Scientific Review – Engineering and Environmental Sciences (2019), 28 (2), 278–284
Sci. Rev. Eng. Env. Sci. (2019), 28 (2)
Przegląd Naukowy – Inżynieria i Kształtowanie Środowiska (2019), 28 (2), 278–284
Prz. Nauk. Inż. Kszt. Środ. (2019), 28 (2)
http://iks.pn.sggw.pl
DOI 10.22630/PNIKS.2019.28.2.26

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Optimizing the machine ensemble to perform construction tasks

Key words: optimization, machine ensemble, work planning, construction

Introduction

The problems of planning the construction production may be different. In planning, we design comprehensive mechanization systems, determine the best organizational solutions for cooperating work resources, we harmonize the performance of tasks with balancing the needs and availability of resources, we evaluate the costs of carrying out work, analyse risks, etc. However, the basic planning issue is to set a cost-effective team to perform a specific scope of construction works at a fixed or sought-after optimal time. In construction, this issue can be related to the set of construction processes distinguishing the technological order of their performance, or without distinguishing the technological order of performance – which often takes place in the conduct on large construction fronts.

In Poland, there is a technique of scheduling works, more precisely defining the work breakdown structure (WBS), based on cost estimates. It consists in combining cost processes into tasks, with specific material demands and costs (needed to complete the tasks included in the WBS). This technique has one fundamental disadvantage – the work inputs determined on the basis of KNR unit rates catalogue concern generalized machine resources (hereinafter referred to as standard) used in the past, now replaced by more efficient ones. This is irrelevant for the reliability of cost estimation, in which unit prices are related to the machine-working hours of these (generalized) devices. However, the transfer of the data from the cost estimation to the schedule results in an erroneous estimation of the task's duration and actual costs. Hence, in the scientific environment of construction projects' engineering, the problem of verification of labour consumption in the construction performance has been undertaken (Bac & Hejducki, 2017; Jaśkowski & Tomczak, 2017; Plebankiewicz, Leśniak & Karcińska, 2018).

The article presents methods for determining the time and costs of building tasks which include determination of a rational ensemble of machines required to complete those tasks. To make the work inputs factual for the available machines it is proposed to calculate the coefficients of work efficiency for each machine. Work efficiency coefficient is determined as a ratio of a real machine productivity to the productivity of the machine obtained with KNR unit rates.

Decision problem model for designating a set of machines to perform the task

Let us first consider the problem of determining a set of machines required to complete a set of construction processes $\{p_1, p_2, \ldots, p_{|p|}\}$, creating one task z (without distinguishing the sequence of execution of processes), for which work demands were defined using the application for cost estimation. By merging a set of processes into a single task and assigning the task z a new, specific unit of measurement and scope of works $p(z)$, the computer application for detailed cost estimation will determine the unit work demands related to the newly defined unit of measure of the task z. Let these resources form set $M = \{m_1, m_2, \ldots, m_r\}$, and the unit workloads for the execution of task's z single unit are determined in the vector $\mathbf{N} = [n_1, n_2, n_r]$. These workloads are related to resources (e.g. machines) which are standard means of production (included in the KNR catalogues), which in the construction execution are often realized by conversion into real means of production, however, have different productivity characteristics and unit labour costs.

Let us assume that the planner has different types of work resources in their individual types $m_1, m_2, \ldots, m_r$. They form subsets M_i ($i = 1, 2, \ldots, r$) of available means of production. In each subset of the available means of production M_i, different types of machines are distinguished (e.g. specific machines) $\{m_i, m_{i2}, \ldots, m_i|m_i|\}$. They can be mutually substituted and have specific unit labour costs $c(m_{i,j})$, and their number is limited by the variable $l(m_{ij})$ for ($j = 1, 2, \ldots, |m_i|$).

Let us introduce the concept of "machine's work efficiency factor – $e_{i,j}$" for the available means of production. It is determined according to the relationship:

$$e_{i,j} = \frac{W_{i,j}}{w_i} \quad \text{for } (i = 1, 2, \ldots, r;\ j = 1, 2, \ldots, |m_i|) \tag{1}$$

where:
$W_{i,j}$ – efficiency of the j-th available means of production;
w_i – efficiency of the standard means of production determined by the dependence: $w_i = 1 / n_i$.

