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POSUDZOVANIE KVALITY ČASOVÝCH PLÁNOV STAVIEB

QUALITY ASSESSMENT OF CONSTRUCTION SCHEDULES

Príprava časových plánov je tvorivá činnosť. Podľa predstavivosti a vynaliezavosti rôznych riešiteľov sa môžu vytvoriť rôzne verzie plánov rovnakého projektu. Potom je potrebné sa pýtať, ktorý plán je najlepší, s ktorým scenárom vykonania prác je účinok prác navrhnutých riešiteľov najvýhodnejší. Tento článok uvádza formalizovanú metódu posudzovania kvality navrhnutých časových plánov. Jej metodický základ je založený na modeli procesu plánovania výroby v stavebnej výkonnej jednotke. Posúdenie plánu je vztiahnutie na absolútnu stupnicu (v intervale ⟨0,1⟩) a je objektivizované s využitím nákladov na stredné straty pri realizácii.

Preparing a schedule is a creative activity. Depending on the planner's imagination and inventiveness different visions of the plan of the same project are created. At this stage it is worth asking which plan is the best, with which scenario for the works execution the effect of the contractor's construction operation is the most desirable. This article presents a formalized method of construction schedules' quality assessment. Its methodical basis is constituted by the model of production scheduling process in a construction execution unit. The assessment of schedules is referred to the absolute scale (in interval ⟨0,1⟩) and is objectified using the costs of realization means outage.

1. Introduction

Schedule is a tool of material and time planning. In present times, in construction production planning, a computer with selected software for planning and controlling the project execution is used to prepare schedules. It allows constant updating of the vision of the operations, monitoring the progress of works, the engagement of resources, and an assessment of the effects.

Computer planning technique enables experimenting on models. The set of tasks defined by the organizer – planner can be modified in many different ways, thus generating different scenarios for the operations. Preparing a schedule is a creative activity. Depending on the planner's imagination and inventiveness different visions of the plan of the same project are created. At this stage it is worth asking which plan is the best, with which scenario for the works execution the effect of the contractor's construction operation is the most desirable. The answer to this question poses certain difficulties. Production schedules, and project schedules can be assessed using different criteria [1]. The criteria are a set of preferences, whose parts are most often mutually contradictory. In this case it is necessary to combine the criteria using usability functions or employing the technique of reaching compromise evaluations.

It must be stated that in the case of real production programs of construction execution units it is not possible to create optimal schedules in the exact meaning of the word. However, for each prepared production schedule it is possible to devise characteristics enabling its value assessment. In order to compare a few schedules a synthetic assessment index is required, which is always disputable because it is defined on the basis of partial characteristics.

This article will present a formalized method of construction schedules' quality assessment. Its methodical basis is constituted by the model of production scheduling process in a construction execution unit. The assessment of schedules is referred to the absolute scale (in interval ⟨0,1⟩) and is objectified using the costs of realization means outage.

2. Model of the scheduling process

Planning, in order to be concrete and reliable, must be based on real data. These data concern work consumption of construction processes as well as material and prefabricated units consumption, which are termed, in construction terminology, the resources input. In order to manage the resources we need to know their reliably defined input. In construction production planning practice is used a catalog construction database of material input KNR, enabling a computer cost calculation of construction works and computer project planning. For each task and construction project, whose technologies of work processes execution and their scope are known, one is able to determine the resource input for their realization in a relatively quick and reliable (which is the most important) way. The only problem is employing the information in managing the resources, allocating the resources to tasks, and defining the deadlines for works realization. All this is the subject of harmonizing construction production. Let us present a model of the scheduling process created with the use of a computer technique utilizing a catalog database of material input.

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Let us assume that all the catalog database tasks make up the set $O = \{o_1, o_2, ..., o_i, ..., o_I\}$. For each task is determined a quantity survey unit j_i ($i = 1, 2, ..., I$) and the usage of the material input – resources. Let us also assume that the resources constitute the set: $S = \{s_1, s_2, ..., s_k, ..., s_K\}$, in which the r of the first numbers constitute active resources. The remaining resources in set S are passive resources. We can further assume that the register of the active resources names makes up the subset: and the names of the passive resources constitute the subset: $S^b = \{s_1^b, s_2^b, ..., s_q^b, ..., s_Q^b\}$ The resource input per task unit is characterized by:

- labor consumption of the tasks defined in matrix $N = [n_{ik}]_{I\times K}$ by parts n_{il} for $1 = l, 2, ..., r$, representing the resource consumption $l : s_1 \in S^a$ per task realization unit $i : o_i \in O$.
- passive resource consumption defined in matrix $N = [n_{ik}]_{I\times K}$ by parts n_{il} for $q= r + 1, r + 2, ..., K$, representing the resource consumption $q : s_q \in S^b$ per task realization unit $i : o_i \in O$.

