

Analysis of construction sub-processes for the evaluation of the real performance of tower cranes

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Abstract. The productivity of work performed at construction sites is primarily dependent on the effective deployment and use of construction machinery. Nevertheless, manufacturers do not state the actual performance of their machinery because it is difficult to determine due to its dependence on the specific conditions present at each construction site. One of the most important machines used in the construction of buildings is the tower crane, which provides secondary transport of material onsite. In order to evaluate the effectiveness of the use of such machines using a deterministic or stochastic approach, a relatively extensive and exact set of data describing the activities of a given tower crane needs to be prepared. These data describe the real requirements of ongoing construction sub-processes with regard to the utilisation of tower cranes. This contribution concerns the analysis of key construction sub-processes during the building of monolithic reinforced concrete structures in connection with secondary transport at the construction site; in particular, it describes the preparation and processing of this data for the evaluation of real time requirements placed on tower cranes.

1. Introduction

Current modern technical construction processes cannot function without the performance of detailed planning and careful preparation before building production commences. An important aspect of these technically-focused preparatory activities is the creation of a time schedule, and the related effective deployment of construction machinery. This has a direct and significant effect on the smoothness and course of the entire construction project, and thus also the overall financial costs of the undertaking.

A number of approaches have been developed that design and optimise methods and procedures for the effective use and deployment of machinery in construction. The proposals deal with the optimisation of the location of construction machinery (tower cranes in particular in the case of building construction), and also with the effective deployment of machinery in terms of time, performance and thus also financial costs. In order to be able to assess the work efficiency of construction machines and their real work performance, it is no longer possible to rely solely on indicative methods and approximate indicators.

An example of the existing work dealing with this issue is the contribution by Ch. Huang, Optimal Selection and Location of Tower Crane for the Construction of Prefabricated Buildings with Different Prefabrication Ratios. This study presents a method for the selection and optimisation of the placement of a tower crane in relation to the prefabrication ratio in order to reduce costs and construction time. The study



proposes a model and algorithm aimed at determining the scope of crane deployment based on the localization relationship between the location of the crane and the source and destination of the prefabricated load, as well as the prefabrication ratio. The prefabrication ratio P of a building is defined as the ratio of the weight of the prefabricated components in the concrete structure to the total weight of the building. Other input parameters are the lifting capacity of the crane and the weight of the lifted load. The study also includes the calculation of crane costs and the calculation of load lifting time [1].

In his article, author S. M. Biju describes a newly developed application, “Crane Locator”, which will make the process of placing a crane easier. The software user defines all of the objects on the construction site (position, dimensions) and the maximum weight of the lifted load. The output from the application is a position for the crane (a construction site equipment drawing), as well as the number, model and type of crane [2].

BIM technology is also used when designing the effective use of machines and their localization. In his paper, B. Dasovic presents the use of BIM for the optimum placement of tower cranes and storage surfaces on construction sites. He describes the method of exporting the required data from the BIM and the method of importing it into the optimisation model. The input parameters of the optimisation model are the coordinates of material storage areas on the construction site and the destinations for transported materials, the coordinates of possible tower crane positions, the number and type of available tower cranes, the coordinates of the building and the perimeter of the construction site. The aim is to shorten the work cycle of the crane and save on financial costs [3].

Prof. J. Gašparík uses more detailed input data in the proposed procedure called the “method of optimizing the selection of machines”, which he applies when selecting a set of machines. The basic input data for selecting the most suitable set of machines are the dimensions of the final product of the construction process (e.g. construction pits), the type and class of soil, the total volume of excavated soil, transport distance, required duration of work and type of road surface. It describes the design of the “Machine Selection” application for the selection of a machine which was created to support the software for the method described in this paper. The output of the application is a list showing all the variants of sets of machines which are capable of dealing with the task within the required time. The use of this application will increase the efficiency of the selection of construction machinery in terms of the key optimisation criteria: quality, time and energy consumption [4].

In his work, K. Schabowicz deals with the determination of the productivity of construction machines and sets of earthmoving machines using an artificial neural network. Excavators and dump trucks are considered as sets of machines here. The input data for the creation of the neural networks are the technical parameters of the machines and their performance. These parameters are, for example, the loading time of the truck, the capacity of the excavator bucket, the capacity of the loading platform of the truck, etc. [5].

