by the crane (operator priorities) and an additional requirement for the work cycle of each individual CSP is its division into durations of work with a crane (t_c) and without a crane (t_p), alongside the total amount of material for each CSP for each shift and the total number of cycles for each CSP planned for one shift. The priorities for CSP servicing can be freely entered and changed.

Priority	Color	CSP	Operation	t_c	t_p	T	Amount of work [meas. unit/shift]
↓ 1 ↑	■ ⌄	CSP ⌄	Formwork	2	4	6	2
↓ 2 ↑	■ ⌄	CSP ⌄	Reinforcement	1	3	4	2
↓ 3 ↑	■ ⌄	CSP ⌄	Concreting	2	4	6	2

Figure 5. Screenshot of the software—input modelling data for the evaluated construction sub-processes for the work shift calculation.

An example of part of the graphic output for an evaluated work shift is shown on Figure 6.
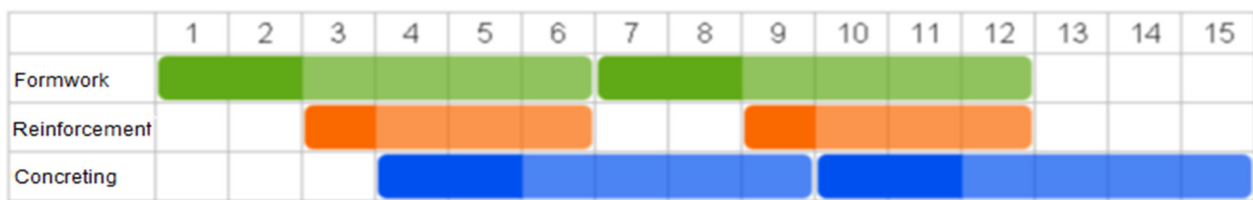
Figure 6. Screenshot of the software—an example of part of the graphic output for an evaluated work shift.

Based on the mathematical simulation model, the resulting time required to serve all the entered CSP is graphically and computationally displayed and compared and evaluated with the total length of the work shift. The result is the total time the crane is used in this shift and its expression as a percentage.

After the preparation of the input data for the served individual CSP, these input data can be stored in database software for further re-use in the evaluation of tower crane utilisation and other stages of the construction process or other building projects.

6. Method for Assessing the Utilisation over Time of a Tower Crane on a Construction Site and Its Verification

The next part presents a method for assessing the utilisation over time of a tower crane on a construction site. It is based on the aforementioned simulation model and can be used in the pre-construction phase. The data needed for its use are available in the documents for a given construction project and can be directly available from the BIM.

The necessary materials for assessing the utilisation of tower cranes over time according to the priorities of the construction sub-processes are the detailed project documents, the list of necessary materials for the assessed part of the construction project and the time schedule in the details of the construction sub-process.

The assessment process takes place in the following individual steps [32]:

1. Determination of the building site, structure or technical stage of construction to assess the utilisation of tower cranes over time.
2. Preparation of the input data

It is based on the contractual schedule of the assessed part of the construction project. It is created using network analysis, processed using the CPM method in the details of the aggregated construction sub-processes.

If the construction schedule is produced only at the stage process level, it is necessary to calculate it with a time breakdown for one work shift and to break it down factually into details for each of the individual CSP.

Next, the CSP requiring tower crane service are allocated and analysis data are determined for these individual sub-processes, as described in Section 3.

The construction sub-processes which need to be served by a tower crane for an individual shift, i.e., the construction sub-process requirements for crane service during one work shift, become apparent from the binding construction schedule.

3. Setting service priorities

The order of priorities to be set for all combinations of construction sub-processes for each work shift of an assessed technical stage of construction is detailed in Section 4. This order can be chosen at one´s own discretion when preparing to assess tower crane utilisation.

4. The calculation of the utilisation of a tower crane over time using a simulation model

For individual work shifts, the input data for the evaluated construction sub-processes are entered into the Crane Occupancy 0.4 application for the calculation of crane utilisation, and the duration of the evaluated work shift T_s is calculated, as well as the total time the crane is used in this shift T_j, with its expression as a percentage.