The active resources found in the database of tasks should help characterize the *production potential of the tasks' contractor* (or the contractors), defining their "state of possessions." Let us assume, for the sake of generality, that we will be considering many "contractors" and that for each of them we will be examining the quality of the schedule, of course as it relates to the given contractor. Such an approach is necessitated by the planning and construction realization practice. In any construction process are engaged many subjects – construction execution units, for which the issue of scheduling quality is a separate problem. Obviously, there is also a problem of global assessment – of harmonizing the work for all the contractors.

Let us assume that in the model the contractors constitute set $R = \{r_1, r_2, r_z, ..., r_Z\}$. The contractors' state of possessions will be described by matrix $\boldsymbol{P} = [p_{zl}]_{Z\times r}$, in which p_{zl} will determine the amount of the l-th resource in the z-th organizational unit of the set of contractors. Sets S, O, R and matrixes N, $\boldsymbol{P}$, and the unitary vector $\boldsymbol{J}$ constitute a computer database, which is very useful for planning analysis in organizing the operations. A block algorithm of organizational proceedings with computer facilitation is presented in fig. 1. In the process presented there one can distinguish three stages:

- *the assessment of the labor consumption and of the material needs* to carry out the tasks planned for realization;
- *harmonizing the operations* along with an assessment of the needs as to the means of the operations;
- *planning the use of the contractors' production potential* (examination of loading and reserves in the active resources work).

It is not difficult to carry out the first two stages using the existing computer programs (programs for analyzing the input, cost calculation, planning and controlling the project realization). Commonly used in construction, the technique of transmitting data from one application to another allows conducting the primary analysis of the operation's plan, that is tasks' realization schedule, efficiently and reliably.

The task database helps to quickly define the kind (set O^k) and the scope (vector $\boldsymbol{J}^k$) of works in the discussed projects and of the automation of material input calculation for their execution. Defined by the planner, set O^k, vector $\boldsymbol{J}^k$ and the calculated inputs- $N_k = [n_{ik}^k]_{I^k\times K}$; of work consumption n_{il}^k ($l = 1, 2, ..., r$); of passive resources usage - n_{iq}^k ($q = r + 1, r + 2, ..., K$), constitute an indirect database for the task scheduling stage. On their basis the set of harmonized tasks O^h is created, and the resource input is calculated for a newly defined task structure.

In this procedure are created subsets Y_i ($i = 1, 2, ..., I^h$) of set O^k. Each of subset determines the labor consumption and the usage of a passive harmonized tasks input (of set O^h). The labor consumption for these tasks (consuming the hours of work of the people and equipment), in the case of determining the composition of the execution team, is a decisive factor for the tasks deadline t_i:

$$t_i = \max_{l\in S^a} \frac{n_{il}^h}{\overline{x_{il}}} \qquad \text{for } z : o_i^h \in O^h \tag{1}$$

where: n_{il}^h – the labor consumption of the i-th task in relation to the l-th ($l : s_l \in S^a$),

$\overline{x_{il}}$ – the amount of resources of the l-th type directed to realizing the i-th task.

In the case of defining time $\bar{t_i}$, the amount of the needed active resources is generated:

$$x_{il} = \frac{n_{il}^h}{\bar{t_i}} \qquad \text{for } i : o_i^h \in O^h, l : s_l \in S^a \tag{2}$$

However, if the composition oft he execution team bas been determined – $\overline{x_{il}}$ and the time of task execution – $\bar{t_i}$, it is possible to calculate the maximum task labor consumption:

$$\overline{n_{il}^h} = \overline{x_{il}} \cdot \bar{t_i} \qquad \text{for } i : o_i^h \in O^h, l : s_l \in S^a \tag{3}$$

If this labor consumption is lower than the one required, the chosen values need to be verified, so that:

$$\overline{n_{il}^h} \geq n_{il}^h \qquad \text{for } i : o_i^h \in O^h, l : s_l \in S^a \tag{4}$$

Both the task and resource input are visualized in time scale, after the deadlines, time, and the mutual dependence of tasks are defined, generating the task execution and resource needs schedule. A generated schedule gives an overview of the sequence and timing of the operations execution. It lacks, however, any insight into the contractors' efforts towards these tasks. For this end, a dual analysis of the operations plan is used.