Another author who deals with optimisation calculations for the use of earthmoving machines is B. S. Kim. He has developed a method according to which it is possible to select different combinations of machines with regard to defined criteria and the difference in their significance. The input parameters for the selection of a set of machines are the cycle time of each machine, the types of machines and their energy consumption, the volume of excavated and transported soil, the type of soil and the transport distance. The method is demonstrated using a hypothetical case study which presents the dependence of the impacts of construction on the environment depending on the choice of machinery, construction time and costs [6].

Prof. M. Kozlovská from the University of Technology in Košice deals with the comparison of deterministic and stochastic approaches to the specification of the technical and operational performance

of construction machinery in her work New approaches to specifying performance of construction machinery from 2015. To compare the approaches, a case study focused on the process of concreting using a tower crane and a crane bucket. The input parameters are the technical parameters of the used construction machines, transported volumes of materials and the transport distance. The study concludes that the stochastic approach is more accurate and better reflects real conditions on site [7].

The exact assessment of the performance of construction tower cranes lies among the subjects investigated by Brno University of Technology staff. The results can be found in, e.g. the work of M. Štěrba, L. Klempa, J. Štastný and V. Motyčka [8, 9]. It concerns a new approach to the assessment of the time utilisation of tower cranes using a simulation model whose calculations are based on detailed input data. The initial conditions and input data for the creation of the model are: a binding construction schedule, a modelled time unit (e.g. one work shift), the total volume of work for the individual construction sub-processes, concurrencies between construction sub-processes; crane type, the position of material storage sites and deposition sites in relation to the position of the crane, and the volume of work in the individual construction sub-processes in the individual assessed work cycles. Based on the input data, the designed software will choose specific suitable types of crane from the database and the required number of them for the specific construction conditions and implementation time. The proposed sets of machines will then be compared from the economic and ecological point of view. The input data are: the location of the construction site, the shape and dimensions of the structure to be built, the shape and weight of the lifted elements, the character of the construction site, and the required speed of construction. The software also evaluates the options for transporting the crane to the construction site and the possible method of its placement and assembly at the site. The aim is to achieve the fast and efficient selection of lifting mechanisms for a specific construction site, and also the comparison and evaluation of various alternatives.

The works listed above are examples of possible approaches to the issue. They provide confirmation that it is no longer possible to use approximate input data for exact calculations when dealing with the efficiency of construction machines.

It is generally true that various approaches to the solution of this issue require the preparation of relevant input data, which are a prerequisite for exact mathematical modelling and enable the acquisition of results that are usable in real-world practice. Such data are essential for the meaningful assessment or determination of the real performance of machines or sets of them, and their optimum use.

It is clear that a number of boundary conditions related to the nature of construction projects are involved in the determination of the real performance of construction machines, and it is not always possible to capture all of these circumstances exactly in a model. Nevertheless, the quality of the preparation of the input data for use in model calculations affects these outputs significantly.

After first paragraph, other paragraphs are indented as you can see in this paragraph. After Introduction, divide your article into clearly defined and numbered sections.

2. Definition of the investigated task

This contribution describes the design of a procedure for the preparation of input data for the exact assessment of the real performance of construction machines and the evaluation of the time utilization of machines during the execution of construction sub-processes. Specifically, it deals with the preparation of input data for the evaluation of the real performance of tower cranes. The analysed input data concerns the construction of reinforced concrete multi-storey buildings. First, the typical work cycle of the tower crane is analysed, after which the selected construction sub-processes that have a decisive influence on the construction process are also studied. Their analysis is performed with regard to their secondary supply role during construction.

In the next part of the paper, a procedure for the experimental verification of the analysed data in the context of executed construction projects will be described, and the conclusions that can be drawn from the results hitherto achieved will be presented.

3. Analysis of input data for the evaluation of the time requirements of secondary transport using tower cranes

Basic terms and input data. In order for the input data to be analysed, they must first be identified and defined. The supply of building material on a construction site mainly takes place in cycles. The monitored input data for the stated purposes are thus values expressing the durations of predominantly cyclical construction sub-processes, which are divided into the duration of a crane's work cycle and the duration of work performed without service from a crane [10].

