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Technical normalization of working processes in construction based on spatial-temporal modeling

Техническое нормирование рабочих процессов в строительстве на основе пространственно-временного моделирования

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Ключевые слова: BIM+4D технологии; техническое нормирование; визуализация; карты трудовых процессов; синхронизация; монтаж плит перекрытия

Abstract. Application of spatial-time modeling to the rate setting of operational sequence is a practical way to reduce the labor required for this work without losing any accuracy and authenticity of the results was analyzed. The methodology provided the analytical algorithm of rate calculation in MS Excel is synchronized with the visualization of operational sequence in Cinema 4D. The sequence of visualization of rate setting is considered with the example of a common operational sequence for mounting reinforced-concrete ceiling slabs of a five-storey brick apartment building. A peculiarity of the framework shows in the variable parameters of production activities. During the animation the calculated standards of working time were corrected in order to provide a safe working environment. The application of visual modeling and computational and analytical method for designing the flowsheets of operational sequence proved the given method to be effective and appropriate for extensive use in rate setting for various sequences in construction with the base of improves software, such as Synchro Pro, SOMOKS.CMR and a number of other tools for automated scheduling of construction operational sequence.

Аннотация. Рассмотрено использование пространственно-временного моделирования для технического нормирования рабочих процессов как реальный путь к снижению трудоемкости этой работы без потерь в точности и достоверности результатов. В предлагаемой методике алгоритм расчета норм аналитическим методом в MS Excel синхронизирован с визуализацией рабочих процессов в среде Cinema 4D. Порядок визуализации технического нормирования рассмотрен на примере технологического процесса на монтаж железобетонных плит перекрытия пятиэтажного кирпичного жилого дома. Характерная особенность технологии – постоянно меняющиеся параметры производственных операций. В процессе анимации выполнялась корректировка расчетных норм времени для обеспечения безопасности на фронте работ. Опыт применения визуального моделирования и расчетно-аналитического метода для разработки карт трудовых процессов доказал эффективность предлагаемого метода и возможность его широкого применения для технического нормирования различных процессов в строительстве на основе более совершенных программных продуктов, к которым можно отнести Synchro Pro, СОМОКС.СМР и ряд других инструментов по автоматизации процессов планирования строительных работ.

Introduction

The principles of spatial-time modeling, known as BIM+4D framework (Building Information Model), have produced new approaches and possibilities in construction design [1–6]. The benefit of this type of modeling is determined by the combination and integrity of architectural, constructional engineering, executive and economical elements of construction industry in a single dynamic unit. At first the main goal of BIM was the 3D presentation of design concepts of venues. Later the informational technologies were developed for visualization of the construction operational sequence by means of combining the schedules designed in MS Project, Oracle Primavera etc, with the 3D models of the venues.

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At present this method, sometimes called the method of visual planning (MVP) [7–9] becomes more and more widespread. The crucial elements of the method in question, according to many authors, are the well-thought and organized structure of venues and operational sequences, modular decomposition of systems of production logistics, relevance and authenticity of used data, availability of multivariable element libraries for determination of the most effective project alternative based of the multicriteria rating [10–12].

The methods of visualization have gone through a revolutionary advance in comparatively short time, allowing the broadening of functional opportunities of construction modeling in various fields of construction industry [13–16]. New inventions in information modeling provide solutions for the matter of higher safety of construction, analysis for clashing operational activities at the construction site, informational support to choose an optimal solution [17–20]. Different companies utilize specialized software complexes Synchro Pro, SOMOKS.CMP, focused on effective informational management of operational lifetime of a construction at every stage of engineering design development:

- designing engineering documentation;
- arrangement of construction operations;
- construction, reconstruction, overhaul;
- operation;
- decommissioning.

For the construction of the most complex venues of nuclear power industry a special standard has been developed: “Visualization of the construction management sequence. In-process control testing.” (Standard of Organization STO SRO-S 60542960 00042 – 2015) [21].

The matters of visual modeling, which could be solved with the given system, concern a wide scope of specialists in construction industry. At the same time, the more the peculiarities of preproduction planning and scheduling are taken into account, the more relevant models and reliable terms of project execution we shall achieve [22–24].

The importance of BIM+4D framework in the matters of providing the safety of workplaces, minimizing the losses of time, human and technological resources, improving the energy efficiency of the project solutions, optimizing the duration of construction is mentioned by the researchers, involved in the given field [25–28].

It is well-known, that the real duration of construction of many venues exceed the terms, set by the schedule of construction master plans (CMP) and work production plans (WPP) [29, 30]. One of significant reasons for such a discrepancy is the lack of reliable information about the standard terms of certain classes of work, about synchronization of operational sequence while combining the lateral and temporal operational activities.

The use of current informational technologies for automated planning of construction management in MS Project, Oracle Primavera etc minimizes many technical complexities of scheduling, reduces the labor required for designing executive documentation, but does not solve the matter of setting an optimal term of operational sequence execution, based on the current regulatory system.