The options for the pre-supply of some construction sub-processes and the use of crane idle times for the service of construction sub-processes from the 3rd group (the group of sub-processes which have irregular and unpredictable requirements for crane service—see Section 4, which are taken into account via the coefficient $k_3 = 0.1$) are assessed and the utilisation of the tower crane by the 3rd group of construction sub-processes is taken into account.

The following relation applies to the calculation of the total work shift time, with consideration given to the serving of construction sub-processes from the 3rd group:

$$T_\Sigma = k_3 \cdot T_s + T_s \tag{5}$$

T_Σ—the total duration of the evaluated shift,

k_3—coefficient taking into account the handling of irregular or unpredictable requirements,

T_s—the duration of the work shift according to the calculation for the planned servicing of the construction sub-process.

If the utilisation of the tower crane is less than 90%, the construction sub-processes classified in the 3rd group can be served during crane idle times crane and coefficient k_3 does not need to be considered in the calculation.

7. Evaluation of the Results

The results of the outputs from the Crane Occupancy 0.4 application must be evaluated and a conclusion must be drawn with regard to the investigated task. The assessment and evaluation of the results are carried out by each employee involved in the pre-construction phase at their own discretion, preferably in consultation with the site manager. The following recommendations can be followed:

If a work shift is extended as a result of tower crane utilisation, the following approaches are possible:

- Consider whether an extension of the work shift of the necessary scope is possible;
- Pre-stock the construction sub-processes, where possible, with the required material;
- Propose a work shift extension or two-shift operation for a selected part of the assessed construction period, or the entire period;
- Propose another tower crane for a selected part of the assessed construction period, or the entire period.

The verification of the proposed method took place via a case study—two five-storey monolithic reinforced concrete buildings with masonry partitions, served simultaneously by one Liebherr 71 K tower crane. The layout of both buildings is very similar. Site plan for the investigated case study is shown on Figure 7.

The following table (Table 6) documents the output values for data evaluated by the Crane Occupancy 0.4 application for a part of the period considered in the case study. Each evaluated day represents one work shift. The table shows the total shift time in minutes, which is required for the planned work in the monitored shift, with regard to the provision of service to all the requirements of the construction sub-processes for crane operation. Other data show the net time the crane is in use during the monitored shift and also the time when coefficient k_3 is taken into account, i.e., when unforeseen requirements are considered (this was described in Section 6). The time data are given in minutes. The next part of the table shows the crane utilisation values during the monitored shift, expressed as a percentage.
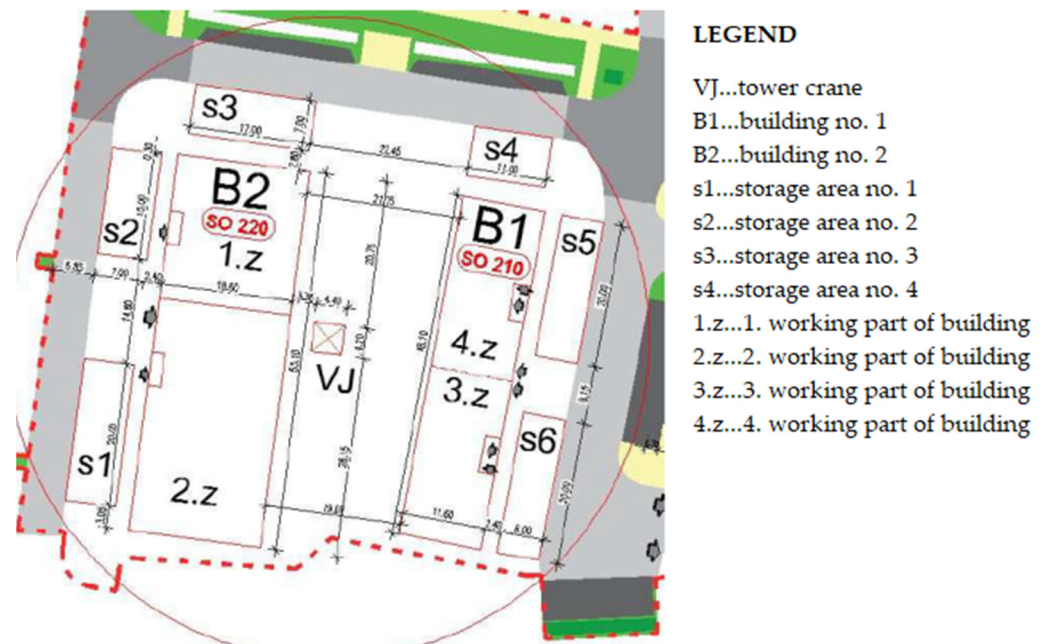
Figure 7. Site plan for the investigated case study.

