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Modelling the set of earthworks machinery with the use of computer simulation

Key words: building works modelling, earthworks effectiveness, technology design, stochastic processes, computerized simulation

Introduction

Nowadays, completing the ordered construction works within assumed time is a must for a responsible contractor. The future orders strongly depend on the opinion about a given contractor, especially about their responsibility (Leśniak, Plebankiewicz & Zima, 2012; Ibadov, 2017). Completing the ordered construction works on time is one of the ways to earn the clients' good reputation. Once the general schedule is agreed between a client and a contractor, it is necessary to prepare the detailed plan of every work execution – the technology design. It allows to assign required resources to every construction activity, thus providing further smooth operation and keeping-up the schedule. Usually the assignment of the resources is based on deterministic values of the machinery and labor efficiency. During the phase of the work execution occurs that – when even unnoticeable disturbances are noted – the real duration of a given scope of work is longer than planned. It leads to the conclusion that the average efficiency of means of production is not a sufficient base for the technology design. The case, where five types of machines execute five types activities leading to the creation of the compacted sand layer (as a part of the road structure) is analyzed in two ways: deterministic and stochastic one. For the assumed scope of work and the assumed time of the work execution, the set of machines was assigned with the use of the traditional deterministic method. Therefore, assuming that the time of the single cycle of the machine is not stable, simulations were proceeded for modelling real circumstances of the earthworks. As it was expected, the total time of making the complete san layer was longer than calculated on the deterministic data. The necessity of not exceeding the planned time was the reason for working out the solution. The correctness of the solution found was proved on the statistic bases. The choice of the optimal set of construction machinery is important for the cost of the work execution (Sobotka, Radziszewska-Zielina, Plebankiewicz & Kowalik, 2014) and for the level of environmental pollution too (Pawłowska, 2018).

The case

It is assumed the 4 km section of a new road is built and 20 cm thick sand layer has to be placed. The high capacity trucks deliver the aggregate to the storage area located 1 km away far from the beginning of the road under construction. There the medium capacity, all wheels drive (AWD) trucks are loaded and they transport the aggregate to the destination, starting from the furthest place, i.e. located 5 km from the storage area (not to drive on the sand layer just placed). The aggregate is levelled by the bulldozer and then compacted by a roller. The set of activities is shown in Figure 1. The total time of the process was limited to 21 days (8-hour shift). The input data to the model is summarized in Table 1.

The efficiencies of the loader, bulldozer, and roller were assumed – for the paper purposes – as exactly suitable for completing the layer in 21 days. The

TABLE 1. Assumed input data

Element	Parameter	Value	Unit
Quarry	distance to the storage area	7.0	km
Heavy trucks	load	24.0	t
	average velocity	25.0	$km \cdot h^{-1}$
	loading time	6.5	min
	unloading time	3.0	min
Storage area	capacity	100.0	t
Loader	efficiency	0.01667	$h \cdot m^{-3}$
AWD trucks	load	13.0	t
	average velocity	10.0	$km \cdot h^{-1}$
	loading time	8.0	min
	unloading time	2.0	min
Bulldozer	efficiency	0.01667	$h \cdot m^{-3}$
Roller	efficiency	0.01667	$h \cdot m^{-3}$
Sand Layer	width	12.0	m
	thickness	0.2	m
	length	4 000.0	m
	volume	9 600.0	m^3
	weight	15 840.0	t

number of necessary heavy trucks and AWD trucks was calculated to match the efficiency of the rest of the machines.

Research method

The technology of the process of laying the aggregates was assumed as follows (Martinek, Nowak & Woyciechowski, 2010; Martinek, Jackiewicz--Rek, Książek, Kaczorek & Rosłon, 2015):

FIGURE 1. The analyzed process – the set of activities

– the whole section of the road built is divided into 20 identical fields (12 m by 200 m);
– the aggregate delivery and levelling to one field is done during one eight--hour shift;
– the compaction of the layer is done the next day and lasts 8 h;
– the work starts from the furthest field (from the storage area).

The schematic layout of the construction site is shown in Figure 2.

The results were rounded up to integer values. There were 9 AWD trucks necessary to handle the assumed 480 m^3 per shift efficiency for the furthest Field 1, and 3 of them for the closest Field 20. The number of heavy trucks necessary for deliveries of aggregates to the storage area was calculated in the same manner but it was constant for each of day, i.e. three heavy trucks required.