This problem of construction engineering is mentioned by a number of authors [31–33], considering the vulnerability of current informational technology application to be the transference of rate setting and following scheduling, which are not efficient enough, into automated project management mode. M.M. Kalyzhniyk [31] points out the lack of works among the current papers on scheduling, which are devoted to the problems of rate setting of basic operational activities. Insufficient specificity and standardization of operational sequence cannot be compensated only by utilizing temporal probability parameters of isolated work classes. Thus, Y.B. Kalugin [34, 35] has shown, that the calculation of project network with the highly recommended system PERT provides the boosted positive results and therefore confuses project managers. The reliability of scheduling may be achieved with a number of measures, one of which would be the improvement of accuracy and authenticity of standards for operational activities and operational periods within flowsheets.

The importance of facilitating construction with the flowsheets during the automatization of designing work WPP is specified by professor S.A. Sinenko [36]. According to him, the crucial principles of the work in question are:

1. Goal statement and development of the project tasks structure;

2. Preparation and development of a knowledge database based on regulatory, methodology and reference tools;

3. Automatization of individual task solution, including the bulk of scheduling.

All the above mentioned principles, most of all the latter, are corresponding to the goals of the given paper. Executive technological modeling is the foundation for automated designing of CMP and WPP. The documents in question use the flowsheets, software and regulatory databases to determine the correlation of the main elements of construction: the scopes of workload, agents, technological and physical resources [37–39].

Officially active standards of work load and operating time for corresponding work class operations, issued as Unified Norms and Prices, are ethically and practically outdated.

The system of budgeted pricing currently employs State Itemized Cost Estimate Standards. These documents determine the standards of requirements for human, technological and physical resources predominantly in the complex operational sequences. New issues of Standards do not reflect current innovations and changes in equipment and technology on time. More relevant to the needs of rate setting and automated construction management planning are the standards of the flowcharts of operational sequence (FOS). Current issues of the documents in question are the updated versions of the previous ones, while new developments are rare. Sometimes regulatory documentation for operational sequences is issued as company standards.

Development of this documentation requires a lot of labor, and is carried out after the commissions of engineering and construction companies. Engineering solutions in these documents are not variable-oriented in case of use of interchangeable equipment. The matter of technical standards for determining the operational duration of activities in construction schedule is still of vital importance. Well-organized and scientifically valid rate setting is at the same time one of the crucial conditions of better performance, saving physical, technological and financial resources. The use of current informational technologies for rate setting is the most likely way to reduce the labor required for the work in question without losing accuracy and authenticity of results. It is especially important to rate the standard duration of operational activities when utilizing new equipment and technologies.

The goal of rate setting is to determine scientifically valid standards of expedience of labor, equipment and physical resources per unit of production. Operational standards can be developed via two main methods of rate setting: computational research and computational analysis [40].

For calculations of physical and operational capacity of equipment and time standards for performance we have developed the software based on MS Excel [33, 41]. Our experience in rate setting of road construction plants, including the modern plants of high efficiency, has shown that changes in environment cause the efficiency of mechanical units vary within a broad range. For example, the operational rates for excavation by Caterpillar 320L, set by means of computational analysis, take the following into account: the conditions of dumping (to spoil, or into a vehicle); type of ground (six types, graded by complexity of excavation); type of scoop (shovel bucket, back hoe, dragline), steering angle, deg. (90, 110, 135, 150, 180).

Considering the given factors, it is possible to calculate 150 types за operational rates for excavation of 100 m^3 of ground by Caterpillar 320L. Within the range of the easiest to the hardest environment time rates vary from 0.3 to 4.9 veh/hr.

The method in question is rather broad-based, applicable for efficiency calculation and for comparison of operational losses of different types of leading equipment during operational activity [38, 42]. At the same time automated calculations in MS Excel would not improve the authenticity of rate setting or analyze the availability of working area and the probability of safe combining of the operations.

The models for testing work areas during the construction, providing safe work environment were presented in paper [25]. As a result of the given research the method of software integration was evaluated for visualization of work areas and determining the conflicting zones of the human and technical resources in these areas.

According to S.A. Bolotin [43] the application of current methods of visualization and informational technologies in rate setting is the most valid way to reduce the labor required for the given work without losing accuracy and authenticity of rate results.

The goal of developing of visual flowsheets of operational sequence (VFOS) is to graphically present the operational sequence of activities, the plan of work area setting, (dimensions, arrangement of workers, physical resources, equipment and tools).

Flowsheets reflect all the components of operational sequence: availability and condition of work area, material, construction, production handling, preliminary work. The final document includes the schedule of operational sequence by the elements (operations, activities) with the agents, labor required for certain elements, terms of operation, rest and routine breaks at work.

The algorithm of spatial-time modeling is presented in Figure 1.