Table 6. Example of results evaluated for a part of the assessed period of the construction of two buildings; the planned work shift length is 720 min.

Evaluated Day		Total Time (min)	Crane Usage Time (min)		Crane Usage Percentage (%)	
Date	Day of the Week		SW Crane Occupancy 0.4	After Taking into Account the Coefficient k_3	SW Crane Occupancy 0.4	After Taking into Account the Coefficient k_3
15 June 2020	Monday	732	66	72.6	9.02	9.92
16 June 2020	Tuesday	732	66	72.6	9.02	9.92
17 June 2020	Wednesday	732	66	72.6	9.02	9.92
18 June 2020	Thursday	732	66	72.6	9.02	9.92
19 June 2020	Friday	732	90	99	12.3	13.52
22 June 2020	Monday	726	42	46.2	5.79	6.36
23 June 2020	Tuesday	727	123	135.3	16.92	18.61
24 June 2020	Wednesday	1214	746	820.6	61.45	67.59
25 June 2020	Thursday	720	18	19.8	2.5	2.75
26 June 2020	Friday	732	150	165	20.49	22.54
29 June 2020	Monday	732	150	165	20.49	22.54
30 June 2020	Tuesday	759	333	366.3	43.87	48.26
1 July 2020	Wednesday	1402	842	926.2	60.06	66.06
2 July 2020	Thursday	732	114	125.4	15.57	17.13
3 July 2020	Friday	738	162	178.2	21.95	24.15
6 July 2020	Monday	755	210	231	27.81	30.60
7 July 2020	Tuesday	738	138	151.8	18.7	20.57
8 July 2020	Wednesday	747	219	240.9	29.32	32.25

Table 6. *Cont.*

Evaluated Day		Total Time (min)	Crane Usage Time (min)		Crane Usage Percentage (%)	
Date	Day of the Week		SW Crane Occupancy 0.4	After Taking into Account the Coefficient k_3	SW Crane Occupancy 0.4	After Taking into Account the Coefficient k_3
9 July 2020	Thursday	738	138	151.8	18.7	20.57
10 July 2020	Friday	738	219	240.9	29.67	32.64
13 July 2020	Monday	750	243	267.3	32.4	35.64
14 July 2020	Tuesday	1420	866	952.6	60.99	67.08
15 July 2020	Wednesday	744	219	240.9	29.44	32.38

These results show that during the documented month, the working hours were used to the maximum extent. There was a significant extension of the work shift in the case of three working days (24 June 2020, 1 July 2020 and 14 July 2020) due to the concurrent requirements of some construction sub-processes for service from a crane. At the same time, the tower crane utilisation is only somewhat over 60%. In this situation affecting the three work shifts, a suitable proposed solution is to pre-supply the required construction sub-processes whose nature enables this, which could be done even during the work shifts.

8. Discussion

The impulse for the development of a solution to this task was the fact that the methods currently used in industry practice for the evaluation of technical performance have become outdated, inexact and unsuitable. They are founded on the empirical observations and intuition of experienced experts and are described in [3–5,18,33].

Our first attempt at research in this direction was the work Motyčka et al. [3], which is based on a stochastic approach using queueing theory, though it only deals with the average service time of all CSPs. This led to imprecise evaluation results. Therefore, we searched for new impulses and approaches to dealing with the task.