The unit workloads of the available means of production in the performance of the task z can be determined by dividing the standard unit workloads $\mathbf{N} = [n_1, n_2, n_r]$ by coefficients $e_{i,j}$:

$$N_{i,j} = \frac{n_i}{e_{i,j}} = \frac{1}{w_{i,j}} \quad (2)$$

for $(i = 1, 2, ..., r;\ j = 1, 2,\ ...,\ |m_i|)$

It is important in these analyses to relate the efficiency of the available means of production to the uniform (for all means of production) conditions during the implementation of task *z*.

To solve the problem, we determine the number of types of work resources involved to perform task *z*, ensuring its execution in the available time $<t_{min}, t_{max}>$. Let's seek solutions by minimizing the costs of task execution, or by minimizing the time required to complete this task (assuming simultaneous operation of all machines). The mathematical model of such a problem may be as follows.

Let the decision variables be $x_{i,j} \in R^c$. They define the number of available resources directed to complete task *z*. The index *i* will identify the resource, while index *j* – its type, characterized by a specific efficiency $W_{i,j}$ (achievable in the conditions of task *z* implementation). These variables should meet the condition of integrity and limitation:

$$x_{i,j} \leq l(m_{i,j})$$

for $(i = 1, 2, ..., r; j = 1, 2, ..., |m_i|$ (3)

Decision variables must have such values that the conditions for the performance of the entire work are met, namely:

$$p(z) \leq \sum_{j=1}^{|m_i|} \frac{x_{i,j}}{N_{i,j}} \cdot t(z) \quad (4)$$

for $(i = 1, 2, ..., r)$

where $N_{i,j}$ specifies the workload of the *i*-th resource of the *j*-th type, when performing task *z* unit and it is specified according to the relationship (2).

The duration of task *z* performance can be determined from the dependency:

$$t(z) = \max_i \frac{p(z)}{\sum_{j=1}^{|m_i|} \frac{x_{i,j}}{N_{i,j}}} \quad (5)$$

for $(i = 1, 2, ..., r)$

The duration should meet the condition:

$$t_{min} \leq t(z) \leq t_{max} \quad (6)$$

If we assume that the resources in the number $x_{i,j}$ will participate in the performance of the task *z* throughout the entire time $t(z)$, then some of them (due to the efficiency mismatch) will be just partially used. This underutilization of resources should be minimized through the cost of loss (Marcinkowski, 2007, 2015; Marzantowicz, 2016; Krawczyńska-Piechna, 2017). However, without knowing the distribution of resources' involvement into task *z* completion, let us determine $x_{i,j}$ by minimizing the cost of their work, assuming that all resources involved into task performance work the entire time $t(z)$:

$$\min K:\ K = \sum_{i=1}^{r} \sum_{j=1}^{|m_i|} t(z) \cdot x_{i,j} \cdot c(m_{i,j}) \quad (7)$$

The optimization problem consists in determining decision variables $x_{i,j} \in R^c$ and minimizing the value of the function (7), or (5) (min $t(z)$),while meeting the conditions specified by the relationships (3), (4) and (6). Such model can be solved with the use of computer simulation, using for example Solver in the

MS Excel spreadsheet. The use of a spreadsheet allows the planner to experiment: limit the number of available resources to complete the task *z*, or change the available time interval <t_{min}, t_{max}> to complete the task.

Determining the machine ensemble organization to perform the construction undertaking

The construction contractor often faces the problem of organizing a brigade to carry out a set of works at a specific place (work front). These works of various nature and scope often require the involvement of various means of work to a different extent. Knowing the types and ranges of building processes to be carried out in the situation under consideration (let's call them an undertaking), the contractor wants to establish a brigade (the type of resources and their number), which will be able to complete the undertaking within an acceptable time, and these resources can be used effectively. Therefore, the goal is the same as in the problem of organization of the team to perform the task, but the "task" is represented here by the sequence of processes with heterogenous demand for resources, more precisely – heterogenous workload demands.