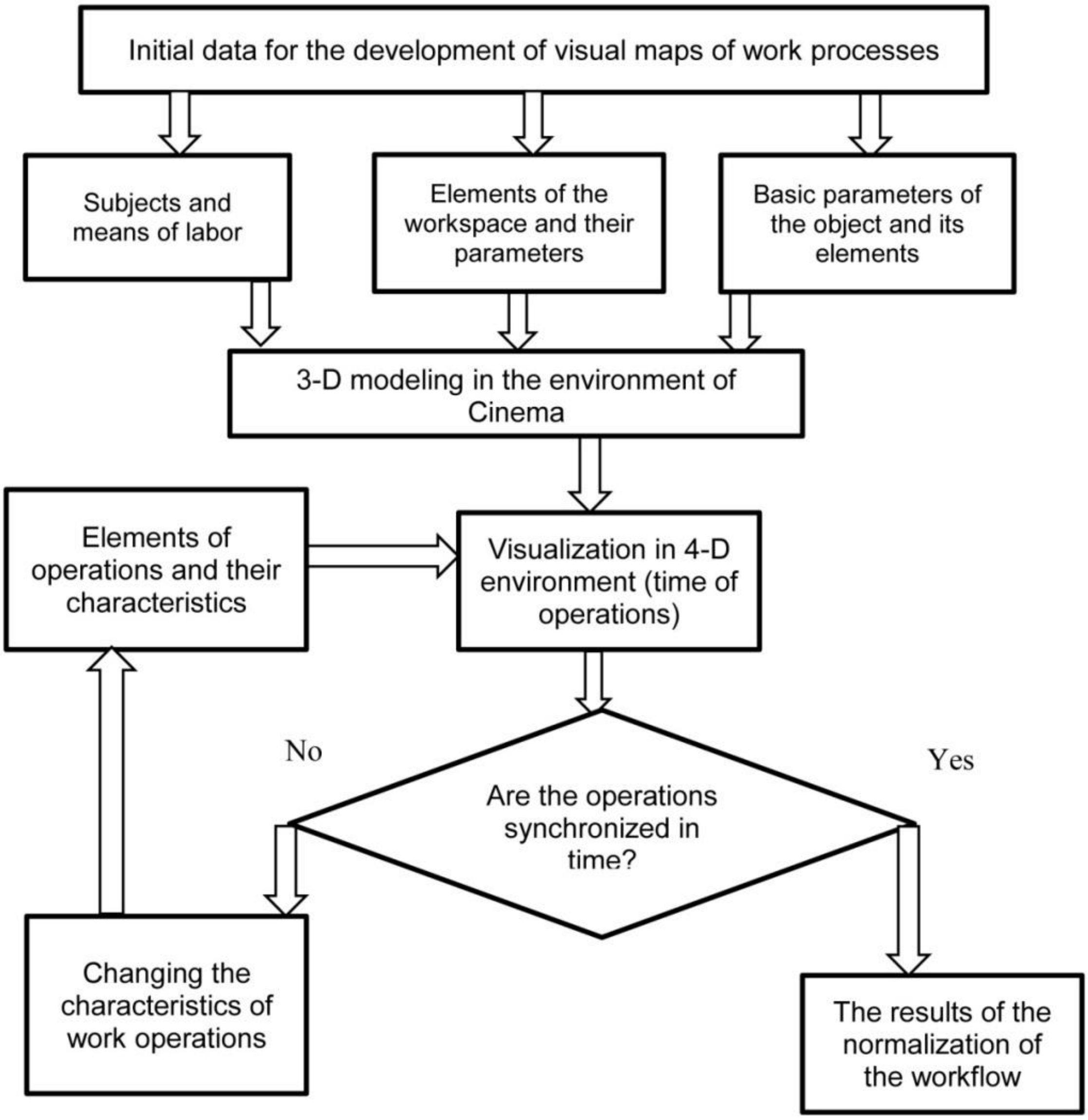

Figure 1. Algorithm of spatial-time modeling of operational sequence

Methodology of visualization the rate setting is shown with the example of developing VFOS for arranging reinforced-concrete ceiling slabs of a five-storey brick apartment building. The object is chosen due to a number of reasons: the specialty training of the graduate student being carried out in the construction of the given type of residential buildings; the request of a construction enterprise to develop the flowsheets of operational sequence; engineering documentation available for the research. The experience in rate setting for transport construction has been useful, while the algorithm for time rates calculation has the foundation in the general approach based on computational analisys [40].

The complexity of operational process is determined by constant variation of operational parameters (the height of slabs handling, angle of boom swing, etc). The visualization is carried out in Cinema 4D software, which is a general-purpose package program, meant for spatial modeling as well as for animation [44]. At the present stage of research the crucial benefit of the program was its relative simplicity and availability. Before working in the “space + time” coordinates, the preliminary technicalities were solved:

1. 3-D models were designed for a building, mounting crane, ceiling slabs storage site, crane ways. 3-D models preserve the correspondence of real dimensions of sites and work area, taking operational safety into consideration.