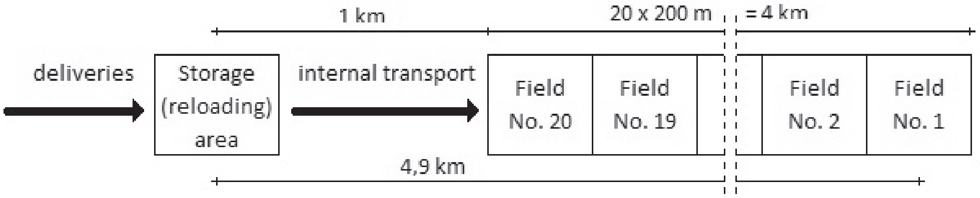

FIGURE 2. The schematic layout of the construction site

Deterministic approach

Calculations were done based on the required daily efficiency equal to 480 m^3 of aggregates delivered, reloaded, transported and levelled on one field. The centers of gravities of the storage area and the field were assumed for calculation of the average distance that the AWD trucks had to drive twice a cycle. Knowing their average velocity and the load it was possible to calculate the required number n of AWD truck for each day using the following formula:

$$n = 480 / \left(\frac{T}{t} \cdot L \right) \tag{1}$$

where:
T – the time of one shift [min];
t – the average cycle time of AWD truck [min];
L – the load of a single AWD truck [m^3].

Stochastic approach

The simulations are used in many papers concerning earthworks (Liu, Lu & Johnson, 2013; Furian, Neubacher, O'Sullivan & Walker, 2017). In case described, the stochastic approach allowed to get closer the whole process to real conditions, where the cycle time of all machines, as well as its capacity is normally distributed. In order to estimate the total time of construction works, the authors decided to simulate data, drawn with a normal distribution. The simulation is made using the algorithm developed in Microsoft Excel environment.

The time step of simulation is 0.1 min. The simulation begins with the delivery by heavy trucks, which cycle time and capacity are drawn with the deviation assumed. Heavy trucks are able to unload the sand at storage area as long as its maximum capacity of 100 t is not exceeded. The loader, which efficiency is drawn, is able to work as long as AWD car is substituted and capacity of reloading area is greater than the capacity of the AWD truck. The number of AWD trucks working on particular days is determined on the basis of deterministic approach with the difference of distance taken for the calculation. During the simulation the authors have noticed that determining the necessary truck number on basis of the center of working field leads to additional delays, as loaders efficiency is not sufficient in the second half of each day. This was the reason for changing of the initial assumption and determining the number of necessary trucks on the basis of the distance between the center of gravity reloading area and end of the each field.

In case of AWD trucks, the authors modelled the cycle time and the capacity with deviation. The trucks responsible for internal transport can be loaded, as soon as loader is released. The efficiency of a bulldozer and a roller were drawn with deviation too. The roller begins its cycle when the bulldozer level at least 50 m of the road. Data used in the simulation is presented in Table 2.

The simulation was repeated 100 times. Each iteration consist of delivering, loading or unloading the aggregates is registered. The labor of the bulldozer is registered every 60 min. The labor of the roller is registered every 50 m of the compacted road, which is in this case every 198 t.

The simulation code consists of almost 1,000 lines. Despite the fact, that in the case described, the loop is repeated around 110,000 times, simulating a single case that lasts around 30 on an ordinary personal computer.

TABLE 2. Assumed deviation of machines cycle times and efficiency

Element	Type and value of the deviation
Heavy trucks	capacity deviation – 2.5 t, time deviation – 4 min
AWD trucks	capacity deviation – 0.5 t, time deviation – 10% of driving time
Loader	$0.0015\ h \cdot m^{-3}$
Bulldozer	
Roller	

It may be worthy carrying out this kind of calculation in the construction site office prior to work execution to avoid unexpected delays.

Results

The initial authors' expectations of the significant influence of inconstant time and quantity of works done during each cycle for the construction work on total time have been confirmed, as single delay of any machine affects the work of all machines involved in the process. Nevertheless, the influence was greater than expected. The average time of construction works after simulation of 100 cases is almost 193 h (24 days). Moreover, the lowest result is over than 190 h, i.e. over three days longer than expected. The maximum deviation assumed is lower than 11%, while the deviation of total construction works time is almost 15%.

Registering each cycle of all machines involved in the process during the simulation allowed to find the weakest links. They are: waiting for the storage area, waiting for loading AWD trucks and internal transport. Furthermore, as the simulation shows the machines with the greatest deviation, i.e. heavy trucks, are not responsible for the delay.

The total downtime of heavy trucks for waiting unloading was the greatest (95.6 h at average). The total downtime of AWD trucks is 54 h, and downtime of other machines is around 30–33 h. The total downtime of AWD trucks depends not only on their capacity, but also on its quantity working on particular hours.