Built structures and their elements are created via production processes. A construction sub-process is a part of the production process, carried out by one work team, and its product is a built structure [11].

The period of one work cycle of a construction sub-process is further marked as T . It is composed of two main time values, the period of the work cycle of the crane, t_c , and the period when the service of the tower crane is not required, t_p . It can be written down as the following equation:

$$T = t_c + t_p \quad (1)$$

The time of one work cycle T is thus the time interval between the individual requirements of the evaluated construction sub-process for the supply of building material.

The typical work cycle of a tower crane. Cranes are machines that work in cycles. Generally, the work cycle of a crane can be illustrated as shown in the image below.

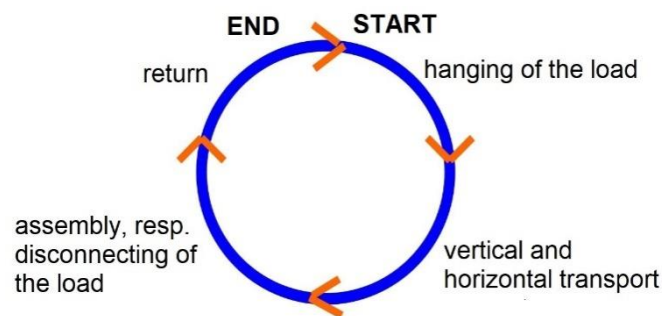


Figure 1. Work cycle of a tower crane

To determine the calculated duration for the crane work cycle (figure 1), t_n (figure 2), the period is divided into three parts according to the following equation:

$$t_n = t_j + t_m + t_a \quad (2)$$

t_n – calculated duration of the crane work cycle,

t_j – time needed to transport a unit quantity of material,

t_m – time needed to hook up and disconnect the transported material,

t_a – crane service time.

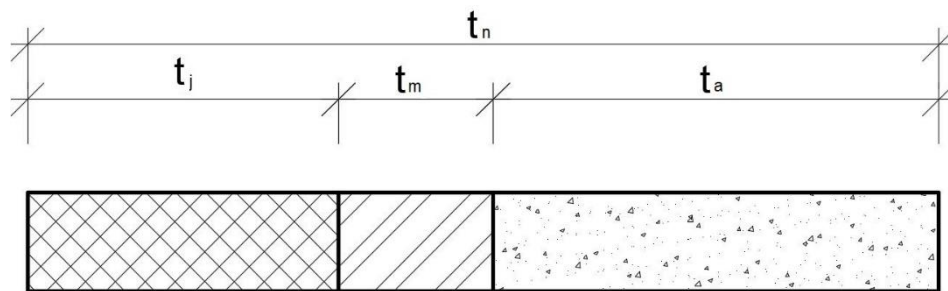


Figure 2. Diagram of the time division of the tower crane work cycle

The value of quantity t_j is based on the typical work cycle and can be determined on the basis of the technical parameters of the machine by, e.g. using the Critical Path Method. The value of quantity t_m can be obtained from the professional literature, e.g. [12], and can then be checked by monitoring such activities at the construction site. As regards value t_a – crane assistance time, it is not stated in the professional literature at all, and had to be determined via monitoring at construction sites

To determine the work cycle of a crane, other objective and subjective influences on productivity should also be considered (e.g. weather conditions, the layout of the site, the performance and experience of the crane operator, etc.) These influences, which are difficult to determine precisely, are assessed in the literature [12] and are listed in the following table (Table 1).

Table 1. Examples of coefficients of the influences chosen construction sub-processes have on productivity

Construction sub-process	Value of productivity influence coefficient k_s
Formwork	1.2
Reinforcement	1.1
Concreting – solid structures	1.1
Concreting – thin-walled structures	1.4
Formwork removal	1.2

After taking into account the mentioned influences, the duration of the tower crane work cycle for the monitored construction sub-process can be expressed by the following equation (Eq. 3):

$$t_c = t_n + k_s \quad (3)$$

t_c – duration of the crane work cycle,

t_n – calculated duration of the crane work cycle,

k_s – coefficient of influences on productivity.

Analysis of selected construction sub-processes. A construction sub-process is composed of two time intervals: time t_c (the work cycle duration of the tower crane) and time t_p (the time when the unit quantity of material is processed without requiring service from the tower crane); see Eq. 1.