2. Movement of objects was described with spline functions: for a crane, load weight, bogey, workers (sling-operator and two adjustors), and equipment [45].

3. Connection layout of ceiling slabs was designed, gravity centers of slabs marked, sequence of mounting and distance of handling from stacks to the mounting site, considering the variation of stack height during the mounting, determined; crane staging area marked. These measures are described in details in paper [46]. The given work is not concerned with the details of animation process, immediately related to Cinema 4D software. However, the instructions of the program let the user, familiar with MS Excel, AutoCAD, prepare the necessary data.

Cinema 4D software, using the calculations in Excel spreadsheets, records the moments of beginning and end of every operation of the system elements via the recording of "active objects" (according to Cinema terminology). When the input data is changed in MS Excel, Cinema 4D software is changed automatically, which is immediately reflected in the operational duration during the visualization.

Visualization of manual operations is carried out by moving the figures of the sling-operator and adjusters along certain trajectories (splines). For example, for the sling operator circling the slab a rectangular spline was used. The moments of beginning and end of the manual operations are set by changes in elements of figures of workers (raising and lowering hands).

All the motion plans of the system are presented in animation, factoring real trajectories. The motion of the hook at the rotation of the swing and its simultaneous rise or descent goes by a rather complex trajectory, that is, by a three-dimensional spiral. Circular alignment determines the circular trajectory of an object, instead of a chord, and this way of rotation setting is used for the bogey and the hook, as well as for the slab. The variation of handling radius has also been set.

Detailed development of the flowcharts of operational sequence for slabs mounting cycles makes it necessary to describe these cycles spatially and temporally. The calculations of terms of operational activities for a given machine was carried out with the method of analytical calculation using passport specifications and motion distances in MS Excel, with and without the load weight. Terms of manual labor were estimated with the data from chronometer reviewing of similar operations [47]. Time of manual labor, simultaneous to crane operation, is not included into the general cycle, but is used for working hours calculation. The model of the site and work conditions is shown in Figure 2.

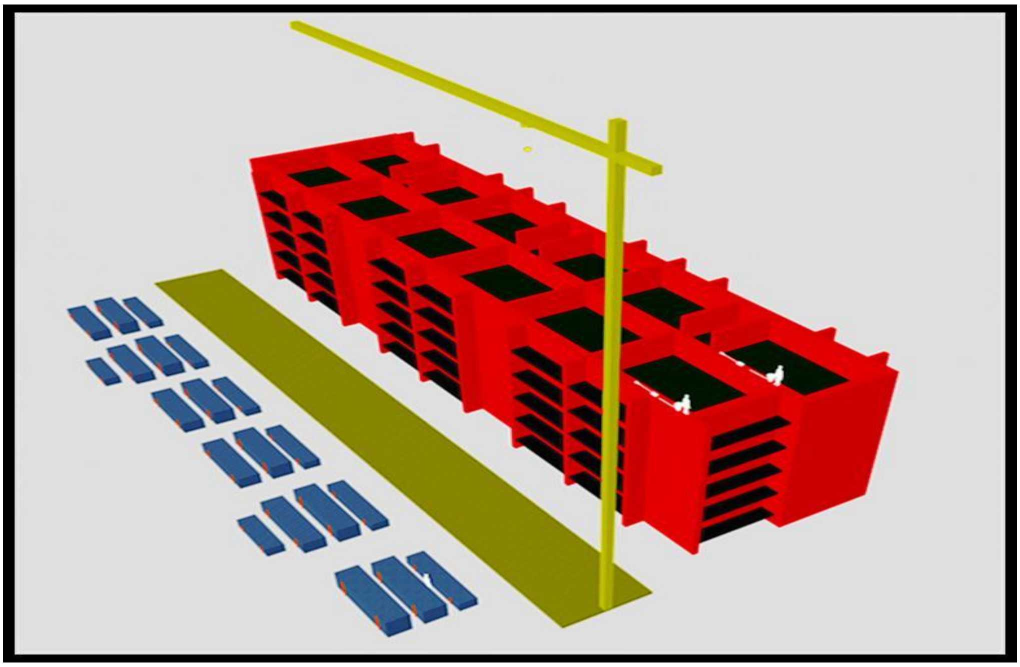

Figure 2. Model of the site and work conditions

Principal passport specifications of various cranes, used for the animation of mounting, are shown in table 1.

Cycle duration was determined according to the following sequence:

1 – slab strapping;

2 – rising the slab to the mounting height;

3 – modification of the operating radius for mounting;

4 – rotation of the swing to the mounting site;

5 – setting the load weight;

6 - leveling;

7 – unstrapping the slab;

8 – modification of the operating radius to strap the next slab;

9 – rotation of the swing to the site of strapping the next slab;

10 – descent of the hook.