3. Planning the contractors' resources usage

Creating work schedules of each of the contractors' resources is a relatively problematic task, when conducted with the use of the commonly known applications. The programs for project planning exhibit certain flaws in this respect. If, for example, it is possible to monitor the labor consumption of the resources, at this particular stage of the program's work, there is no way of defining the tasks for the contractors. This problem can be solved as follows.

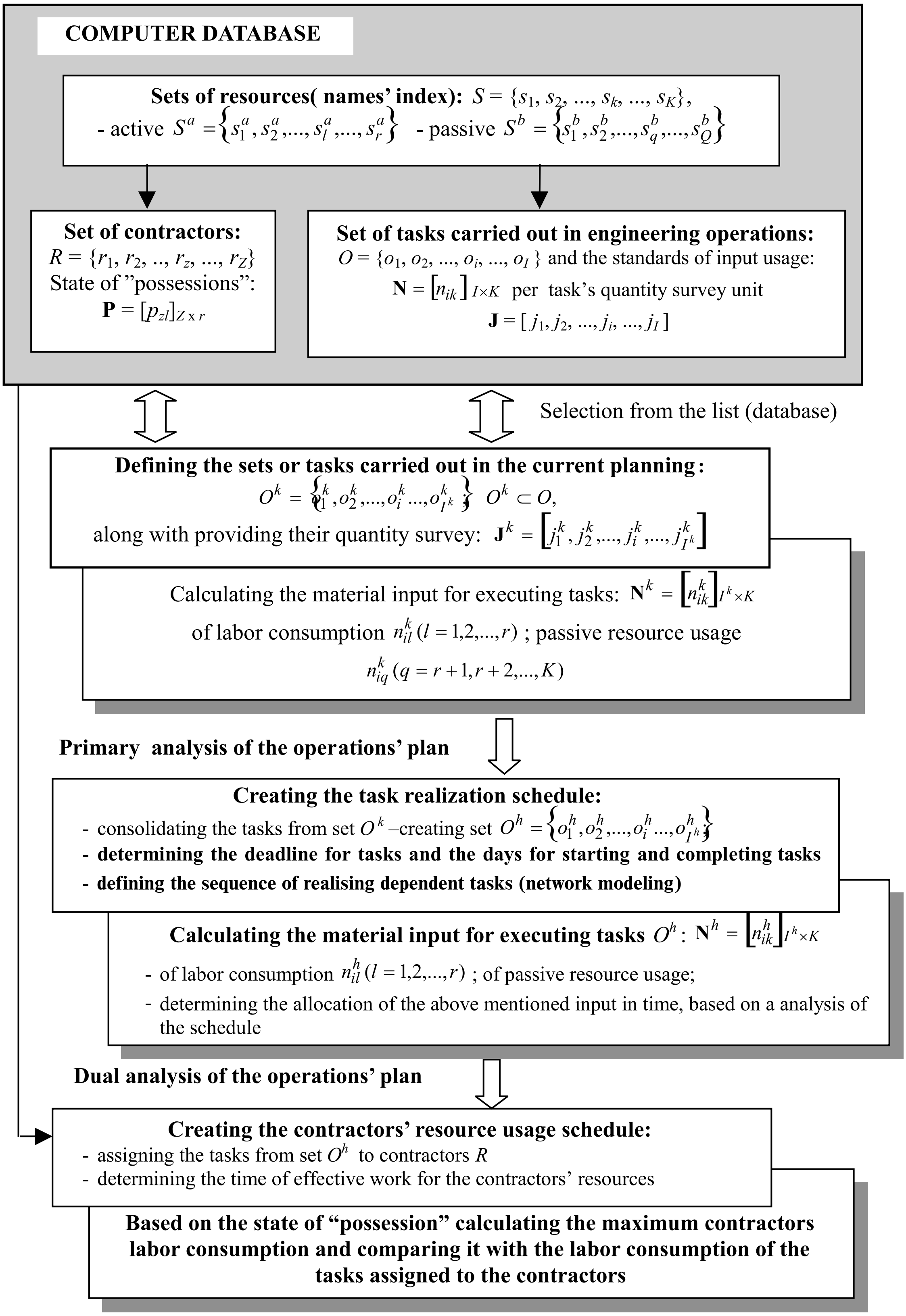


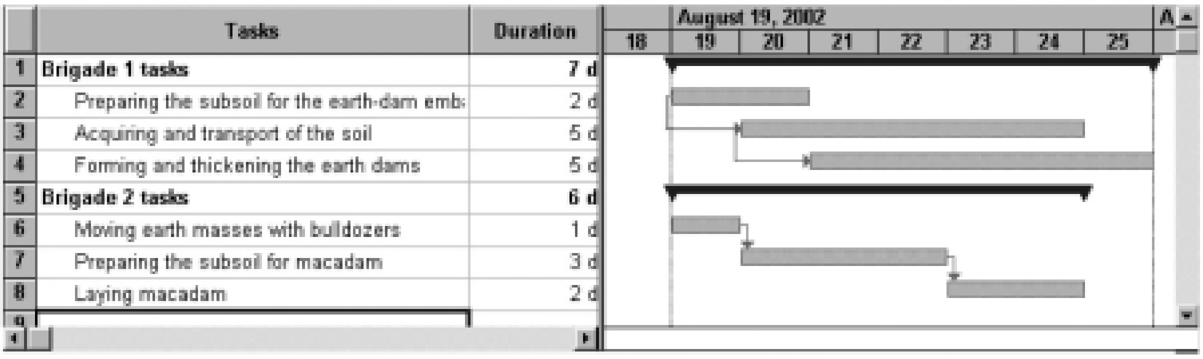
Fig. 1 Block scheme of planning the organization of operations with computer facilitation

For each of the contractors, we filter the initially created schedule (for *a″* the tasks). Thus we create separate schedules for the contractors, at the same time bearing in mind that the terms appearing in the general schedule should be defined. The available programs for project planning most often do not enable determining the allocation of the resources to the tasks defined in the

Taking-off quantities

No	Basis	Description	Quantity-survey unit	Quantity survey
1	KNR 2-01 0405-01 + KNR 2-01 0406-02	Preparing the subsoil for the earth-dam embankments	m^3	346