The determination of time T can be based on the available time consumption standards for individual construction sub-processes, or alternatively on a binding time schedule for a specific construction project. It is based on the idea (assumption) that the construction process takes place

smoothly, and that according to the binding construction schedule [13] the planned amount of material needs to be relocated for the given construction sub-process. The unit quantity of material to be hoisted by the crane in one work cycle is determined. It is then possible to calculate the number of work cycles of a construction sub-process required for the monitored time interval (e.g. for one work shift) and thus also for one work cycle T . *The input data for the analysis of the individual construction sub-processes* thus include:

- the amount of material transferred during the evaluated period (e.g. one work shift),
- the unit quantity of material moved by the tower crane in one work cycle,
- the number of work cycles in the evaluated period (e.g. one work shift),
- the time T of one work cycle of the monitored construction sub-process,
- the time t_c for which the service of a tower crane is required by the construction sub-process during one work cycle,
- the time for which the construction sub-process does not require the service of a tower crane during one work cycle

The decisive construction sub-processes for the execution of monolithic reinforced concrete structures were analyzed in detail in this way, and the above-mentioned input data concerning the investigated type of monolithic structure were gradually calculated. These include the formwork used for vertical and horizontal structures, the reinforcement and concreting of such structures, formwork removal and the laying of the masonry for load-bearing and peripheral structures [14].

4. Experimental monitoring of the work of tower cranes

To verify the analyzed input data obtained via calculations, extensive experimental monitoring of the work of tower cranes was performed at selected construction sites.

A brief description of the monitored structures. The types of monitored structures were selected on the basis of their structural design, the layout of the construction site and the wider surroundings of the site, as well as accessibility with regards to the cities of Brno and Bratislava. Administrative buildings, apartment buildings and combinations of these were among the monitored monolithic reinforced concrete structures. Examples of the monitored structures are listed and briefly described below.

An office building with rented commercial space (figure 3). One of the monitored examples is a building in the southern part of Brno, which is a densely populated part of that city. The building consists of a basement and eight floors.



Figure 3. The load-bearing monolithic reinforced concrete structural system of the monitored structure

The foundation of the building utilises drilled piles and a base plate. The load-bearing structure is a combination of monolithic internal reinforced concrete columns, and internal and peripheral walls. It includes walls in the stair cores and elevator shafts. The monolithic reinforced concrete ceiling slabs are the same for all floors. The monolithic reinforced concrete cores of the staircase are made up of monolithic landings with prefabricated flights. The monitored elements were reinforced concrete columns on the 6th floor and the ceiling on the 7th floor. The deployed lifting machines that handled them were Liebherr 81 K.1 and 71 K stationary tower cranes.

Apartment buildings with rented commercial space (figure 4). The buildings are part of the densely populated northern sector of the city of Brno. They all have a basement and four floors.



Figure 4. Construction of the monitored apartment building

5. Design of the methods and tools to be used for experimental monitoring [15]

For practical reasons, the experimental measurements (monitoring) were taken directly at the construction site with the aid of a recording device. Because the procedures for the acquisition (and administration) of data obtained during the monitoring had to be repeated, it was necessary to design a set of data measurement and administration methods which includes procedures to be performed in chronological order as well as the necessary equipment to work with the recorded data.

Description of the methods:

- 1) Determination of the investigated research plan – The technical performance of lifting mechanisms in construction processes.
- 2) Acquisition of hardware (time-lapse cameras with the required accessories, specifically memory cards, rechargeable batteries, tripod, PC) and software (operating system, media player, cloud service).