The issue can be solved during project scheduling, using variant allocations of available means of work and verifying workloads with the machine work efficiency factor – $e_{i,j}$ (1). Of course, in each organizational variant, the unit cost of working resources (machines) should be made real, and in additional, the analysis of the cost of losses due to resources underutilization should also be carried out – as in Marcinkowski (2015) and Krawczyńska-Piechna (2017). The planning analyses in cost estimation applications (here Norma PRO) and scheduling ones (here MS Project) should be conducted according to the following methodology:

1. The following should be done using the cost estimation application:
   a) determine a set of tasks in WBS, combining budget items with tasks that will be harmonized in the schedule;
   b) make working resources (in several variants) real – specify machines that can actually be used in the implementation of tasks, set real unit productivity rates for them and real costs of their work;
   c) save the data in order to develop variant schedules in a format that will allow for data import into a scheduling application, e.g. MS Project.
2. The following should be done using the project scheduling application (here MS Project):
   a) define the project calendar and the start data of the planned project;
   b) for each variant of the set of resources allocated to complete tasks:
      – determine the availability of working resources and their calendars;
      – allocate resources to tasks (specify allocation units), determine tasks' duration;
      – introduce the network model to the undertaking and ana-

lyse the obtained workloads of available resources;

– in case of an unacceptable overload of resources, balance the resources and allow for adjusting resource allocations to tasks and division of remaining work (standard settings);

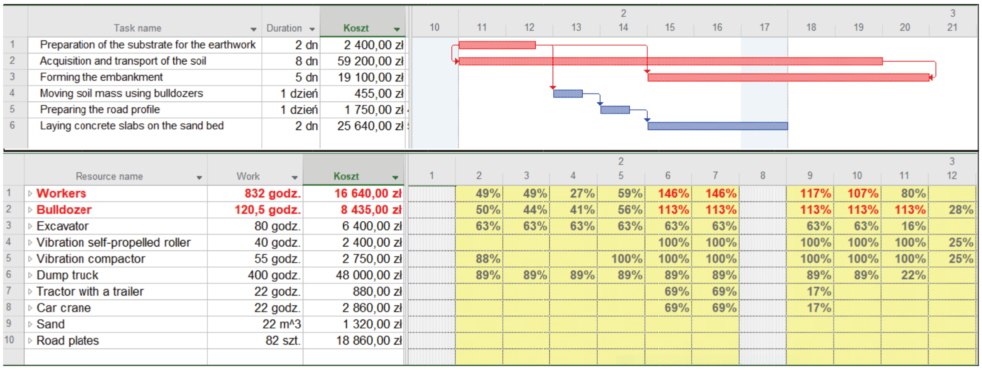
– print the resource usage table (Fig. 1) with the remaining availability.

c_i – unit loss due to the underutilization of the *i*-th resource – related to the workload unit (e.g. *m-h*);

n – number of analysed resources.

We can determine unit losses c_i according to the principles presented in Kapliński (2007) and Marcinkowski (2013), which is brought down to their calculation for each considered resource according to the formula:

$$c_i = c_i^p \cdot \frac{w_{kp}}{100} \cdot \left(1 + \frac{w_z}{100}\right) \qquad (9)$$



	Task name	Duration	Koszt
1	Preparation of the substrate for the earthwork	2 dn	2 400,00 zł
2	Acquisition and transport of the soil	8 dn	59 200,00 zł
3	Forming the embankment	5 dn	19 100,00 zł
4	Moving soil mass using bulldozers	1 dzień	455,00 zł
5	Preparing the road profile	1 dzień	1 750,00 zł
6	Laying concrete slabs on the sand bed	2 dn	25 640,00 zł

	Resource name	Work	Koszt	1	2	3	4	5	6	7	8	9	10	11	12
1	**Workers**	**832 godz.**	**16 640,00 zł**		49%	49%	27%	59%	146%	146%		117%	107%	80%	
2	**Bulldozer**	**120,5 godz.**	**8 435,00 zł**		50%	44%	41%	56%	113%	113%		113%	113%	113%	28%
3	Excavator	80 godz.	6 400,00 zł		63%	63%	63%	63%	63%	63%		63%	63%	16%	
4	Vibration self-propelled roller	40 godz.	2 400,00 zł						100%	100%		100%	100%	100%	25%
5	Vibration compactor	55 godz.	2 750,00 zł		88%			100%	100%	100%		100%	100%	100%	25%
6	Dump truck	400 godz.	48 000,00 zł		89%	89%	89%	89%	89%	89%		89%	89%	22%	
7	Tractor with a trailer	22 godz.	880,00 zł						69%	69%		17%			
8	Car crane	22 godz.	2 860,00 zł						69%	69%		17%			
9	Sand	22 m^3	1 320,00 zł												
10	Road plates	82 szt.	18 860,00 zł												

FIGURE 1. Example of a schedule and "Resource usage" view in the MS Project, developed for a specific variant of the set of resources assigned to perform tasks

3. In the Excel spreadsheet, analyse the costs of the "remaining availability" using the results obtained from the MS Project (Marcinkowski, 2015).