2	KNR 2-01 0202-02 + KNR 2-01 0214-04	Acquiring and transport of the soil	m^3	1500
3	KNR 2-01 0407-01	Forming and thickening the earth dams	m^3	2340
4	KNR 2-01 0229-02 + KNR 2-01 0229-05	Moving earth masses with bulldozers	m^3	350
5	KNR 2-31 0103-02	Preparing the subsoil for macadam	m^2	7*35 = 245.00
6	KNR 2-31 0204-05 + KNR 2-31 0204-01	Laying the macadam	m^2	7*35 = 245.00

Material tasks' schedule



Schedule of the resources' work

Workload of brigade 1 resources

	Brigade 2 resurses	Labor consumption	19	20	21	22	23	24	25
1	Workers	145.14 h	4.17h	15.24h	15.24h	24.68h	49.71h	36.1h	
2	Bulldozer 74 KW (100 KM)	5.81 h	5.81h						
3	Self-propelled static roller 15 t	5.49 h				2.19h	3.3h		
4	Self-propelled static roller 10 t	2.74 h				2.19h	0.55h		

Workload of brigade 2 resources

	Brigade 2 resources	Labor consumption	19	20	21	22	23	24	25
1	Workers	841.76 h	21h	70.56h	159.95h	159.95h	159.95h	159.95h	110.39h
2	Caterpillar bulldozer 55 KW	14.53 h	8h	6.53h					
3	Self-propelled vibrating roller 9t	44.08 h	5.7h		8h	8h	8h	8h	6.38h
4	Caterpillar digger 0.4 m3	86.55 h		17.31h	17.31h	17.31h	17.31h	17.31h	
5	Self-unloading truck up to 5t	727.8 h		145.56h	145.56h	145.56h	145.56h	145.56h	
6	Bulldozer 74 KW (100 KM)	76.75 h			15.35h	15.35h	15.35h	15.35h	15.35h
7	Vibrating combustion thickener	38.38 h			8h	8h	8h	8h	6.38h