After many trials the authors have noticed, that the storage area capacity has to be increased 10 times more than efficiency of other machines involved in the construction works. To show the effect of this increase, the authors have decided to gradually make improvements.

The efficiency of the loader, the bulldozer and the compactor as well as the capacity of AWD trucks are increased by 2%. To improve the second weak link, the storage area capacity was increased by 20%. Those steps are repeated until the model finds the assumed 21 days of total construction works time. Finally, the total downtime of all machines comes to 20–30 h. Each data is simulated 100 times, what allows to acknowledge the result as obtained on the basis of a big sample (Aczel, 1993). The results of particular calculations are presented in Table 3.

TABLE 3. Variants used for further simulations

Variant	AWD trucks capacity increase [%]	Loader, bulldozer, roller efficiency increase [%]	Storage area capacity increase [%]	Average total time of construction works [h]	Standard deviation [h]
Initial data	–	–	–	192.80	0,810
1	2	2	20	187.20	0,920
2	4	4	40	182.30	0,820
3	6	6	60	177.50	0,750
4	8	8	80	172.80	0,670
5	10	10	100	168.30	0,720
6	12	12	120	163.97	0,755

Summary and discussion

The results of the simulation for each variant have been checked through Shapiro–Wilk test (Kot, Jakubowski & Sokołowski, 2011; Rabiej, 2012) and the normal distribution of the time of the work execution has been confirmed (with the use of Statistica 12 software). The histograms for the base variant and for the variant where efficiency is increased by 12% are shown in Figures 3 and 4, along with the normal curve found. The visual evaluations of the histograms (Internetowy Podręcznik Statystyki, 2018) confirms their near-to-normal shapes too.

Those calculations – made for every variant – allow to check probability of the works completion a given period.

Figure 5 presents the curves for every variant. Planned 168 h can be achieved

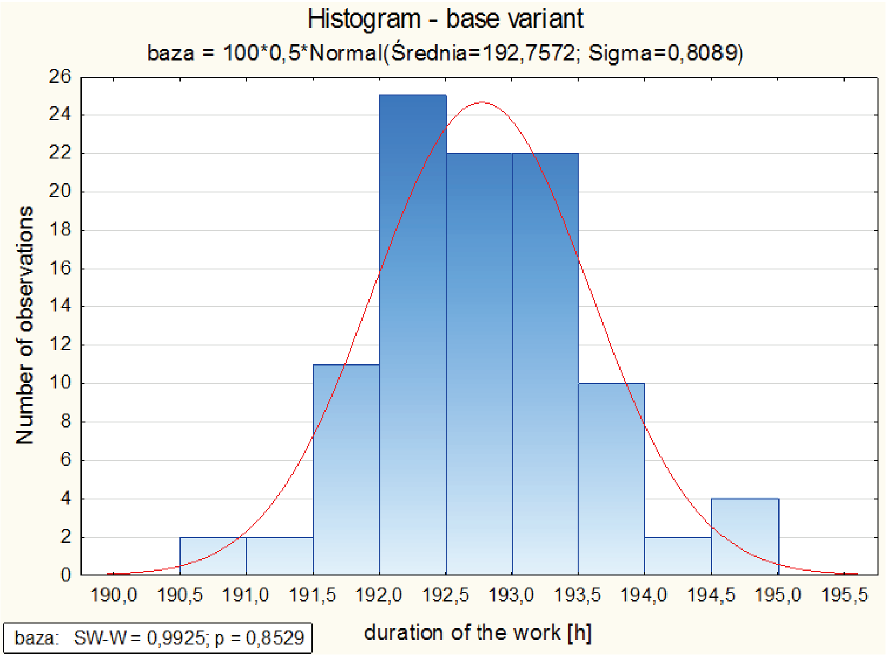

FIGURE 3. Histogram of simulated times of the work execution for the base variant