These are contained in the research of Wu et al. [24,26,27], which is based on the construction schedule of a building project, and the related requirements for the supply of construction materials. The optimising mathematical model devotes particular attention to calculating delays caused when workers are forced to wait for service from a busy crane. This is where our model is similar. In comparison with the method we developed, Wu et al. do not deal with a detailed analysis of the amount of conveyed material, as in their research, it is determined via the use of a consumption coefficient. This may lead to imprecision in their results. Our refinement also occurs due to the detailed analysis of the CSP, which we divide into parts with and without service from a tower crane. This enables concurrent demands from the CSP for service from a tower crane to be monitored and evaluated.

The work of Tarhini et al. [29] is a beneficial and inspiring piece of research. In their deterministic mathematical model, they determine the boundary conditions for the research. These include the prevention of crane collision and the setting out of service task priorities. A question still remains with regard to parts of the construction process in which service is provided by two cooperating cranes. This remains unresolved from the perspective of the priorities for the service of individual CSPs.

It would seem that the use of neural network applications is a very inspiring approach with regard to future developments in this field. The limiting factor is the necessary amount of input data. This is apparent from the work of Petlíková [23].

It can be stated that the presented method of evaluating the utilisation over time of tower cranes during the construction of monolithic reinforced concrete buildings brought the expected results and can be used effectively in practice. The main benefit of this method is the new simulation model compiled in connection with a network construction graph and with regard to the detailed analysis and prediction of CSP service priorities. It uses

exact input data which is available in the project documentation. These new elements are important for the accuracy of the evaluated utilisation over time of cranes. Case studies were employed to test if the evaluation results are in accord with the real situation as regards the utilisation over time of tower cranes. Obviously, the boundary conditions and simplifying assumptions used for the solution of the mathematical simulations affect the precision of the results. However, from the case studies, it was clear that this effect was not significant and that it does not limit the general use of the method. The evaluation method was presented for constructing a monolithic reinforced concrete structure, but it is also possible to use it for other structural systems successfully after analysis and the preparation of other CSPs.

9. Conclusions

The construction industry has had a significant and long-term negative impact on the state of the environment and so it is necessary to look for possible ways and means to achieve the elimination of its strongly negative effects.

Sustainable construction demands new requirements and approaches to the preparation, implementation and operation of buildings so that structures are functional and fulfil stipulated requirements and environmental, social and economic criteria.

The efficient use of construction machinery, including tower cranes, plays an important role in fulfilling the environmental and economic requirements of sustainable construction during the construction process. Such machines directly affect the productive space of the construction site, labour productivity and construction time, i.e., the environmental and economic criteria of sustainable construction.

The proposed method for the assessment of the utilisation of tower cranes over time according to construction sub-process service priorities is a contribution to a solution for the optimum use of the productive space of the construction site and the construction period in the area of the optimisation of the on-site supply of production sub-processes by tower cranes. A method was created for an exact approach for assessing the utilisation of cranes over time—for a specific construction site, carried out at a specific location, using a given technology and within a fixed deadline. The method is based on a detailed data analysis of a specific building site, allowing for more accurate results. The prediction of the servicing of a CSP by a tower crane, which is the basis for creating a deterministic simulation model, can be considered a new contribution to the theoretical field.

With regard to their application in construction practice, the results of this work provide a qualified crane selection and evaluation method for use during the pre-construction phase, which considers the required speed of execution of a given building project.

Work on developing the presented methods and software for evaluating the utilisation over time of tower cranes on construction sites is continuing. Currently, another developmental model is being developed and prepared. It is the fifth in a row and it primarily improves the usability of the user interface and facilitates the work of the user when entering input data. In comparison with other approaches and models by other authors which are available and mentioned in this contribution, "Crane Occupancy 0.4" software is able to obtain more precise results concerning the utilisation over time of cranes on a construction site. This is due to the deterministic approach of the mathematical modelling software, which requires calculations to be supplied with specific and precise input data. This may be more difficult and time-consuming in comparison with other models, but the result is not as burdened with inaccuracies arising during the entering of data as in the case of other software.

The presented new method for the assessment of the effective use of tower cranes on construction sites and its related application, Crane Occupancy 0.4, which was developed as software for use in digital environments, is a contribution to the development of digital technologies in construction as well as smart construction sites.

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