Table 1. Passport specifications of machines

№	Name	Reference	Unit	KB-403B	KB-474A	KBM-401P	KBSM-503B
1	Speed of load rise (descent)	U_{lh}	m/min	40	22	30	19
2	Speed of unloaded hook rise (descent)	U_{uh}	m/min	50	45	46	50
3	Speed of loaded bogey	U_{lb}	m/min	7	30	30	8.4
4	Speed of unloaded bogey	U_{ub}	m/min	30	45	45	25.2
5	Rate of tower rotation	n	rpm	0.65	0.75	0.72	0.64
6	Speed of the crane	U_{cr}	m/min	18	14	20	19.2

Routine breaks were calculated by adding standard time per every 1.5 h of actual work, at the beginning of the work there is time set for preliminary operations.

Calculation of machine operations takes into account tolerable temporal combinations, for example, the motion of the crane and bogey.

Then, via the plan, tower cranes passport specifications and connection layout the duration of mounting cycles of building slabs was calculated, taking the space of height marks into account,

Rating formulae for determining the time of crane operations are shown in Table 2.

Table 2. Rating formulae for the crane operations

Operation name	Operation time rating formula, min	Notes
Raising the slab to the mounting height	$(H_{hm1} - H_{hs1}) / U_{lh}$	H_{hm1} и H_{hs1} – hook marks for mounting and strapping, m
Modifying the operating radius for mounting	$(Z_{m1} - Z_{s1}) / U_{lb}$	Z_{m1} и Z_{s1} – operating radius at mounting and strapping of the slab, accordingly, m
Rotation of the swing to the mounting site	$\alpha_1 / (360n)$	α_1 – angle of swing rotation from the strapping site to the mounting site, deg.
Modification of the operating radius to strap the next slab	$(Z_{m1} - Z_{s2}) / U_{ub}$	Z_{s2}- operating radius for strapping the next slab, m
Rotation of the swing to the site of strapping the next slab	$\alpha_2 / (360n)$	α_2 – angle of swing rotation to the site of strapping, deg
Descent of the hook.	$(H_{hm1} - H_{hs2}) / U_{uh}$	H_{hm2}- hook mark for strapping the next slab, m

Cinema 4D software works not with seconds, but with frames. The default animation speed is 25 frames per second, therefore, to present the operational process in real-time mode the duration of all operations is multiplied by 25. For the faster overview the speed can be modified.

The duration of manual labor in the program, measured in frames, is determined with a formula:

$$D_{rk} = D_r S_v \quad (1)$$

where D_r is the duration of manual labor, sec; S_v is the speed of video (25 fps).

The duration of mechanized operations for the process visualization (with the frame number) is calculated the following way:

$$D_{mk} = \frac{\Delta F}{V_F} 60 S_v \quad (2)$$

where ΔF is the variation of operation parameters, parameter units; V_F is the speed of parameter variation according to the crane passport, parameter units/min;

For example let us examine in detail the animation of mounting the first slab with KB-403B crane. Getting to the first site, the crane stops and starts simultaneously rotating the swing and descending the hook to the site of strapping the first slab. Swing rotation angle is 90 degrees, the height of hook descent is 32.3 m. KB-403B crane has the tower rotation rate of 0.65 rotations per minute (that is, 234 degrees), therefore, the swing rotation takes 23 seconds. The speed of rising (descending) the unloaded hook is 55 m/min, therefore, descent duration is 35 seconds. It is worth mentioning that in the model swing rotation and hook descent are coinciding, and the duration of such a combined operation is determined by the maximum time. It practice such a combination may be not possible, it depends on the professionalism of the crane operator. To take this factor into account, the coefficient of combination is introduced, equaling 0.95. Crane rotation is designed by recording the operating agents. Strapping takes 90 seconds. Strap height is 3 meters.

Setting the slab lasts for 30 seconds. Animation consists of slab rotation around its vertical axis, linear motion of the mounters and the variation of their arm positions at the beginning and the end of operations. During operational synchronization availability of the work area and the operating agents is taken into account. Thus, the setting of mortar bedding is started simultaneously with the strapping. Setting the slab by the mounters starts from the moment of its proximity of 1 m to the wall surface. Combining manual and machine labor factored the routine breaks in operational process to provide safety in the work area. For example, crane operator, after getting the hook to the site of strapping the next slab, does not descent it, as the sling operator does not have enough time to prepare the second slab to strapping (check for defects and cleanse the surface).

During the animation the calculated time rates for slab mounting was corrected for different stores for different crane sites. Various options of mounting plans were considered. Cycle repetition for the next slabs took the variations of operation parameters into account, operational time, number of frames, frame numbers for beginning and the end of each operation were calculated.

Figures 3, 4 show isolated work moments of spatial-time modeling.