Fig. 2. Diagram of methodology of construction tasks scheduling

schedule, along with providing the information on their labor consumption. An example of such an analysis is presented in fig. 2, where in the MS Project program, the workload of the organizational units was examined. The schedules of the tasks carried out by both the units were generated by filtering the project general schedule (the technique of filtering is essentially compatible with the commonly-known technique of filtering the data in spread sheets). The schedule contains all the data referring to the task labor consumption and the material resources usage (not shown in the schedule).

The screen "Resource Usage" shows the work of the resources in time and "after the tasks." Thus we are offered an extremely synoptic view of the production potential of each of the contractors. The sheet can be completed with information defining the unused potential of the contractor's resources labor consumption. It is the result of subtraction of the maximum and the needed labor consumption of each of the resources at the contractor's disposal. Resources shortages can be signaled on the screen.

The presented method of scheduling the work of the resources can be carried out using a properly prepared program for planning projects, or a special spread sheet. In both cases, it must be remembered that the schedule should be generated by the primary computer transformation of the prepared schedule. Of course, here the planner has an important role to play, as it is him who defines the tasks for the contractors, monitoring the results of his decisions on the schedules of their resources usage.

The schedules of the resources work created using the dual analysis of the plan carry very important information for the person directing the operations, since he can quickly evaluate which resources of which of the contractors are overloaded, and which are not used. A diagram of methodology of scheduling construction works is presented in fig. 2.

4. Resources-usage assessment as schedule-quality assessment

The basic problem in resource management is assigning harmonized tasks (set O^h) to the contractors of engineer and construction projects (set R). A planner should be aiming at the fullest use of the contractors' production means, that is assigning sets of tasks which require engaging the contractors' entire execution potential. This objective poses certain problems. The tasks are not dividable, are characterized by a specific sequence of execution, engage various sets of resources and have time-constraints (specified by instructions and implied in the schedule). Additionally, in many situations, "tearing" the contractors' structures (their resources assignment) is not practiced. In such situations, organizational units, for example, military sections receive sets of tasks to perform which do not engage their whole execution potential. Assigning tasks to contractors should depend on:

- the availability of the contractors' resources,
- executing tasks or tasks' stages within the deadlines set by the instructions.

Both these conditions can be effectively monitored by a program for planning and controlling project execution. Such programs make possible defining the deadlines for task realization specified by instructions, as well as calculating the resource needs and comparing them with the level of the resources availability in each time unit. However, how can one assess the quality of the plans as far as the resource use is concerned?

Resources (means of work) are of varied character. The outage of one means can be of negligible importance in the face of making a better use of another. This is why a synthetic index of the assessment of the resources' work time use is needed. It is advised that the index be determined based on the *cost of losses incurred by the work means' outage*. Each active resource, when working, brings the contractor (employer) given financial benefits. The benefits are result of indirect costs and profit calculated based on the direct costs of labor and equipment's work. A percentage index of these costs oscillates between 45 and 80 per cent of the direct costs. Knowing the piecework rate for workers and machines, it is not difficult to determine the cost of losses as a loss of the potential income from the resources' work costs surcharge. So, for example, an hour of a digger's outage can result in a potential loss of about 20-35 PLN, and a worker's outage can cost 5-8 PLN.

Let us assume that towards an estimate of the schedules' quality, an analyst is able to determine the cost of losses c_l ($l : s_l \in \in S^a$) caused by the work means' outage per time unit.

For the purpose of comparing the schedules for different contractors, one should strive to determine the index in the absolute scale. However, because work harmonization varies in the time scale, and the production activity of each of the contractors is practically never-ending, such an index should be determined in the function of time. Here, is meant both the time period for which we are examining the quality of work harmonization and the calendar time, and also the moments in the considered time scale.