The specific device used, which is designed to record data for the execution of field and administrative proceedings is:

- Brinno time-lapse camera (figure 5), model TLC 200, with a protective cover and a clamping bracket,



Figure 5. Brinno TLC 200 time-lapse camera set



Figure 6. The device mounted on a tripod and a clamping bracket

- SD memory card, max. 32 GB, 2 pcs. There is always one in the camera, while data is stored in the second one,
 - battery charger and rechargeable AA batteries, 2 x 4 pcs. There is always one set in the camera while the other is removed for recharging,
 - a tripod, clamping bracket or auxiliary structure to be attached at the construction site (figure 6),
 - a PC with an internet connection, software for playing the recordings (e.g. VLC Player) and a cloud environment, e.g. the Microsoft OneDrive platform.
- 3) Determine a suitable object for monitoring, i.e. a structure that is of monolithic reinforced concrete construction and primarily composed of load-bearing elements: ceilings, walls, columns. The building must consist of at least 4 floors (1 basement and 3 above-ground floors), as in that case the use of a tower crane can be assumed.
 - 4) An agreement on cooperation must be reached with the construction contractor (or builder) concerning their permission for the research to take place, and the arrangement of the field monitoring of the crane on the construction site.

- 5) It is necessary to determine a suitable position or more than one position on a site for the monitoring of the activity of the tower crane and the workers at the place of work (or more than one place of work) with regard to the relevant construction sub-processes (formwork, reinforcement, concreting, removal of formwork) performed for the monolithic reinforced concrete structures of the building.

The site should be chosen in compliance with certain basic requirements:

- when operating the device, there must be no danger of the user falling from height, or being hit by falling objects or transported loads,
- movement must take place only on marked and agreed routes, with the awareness of the construction site management,
- the investigator must not endanger other persons or property at the construction site,
- the site must be prepared in such a way that there is an unobstructed view of the monitored workplace where the construction sub-process activity takes place and also a view of the relevant monitored tower crane,
- choose the site in such a way that it is easy to access and the time-lapse device is easy to control (changing the batteries and memory card should be simple).

Providing the above preconditions are met, the equipment can be set up on scaffolding, in an attic, on a set of containers, etc.

- 6) The means of attachment of the time-lapse device depends on the above-mentioned conditions. In an ideal case, adjacent buildings (existing or newly built ones) should be used. If they include lockable spaces (e.g. balconies) then the device can be attached to the tripod without further restrictions (if no scaffolding is installed on the site). An alternative is to attach the tripod with a chain to elements which are firmly connected to the building and then lock the device in a cage (figure 7).



Figure 7. Monitoring device in a protective cage

- 7) The operator of the device carries out inspections (hardware functionality), changes the memory cards and batteries, and performs the transfer of the monitoring set to another location if necessary.

The frequency with which the battery and memory card require changing depends on the climatic conditions at the construction site. At temperatures of approx. +20 °C and with an optimum setting for evaluation (10 seconds of real time are covered by each approx. 1 second-long image) the battery life is up to 10 days. The TLC 200 model is limited in that it is compatible with memory cards with a maximum capacity of 32 GB. In the summer the operator needs to access and deal with the camera once a week, but in the winter it is two or three times a week.

- 8) The cloud environment (figure 10) needs to be set up; researchers can either use a service provided by the university, or arrange it themselves. The environment allows the use of a server to work with, store and sort data.

The structure for data administration and archiving in the cloud (figure 8) environment was created as follows:

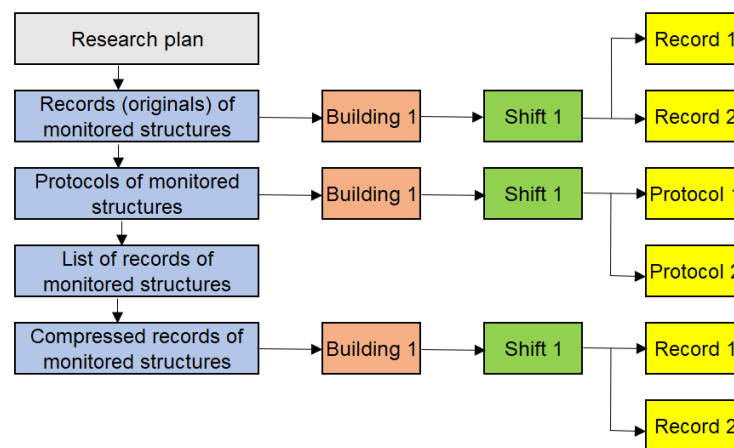


Figure 8. Diagram of the directory structure for the time assessment of tower crane utilisation

The recordings created by the time-lapse camera had to be compressed due to the size of the files created by the device. One file can be up to 4 GB in size, which makes it a technically demanding task to work with a recording on a server.