Figure 5 shows the situation during the ceiling slabs mounting at the mark of 14.000 meters with KB-403B crane.

Picture shows the location of all the workers, the crane, the slabs at the stack site. The table in the upper part of the screen records the data on every cycle of mounted plate. Model allows managing the construction storage facilities more efficiently, in particular, unloading the constructions and materials for the next operational activities.

Application of MS Excel and visualization in Cinema 4D allowed to determine the rate of duration for mounting cycle of every slab of the house, slab mounting duration for the individual floors and the total duration for the whole building. The calculations were carried out for four types of cranes for every height marks.

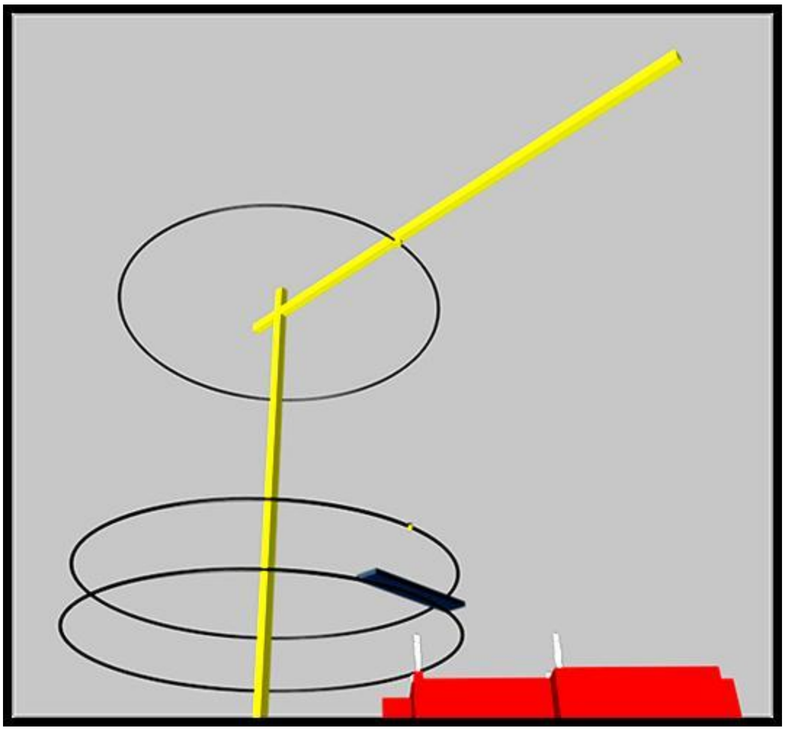

Figure 3. Swing rotation with the operational radius variation

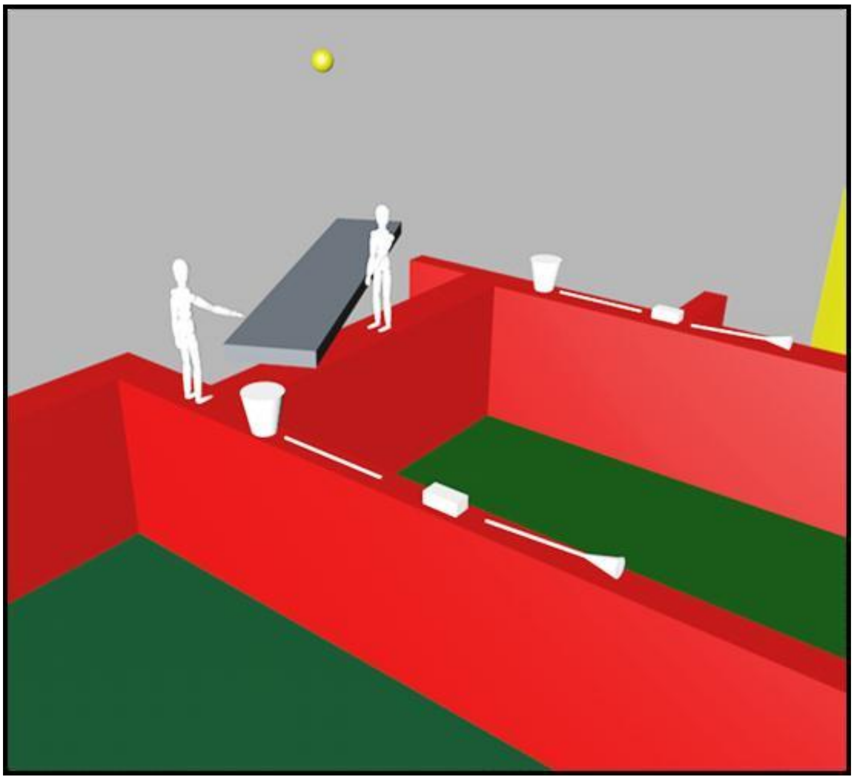

Figure 4. Setting the first slab on the mortar bedding

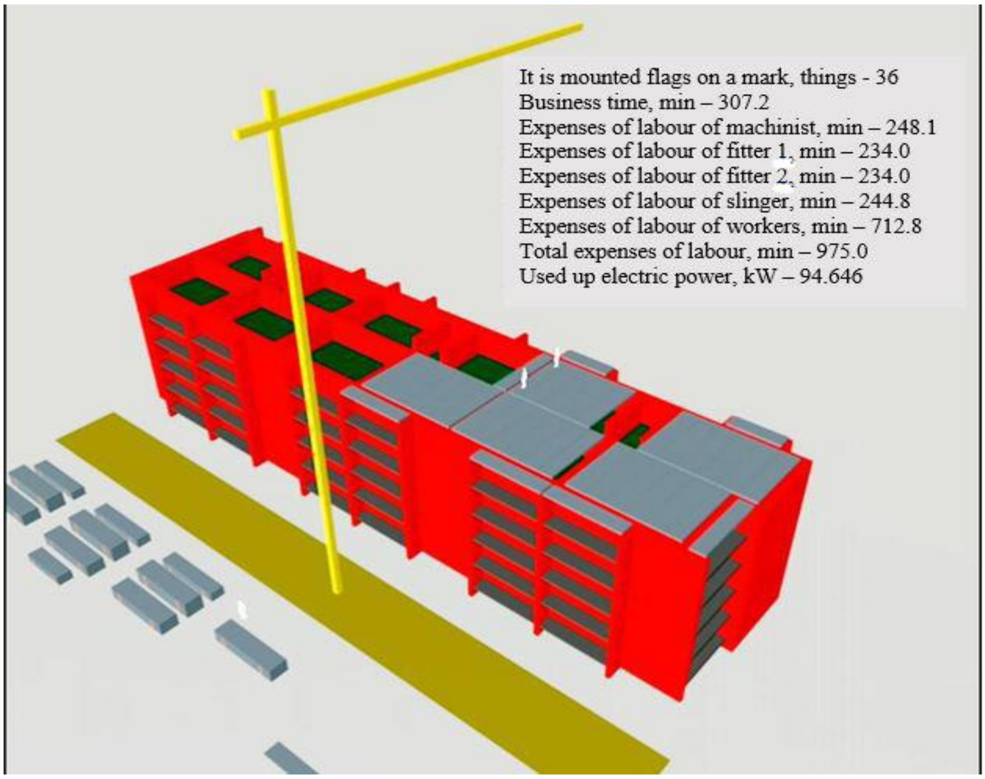

Figure 5. 4D-model of mounting the ceiling slabs

Results and Discussion

Aside from machine and human labor time rates FOS provides the calculation of power consumption, kWt, based on the passport specifications of the cranes. The results of varying labor requirements for the slab mounting on different floors are shown in graphs in Figure 6 (a, b, c). The comparative analysis of work of different cranes allows estimating their efficiency and making a valid choice of crane facilities, referencing the projected construction environment. Naturally, the methods in question may be used not only for ceiling slabs mounting, but for any operational sequence, one only needs to prepare the relevant input data, plan of constructions, types and properties of equipment.

Let us compare the calculated results of mounting duration for 80 slabs of one floor of the building, obtained with the designed FOS and the previously calculated rates without visualization, obtained in MS Excel. The duration in accordance with FOS is on the average 27 % longer. The reason for this is the inclusion of rated routine breaks within the operational activities, as well as the impediments in the crane operation at the collisions at the work area, providing work safety.

Method of computational analysis, carried out in MS Excel, combined with Cinema 4D visualization, reflects the “normal rate” of the operational sequence, that is, considers the current level of equipment and technology, occupational safety rules, complete procedural nomenclature, compliance of workmanship to the rates of work activity regulations. The influence of external factors, complicating the operational activity, may me taken into account with additional coefficients [48].

The provided method of rate setting is a supplement and development of several applications for the visualization software for construction operations. The authors of works, focused on the given matter, point out the drawbacks of regulatory framework for production engineering and organization in construction [10, 11, 14, 16] and propose a number of solutions for its perfection by means of informational technologies: grading and analysis of work activity structure in operational sequence using the graph theory [31, 32]; providing safe work environment for machine operations in the overall work area [20, 25]; reducing the risks of project execution in ambiguous conditions [34, 35, 36, 43], and so on. These propositions were partially considered and would be examined additionally within the improvement of the given method.