In order to assess the quality of work organization, it is suggested to determine the index of the contractors' work harmonization in the examined time interval $\langle T; T + t\rangle$ for period t according to the formula:

$$C^z(t) = \frac{\sum\limits_{l \in S^a} \alpha_{zl}(t) \cdot c_l \cdot p_{zl}}{\sum\limits_{l \in S^a} c_l \cdot p_{zl}} \quad \bigwedge_{(z,l)} (c_l \cdot p_{zl} \neq 0) \tag{5}$$

where: $\alpha_{zl}(t)$ – is the coefficient of the work-time use of the l-th resource in time t.

The coefficient of the work-time use oft he l-th resource of the z-th contractor, for whom $p_{zl} > 0$, in time $t > 0$ is determined according to the formula:

$$\alpha_{zl}(t) = \frac{N_{zl}(t)}{p_{zl} \cdot t} \tag{6}$$

where: $N_{zl}(t)$ – work-time input of the l-th resource of the z-th contractor in time t determined based on the schedule in the examined time period – $\langle T; T + t\rangle$.

Index $C^z(t)$ does not describe the real costs of the losses in plan realization. It is only a quantity expression of the project realization schedule's quality, and more specifically, of work harmonization for the contractors. When the index approaches "1", it manifests a good planning decision, and when it reaches zero, it is a signal that the resources' work has not been harmonized. An examination of the resources use can be carried out for each of the contractors and for the whole task realization schedule, and in both cases - in optionally defined time periods. Such analyses are described in the example that follows.

5. Example of schedule quality assessment

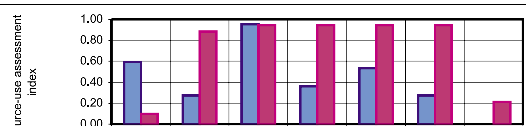
In order to assess the quality of a schedule, the following data referring to specified contractors should be known:

- state of resource availability (workers and machines) – amount of resources allocated to performing works specified in the material tasks schedule (if this availability changes in time, the resource availability profiles in the time scale should be known);
- work input (labor consumption) for each of the resources in the function of time (for example, on each day of the considered schedule);
- costs of the resources outage – potential loss incurred by the outage (non-usage) of each resources in unitary time (for example, during 1 hour).

For the schedule shown in fig. 2 and the labor consumption characterized there, we will carry out an analysis of resources-work harmonization in the case of two brigades. The work input of the resources of both brigades is presented in table 1. The state of the brigades' resources (resource availability) was determined in table 2. The table presents the profiles (the amount of resources changing in the time scale) of the availability of each of the work means. It also contains the assumed costs of losses incurred by the outage of each means during 1 hour. In table 3 are shown the results of work-time-use analysis by the available resources – coefficients $\alpha_{zl}(t)$ needed to calculate the synthetic index of the work-harmonization quality assessment for the considered contractors.

In figure 3 is presented the histogram of assessment of the contractors' resources work harmonization for each day of project execution. The diagram was made using formulas (5) and (6) for an 8-hour resources' workday. For each day were calculated the coefficients of work-time use on the part of the contractor's each resource, and next was determined the harmonization assessment index.

In figure 4 are presented graphs of the function of resource-work-harmonization assessment in variable time period counted from the commencement of the project until the time defined on the axis of ordinates. One can read from the graphs that the coefficients of resource use in the entire project are 0.43 for Brigade 1, and 0.71 for Brigade 2. The planner, however, will not always take under consideration the whole schedule of works. In particular, this will be the case when the scope of works for the single contractor is changing as a result of adding a realization system for tasks not included in the analyzed schedule. More important in this sit-



	19	20	21	22	23	24	25
Brigade 2	0.59	0.27	0.95	0.36	0.53	0.27	0.00
Brigade 1	0.10	0.88	0.95	0.95	0.95	0.95	0.21

Fig. 3. A histogram of the assessment of the resources' work harmonization for individual contractors on the individual days of project execution

Work input of the specified contractors in project execution — Table 1

Resources	Resource-work input in [h] on each day of project execution							Input in total
	10	11	12	13	14	15	16	
Brigade 1								
Workers	4.17	15.24	15.24	24.68	49.71	36.1		145.14
Bulldozer 74 KW (100 KM)	5.81							5.81
Self-propelled static roller 15 t				2.19	3.3			5.49
Self-propelled static roller 10 t				2.19	0.55			2.74
Brigade 2								
Workers	21	70.56	159.95	159.95	159.95	159.95	110.39	841.75
Caterpillar bulldozer 55 KW	8	6.53						14.53
Bulldozer 74 KW (100 KM)			15.35	15.35	15.35	15.35	15.35	76.75
Self-propelled vibrating roller 9 t	5.7		8	8	8	8	6.38	44.08
Caterpillar digger 0.4 m^3		17.31	17.31	17.31	17.31	17.31		86.55
Self-unloading truck up to 5 t		145.56	145.56	145.56	145.56	145.56		727.8
Vibrating combustion thickener			8	8	8	8	6.38	38.38