The files need to be compressed by lowering the quality, but only to such an extent that it is still possible to obtain data from the recording. Working with files (recordings) is then also possible online.

- 9) The management of the acquired data requires the sorting of recordings (the storage of relevant recordings, and the removal of unreadable ones), the registration of recordings, their storage (archiving), and their compression and backup (figure 10).

The list of recordings (figure 9) is necessary for the registration of not only the acquired files but also to obtain an easy overview of previously prepared protocols and to provide information about the given recording.

building:	Lodging house					
place:	Construction site					
record number	date	from	to	state	formwork type	construction sub-process
fig01	19.04.2018	7:22	13:03	evaluated	DOKA - Dokaflex	formwork erection ceiling fourth floor
fig02	19.04.2018	13:04	14:10	evaluated	DOKA - Dokaflex	formwork erection ceiling fourth floor
fig03	20.04.2018	8:59	12:59	evaluated	DOKA - Dokaflex	formwork erection ceiling fourth floor
fig04	23.04.2018	7:39	13:21	evaluated	DOKA - Dokaflex	formwork erection ceiling fourth floor
fig05	23.04.2018	13:21	14:01	evaluated	DOKA - Dokaflex	formwork erection ceiling fourth floor
fig06	24.04.2018	8:37	14:19	evaluated	DOKA - Dokaflex	formwork erection ceiling fourth floor
fig07	24.04.2018	14:19	15:04	evaluated	DOKA - Dokaflex	formwork erection ceiling fourth floor
fig08	25.04.2018	7:05	12:46	evaluated	DOKA - Dokaflex	formwork erection ceiling fourth floor
fig09	25.04.2018	12:46	13:35	evaluated	DOKA - Dokaflex	formwork erection ceiling fourth floor
fig10	26.04.2018	8:20	14:01	evaluated	DOKA - Dokaflex	formwork erection ceiling fourth floor

Figure 9. Example of a list of recordings

10) Data archiving is completely related and linked to the management of the acquired data; after the recordings have been sorted and registered, they are compressed (reduced in size), stored in the cloud environment and subsequently backed up to external devices.

We perform archiving and backup simultaneously on an external medium, currently exclusively on an external disc. A capacity of 1 TB will suffice for about 4 construction sites with cyclic (non-continuous) monitoring.

11) At the end of the monitoring period, the apparatus used for the monitoring device will need to be liquidated. In particular, the means of attaching the device will be removed, as well as any auxiliary fastening structure.

12) The set of monitoring equipment will require servicing: e.g. the protective case of the device will need cleaning (or a new one will need to be purchased), new rechargeable batteries will require purchasing (service life is reduced by about 1/3 after one year of use), and lubricant should be applied to padlocks (to prevent corrosion, if they are not made of stainless steel).