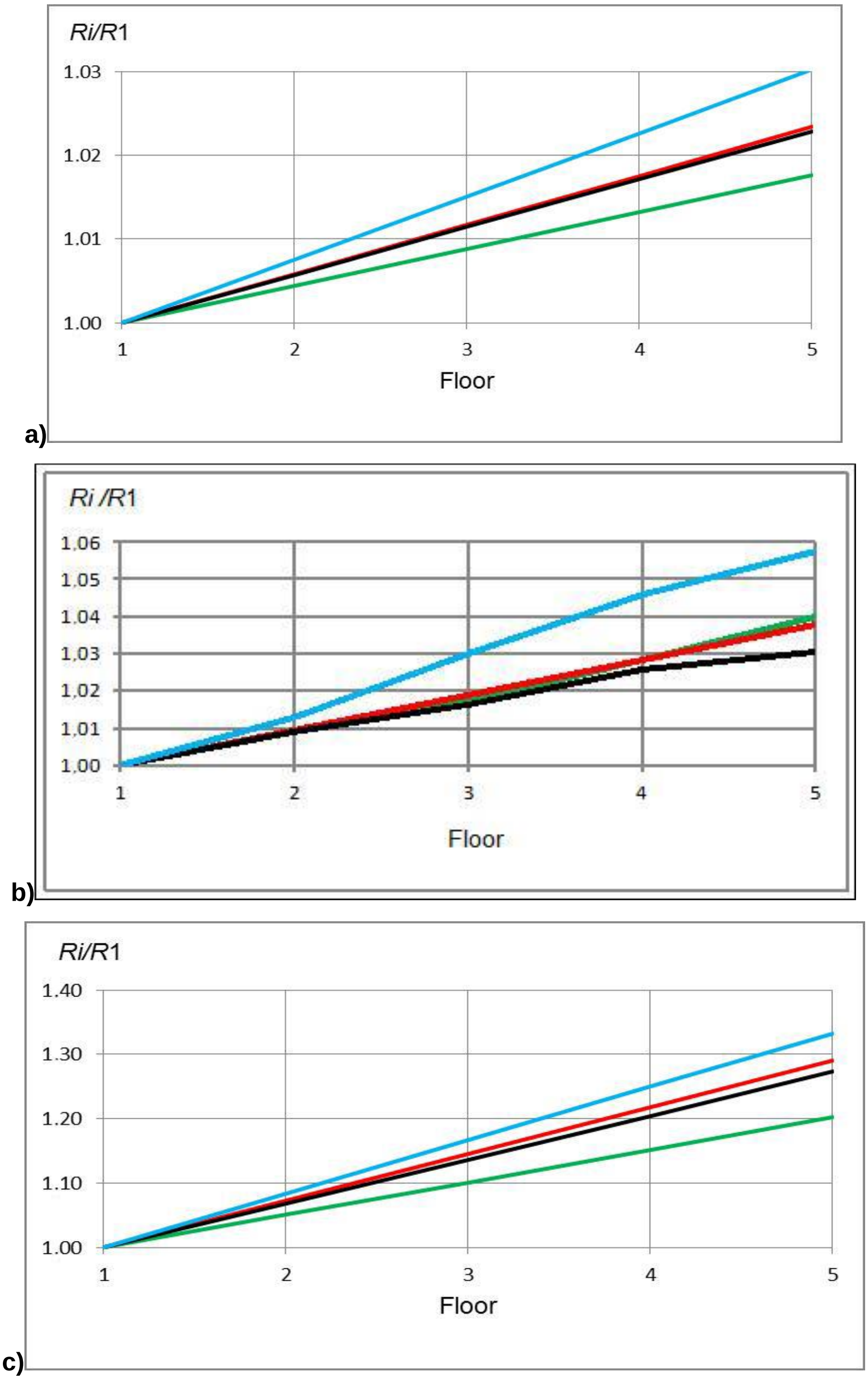

Figure 6. Relative variation of resources R_i required for ceiling slabs mounting on *i*-th floors to the respective resources R_1 required for slab mounting on the ground floor:
a) duration of crane operation;
b) labor required for mounting;
c) power consumption

The approach, laid out in the given paper, allows to use the tools of virtual reality for examination of work activity parameters, their qualitative and quantitative assessment at the construction site. The given suggestion provides new possibilities for rate setting and raising the efficiency of engineering and organization of construction.

Conclusion

The use of spatial-time modeling method in rate setting solves the following problems:

1. Improve the accuracy and reliability of rate setting based on synchronized calculations in MS Excel and software for operational sequence visualization, analyze the possibilities of safe combining the operational activities at the work area;

2. Improve the efficiency of executive solutions within CMP and WPP on the foundation of scientifically valid choice of the options for operating activities realization in flowsheets, using innovational technologies;

3. Reduce the labor required to develop the flowcharts of operational sequence at chronometer works and reviews at the immediate construction sites;

4. Improve the regulatory database of construction scheduling on the base of reference and methodical electronic databases;

Without doubt, the methodology of FOS is to be developed, first of all, with the use of specialized software, secondly, due to consideration of probability parameters of machine and human labor activities. The developing of FOC would allow the broadening of regulatory database for automated scheduling and improve the reliability of venue construction within the deadline.

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