The total costs $S(P)$ due to underutilization of resources are determined according to the formula:

$$S(P) = \sum_{i=1}^{n} (N_i^d - N_i^w) \cdot c_i \qquad (8)$$

where:

N_i^d, N_i^w – work, respectively: available and used for the *i*-th resource in the time period considered (time the resource spends in the construction);

where:

c_i^p – unit work cost of the *i*-th resource;

w_{kp}, w_z – percentage rates of indirect costs and profit, calculated in the construction cost estimation.

Figure 1 shows an example of project implementation schedule with an analysis of resources' utilziation, for which the calculation of costs of remaining availability is shown in Figure 2.

In the spreadsheet (Fig. 2), having fixed times for the project completion by brigades organized according to different variants, and using the information on unit cost of losses due to resource's

Calculation of remaining labour costs

Resource name	N_i^w	Available resource workloads per day [hrs]											N_i^d	c_i^p	$S(i)$
Workers	832	112	112	112	112	112	84		112	112	112		980	14 zł	2 072 zł
Bulldozer	120,5	16	16	16	16	16	12		16	16	16	16	156	49 zł	1 740 zł
Excavator	80	16	16	16	16	16	12		16	16	16		140	56 zł	3 360 zł
Vibration self-propelled ro	40					8	6		8	8	8	8	46	42 zł	252 zł
Vibration compactor	55	8	8	8	8	8	6		8	8	8	8	78	30 zł	690 zł
Dump truck	400	56	56	56	56	56	42		56	56	56		490	84 zł	7 560 zł
Tractor with a trailer	22					16	12		16				44	20 zł	440 zł
Car crane	22					16	12		16				44	90 zł	1 980 zł
													$S(P)$		**18 094 zł**

FIGURE 2. Excel spreadsheet for calculating costs of remaining availability for a given variant of a set of resources allocated to perform tasks (acc. to Fig. 1)

underutilization, we assess the variants by calculating the total cost of losses due to the incomplete resources' utilization for the entire project. The calculations are carried out according to the formulas (8) and (9), for the time periods in which a given resource is available at the construction site (in the considered front of works).

Recapitulation

The presented approach to the problem of determining machine ensemble does not solve the whole issue. One can imagine a situation that the contractor, for an undertaking with a defined sequence of tasks, will have an opportunity to choose the types of resources, as presented at the beginning of the article. In such case, contractor should choose types of working resources and determine their number. So far, this problem has not been solved yet in modern methods of planning and scheduling – which does not mean that such issue cannot be solved.

A concept outline of dealing with the described problem may be as follows. For individual tasks p_k (distinguished in WBS), means of work (creating subsets M_{ik}) should be defined with unit costs of their work and unit productivity. Finding a solution (a schedule) should be carried out in two cycles that include: (1) drawing machines for each task performance, and (2) scheduling the project incorporating randomly drawn machine ensembles. The scheduling process is particularly troublesome, which in this case should be carried out with a computational algorithm dedicated for this purpose. Each schedule should be characterized by: deadlines for tasks completion, resources allocation and costs of resources' underutilization. Of course, each schedule should meet executive constraints (directive deadlines, availability of resources). This issue can be further extended by risk analysis in schedules by defining data on unit workloads and unit costs of resources as random variables (Marcinkowski & Koper, 2008).

The development of a computer application to run the above-mentioned concept is possible, however, entering data for real construction project into such an application would involve a large amount of work. So long as we do not develop organizational variants of the implementation of construction tasks in dedicated knowledge bases, creating computer tools that simulate and search the best schedules will be pointless.

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Summary

Optimizing the machine assembly to perform construction tasks. The article presents ways to search for the optimal composition of an assembly of machines/set of resources to perform a set of construction processes on separate work fronts, distinguishing the technological order of their execution and without distinguishing the technological order of execution. The method of approach to the problem is subordinated to the scheduling technique using cost estimates, in particular data on material inputs for the performance of work processes and unit costs of these outlays. In the optimization models, the cost and time criteria were used, providing flexibility in the formulation of preferences by the planner.

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