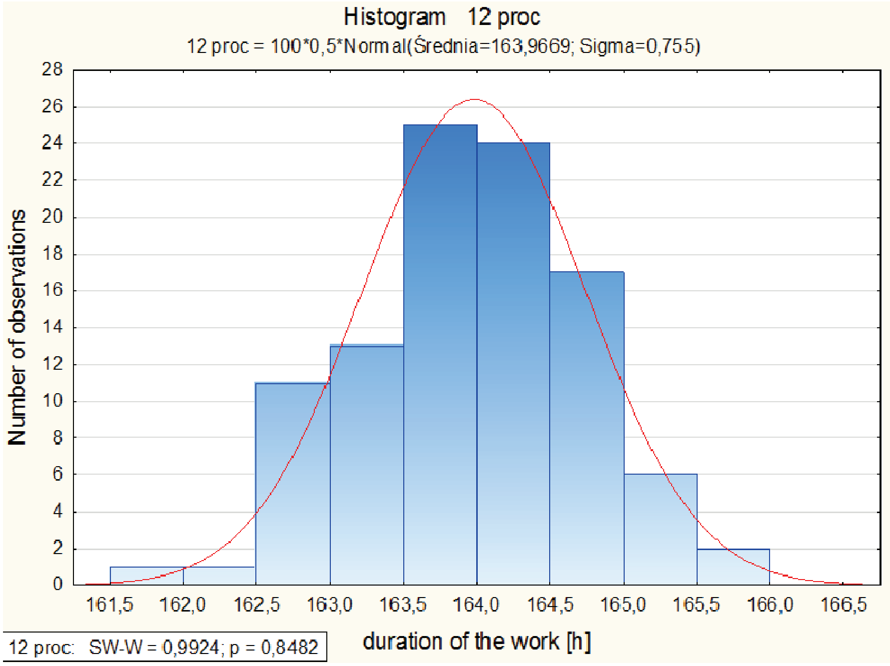

FIGURE 4. Histogram of simulated times of the work execution for the Variant 6 where machinery efficiency was increased by 12%

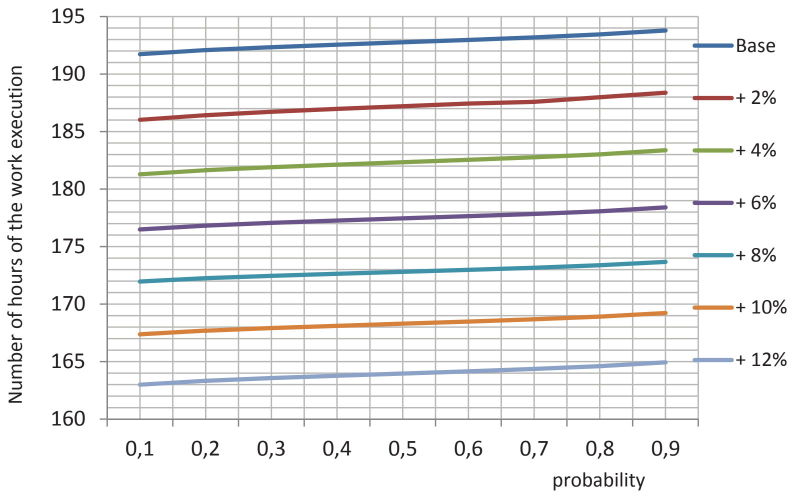

FIGURE 5. The level of certainty of completing the work in a given time for all variants

in Variant 5 with 40% certainty. In Variant 6, it is almost sure that the work is finished before 165 h from the start (90% certainty).

Conclusions

The methodology of quality assurance based on "risk-based-thinking" points out the goal of such analysis as the first stage (Deszcz, 2017). The goal for many linear works is finishing the construction in time assumed. Linear construction works always involve a great number of building machines. Some of those vehicles use public roads, all of them are operated by a human. Every time a huge amount of loose material is shifted – there are difficulties in the precise metering. This leads to the conclusion, that the cycle time of used machines and their efficiency are inconstant. If analyzed separately, the normal distribution of machine cycle time should not affect much the time of the task accomplishment. Nevertheless, in the case as described in the article, where the work of the set of machines is optimized, the time disturbance of each machine affect all consecutive parts of the chain. In the end, it may cause a significant delay of the total construction time, even if no other reason for delay is identified. Identification of such cause of delay – i.e. do not applying stochastic approach for technology design – can be done before the start of the work execution (Anysz, 2017). For this reason, the influence of the cycle time deviation should be identified as the risk in construction works, where a set of machines is involved. The simulation can be used as the reaction to the risk of construction works execution delay (Kulejewski, 2010; Iqbal, Choudhry, Holschemacher, Ali & Tamošaitienè, 2015). It can also contribute to the optimization of the construction equipment cost.

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Summary

Modelling the set of earthworks machinery with the use of computer simulation. The paper presents the comparison of deterministic and stochastic approach for modeling the set of earthworks machinery. Simulation takes into account the normal distribution of cycle time and efficiency of machines and points out its influence for total construction works time. Results of the simulation indicate the need of identification time and efficiency deviation as a risk factor, which can cause delay whenever earthworks cycle includes the serial work of several machines.

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