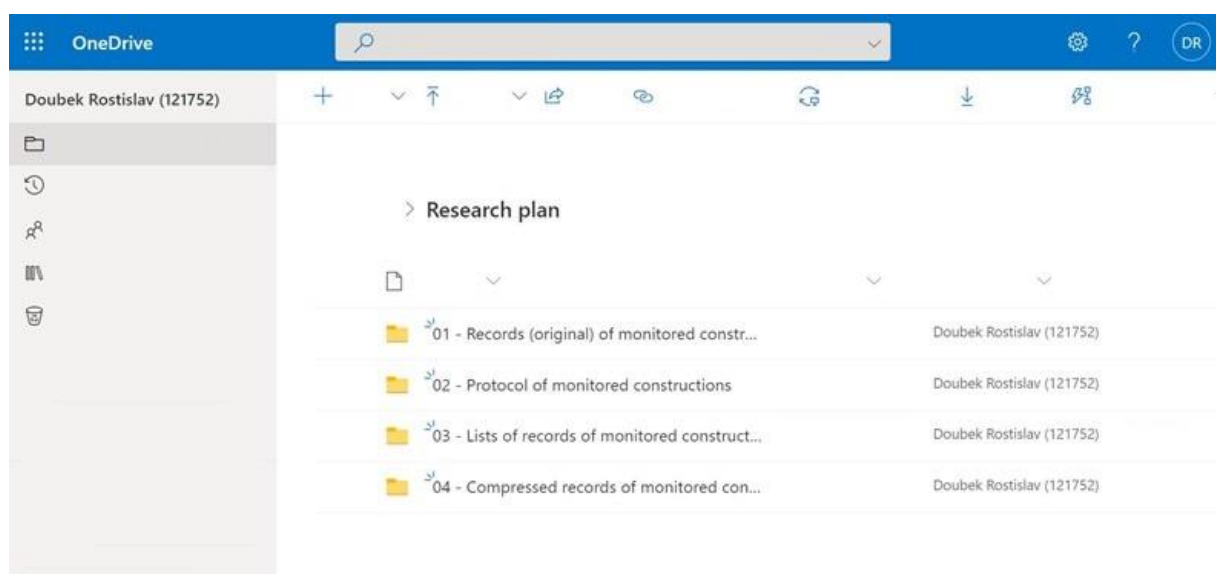


Figure 10. Illustrative image of a cloud environment

6. Evaluation of data from acquired recordings

In order to be able to obtain the necessary data from the acquired recordings, it was necessary to analyse the measured data further. Appropriate forms were used for this. Their structure was based on forms used in previous direct experimental measurements taken when a time-lapse device had not yet been employed. More detailed forms were gradually developed for the recording and evaluation of measured data.

Building: Lodging house				
Part of the construction process: formwork erection ceiling				
formwork type: DOKA-Dokaflex				
Schift number: č.:	86, 87			
Date:	14.05.2019			
first level				
Schift č. 86 start recording: 6:54 finish recording: 11:45	measured work cycles			
	s.n.	tc	tp	T
	1	5	0	5
	2	4	1	5
	9	11	2	13
10	15	2	17	
Number of cycles per hour:		2,76		
Number of cycles per shift:		29		
Sample diameter:		8	1	9
Mode		6	0	6
Median		6	0	7
Maximum		15	10	22
Minimum		2	0	2
Maximum diameter		7	9	13
Minimum diameter		6	1	7
Average deviation		7	5	10

Figure 11. Example of an evaluation form

The obtained experimentally measured values undergo further statistical evaluation, as is shown in the bottom part of the enclosed illustrative form, for example (figure 11). The values are compared and evaluated in connection with the results from the input data obtained via the theoretical analysis.

7. Conclusion

From the values of the input data hitherto obtained by means of theoretical analysis and the input data obtained via experimental measurements and monitoring at real construction sites, and the comparison of such data, the following facts and findings were discovered:

- The performance standards generally used to conduct scheduling for the construction of monolithic structures are obsolete and are not regularly updated with regard to new developments in construction technology.
- A binding contractual schedule must be used to determine the value of the work cycle time, T.
- The performed monitoring confirms the correctness of the theoretical calculation of the input data concerning the calculated duration of a crane's work cycle, t_n .

- The crane assistance time, t_a , can only be obtained by monitoring the service provided by the crane to construction sub-processes.
- In general, it can be said that the values obtained for a tower crane's work cycle time t_c via monitoring are very similar to the values obtained from calculations for all of the monitored construction processes.
- The values for the work cycle duration T (or t_p) obtained from calculations differ from the experimentally obtained values particularly in the case of ceiling formwork construction sub-processes due to the inconsistent use of the maximum unit quantity of the transported material by tower cranes.
- The difference between the calculated values and the values obtained via monitoring for input data T (or t_p) for the formwork used for vertical structures is also due to new developments in the system of quick coupler connection and formwork anchoring. Older performance standards do not consider this.
- With regard to the monitoring of the work cycle time T (or t_p) of vertical structures, the installation of footbridges, safety systems and railings is not taken into account in the monitored values.
- In the case of the input data for other construction sub-processes (removal of formwork, reinforcement, concreting and the laying of masonry for load-bearing structures), the input data obtained via theoretical analysis are similar to the input data obtained by monitoring.

In conclusion it is possible to say that painstakingly exact preparation and analysis of the input data is a basic prerequisite for the exact evaluation of the real performance of construction machinery, but it is only the first step. The accuracy of the result depends, of course, on the approach to the evaluation of that data.

It can also be stated that the experimental verification of input data using real-life construction projects is very beneficial, as facts can come to light which were not considered during the theoretical analysis or which cannot be determined theoretically.

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