Resource availability for the specified contractors in project execution and costs of outage Table 2

Resources	Amount of resources available on each day of project execution							Costs of outage during 1 h
	10	11	12	13	14	15	16	
Brigade 1								
Workers	2	2	2	6	6	6		5 PLN
Bulldozer 74 KW (100 KM)	1	1						25 PLN
Self-propelled static roller 10 t				1	1	1		28 PLN
Self-propelled static roller 10 t				1	1	1		25 PLN
Brigade 2								
Workers	10	10	20	20	20	20	20	5 PLN
Caterpillar bulldozer 55 KW	1	1						30 PLN
Bulldozer 74 KW (100 KM)			2	2	2	2	2	25 PLN
Self-propelled vibrating roller 9 t	1	1	1	1	1	1	1	25 PLN
Caterpillar digger 0.4 m^3	2	2	2	2	2	2	2	30 PLN
Self-unloading truck up to 5 t	20	20	20	20	20	20	20	23 PLN
Vibrating combustion thickener			1	1	1	1	1	17 PLN

Results of the work-time use by the available resources – coefficients $\alpha_{zl}(t)$ Table 3

Resources	Values of the work-time use coefficients by the available resources on each day						
	19	20	21	22	23	24	25
Brigade 1							
Workers	0.2606	0.9525	0.9525	0.5142	1.0356	0.7521	0
Bulldozer 74 KW (100 KM)	0.7262	0	0	0	0	0	0
Self-propelled static roller 10 t	0	0	0	0.2738	0.4125	0	0
Self-propelled static roller 10 t	0	0	0	0.2738	0.0688	0	0
Brigade 2							
Workers	0.2625	0.882	0.9997	0.9997	0.9997	0.9997	0.6899
Caterpillar bulldozer 55 KW	1	0.8163	0	0	0	0	0
Bulldozer 74 KW (100 KM)	0	0	0.95945	0.9594	0.9594	0.9594	0.9594
Self-propelled vibrating roller 9 t	0.7125	0	1	1	1	1	0.7975
Caterpillar digger 0.4 m^3	0	1.0819	1.0819	1.0819	1.0819	1.0819	0
Self-unloading truck up to 5 t	0	0.9098	0.9098	0.9098	0.9098	0.9098	0
Vibrating combustion thickener	0	0	1	1	1	1	0.7975

uation will be a harmonization of the resources' work in the near time horizon. The discussed graphs contain the information needed in this case.

Fig. 4. Graphs of the function of the resources' work harmonization assessment in a period counted from the commencement of the project

6. Conclusion

The presented method of harmonizing the contractors' work can be applied for assessing and comparing the quality of schedules, including ones prepared by a number of independent planners and destined for the same scope of operations. The essence of the described approach is making the evaluation dependent on the time and reducing it to a uniform scale from zero to one, in which "1" denotes the state of full harmony in utilizing the means of work, and zero stands for the contractor's complete idleness.

It is possib1e to carry out an assessment using a synthetic index, as proposed here, only in a situation when one can perform a valuation of outage (idleness) – which is not conducive for the harmonizing process – of various work means (active resources).

It is worth bearing in mind that in practice it is rare1y possib1e to ensure constant work for all the resources. Most often, an elimination of the discontinuity in employing one resource results in breaks of the work of another. This is why there arises a need for a valuation of the resources' work, or strictly speaking, their idleness, which is derived from a valuation of work with costs taken under consideration. Here, was adopted a rule that the more expensive resource, whose work generates greater return, is more important for ensuring a constancy of work than the one whose work brings smaller financial benefits. Of course, a valuation of the idleness of various resources does not have to be determined by these rules. The process of valuation can be performed by the planner, based on the criteria of assessing the importance of constancy of work known to him.

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