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Influence, of time randomness execution of work, on lenght of the construction cycle

Wpływ losowości czasów wykonywania robót na długość cyklu budowy

Abstract

The objective of this paper is to analyse the time reserves in scheduling periods for conducting processes that ensure construction deadlines can be met. By using the probability account and numerical analyses methods, including 'Monte Carlo', execution cycles have been analysed, as well as summary stoppage times for executing teams and working areas. On the basis of calculations made using data from studies made during the construction office building in Krakow it was stated that in order to keep to the planned deadline, must be smaller periods of performance of works by individual brigades, an average of 0,103 times of rhythm.

Keywords: time reserves, random processes, construction cycle

Streszczenie

Celem jest analiza buforów czasu gwarantujących dotrzymanie planowanego terminu realizacji zadania. Z wykorzystaniem rachunku prawdopodobieństwa i metod analiz numerycznych, w tym „Monte Carlo", zbadano okresy cykli realizacji zadań oraz sumaryczne czasy przestojów brygad wykonawczych i działek roboczych (frontów pracy). Na podstawie obliczeń danych z budowy biurowca w Krakowie stwierdzono, że dla zachowania planowanego terminu realizacji zadania, konieczne były mniejsze okresy wykonywania robót przez poszczególne brygady, średnio o 0,103 czasu trwania rytmu.

Słowa kluczowe: bufory czasowe, procesy losowe, cykl zadania

1. Introduction

The execution of particularly large construction projects requires the simultaneous employment of a significant number of staff, often several dozen, and sometimes, several hundred or more. In such cases, the organisation of work for specialist teams is a complex task [1, 2, 6–9, 11, 12]. With the assumption of a constant duration of particular processes, a work execution cycle can be easily determined by using the formulas developed by A. Dyżewski [3, 5, 7, 10]. However, the actual execution of work at the construction site is characterised by random see above note variability in the duration of particular processes. In line with the studies that follow, such random deviations cause many distortions in execution and elongation of the work execution cycles.

The analysed office building in Krakow, with a total area of 57,000 m^2, features one underground car-parking level under the building and from the east, under the car park and greens on the ground level, and under a one-storey administration building. The height difference between the floors is 320 cm, except for the south-western part of the building, where the ground floor is double the height of the standard storey at 675 cm, and the 12^{th} storey, the height is 375 cm.

The building has been designed as a pole-and-slab system made of vertical and horizontal joists and poles, set on a slab of reinforced concrete with a 1.0m thickness, at a depth of 5.05m below ground level, with recesses up to 6.60 m below the lift shafts. The building features: two cores of reinforced concrete, each comprising lift shafts, four for the transport of people, and one freight lift; stiffening shafts and a staircase. The building is constructed as a monolithic of reinforced concrete in Peri formwork: the walls have a thickness of 20 cm, formed with flat multidimensional disks, rectangular poles with dimensions 60 cm × 60 cm. And floors of 26 cm thickness made on supports with stabilising tripods and on wooden beams covered with formwork plywood of 22 mm, while untypical shapes are individually formed, also using Peri systemic elements.

Concrete class C30/37. Concrete mix with S4 and S5 consistencies, with cement setting start after 3 hours.

2. Balanced workload method

Professor Aleksander Dyżewski from Warsaw University of Technology, author of *Doktryna pracy równomiernej w realizacji budowlanej* [*Doctrine of balanced workload in construction works*] [3], and later other authors [7, 10], pointed to the balanced workload method (*PR*) as the most favourable approach for the organisation of work at the construction site.

In order to apply the *PR* method, the works differentiate *n* – work areas. Each work area should be a construction area which:

- comprises the entire facility, in the case of several small facilities forming the works, or a part of a large facility resulting from its division into fragments requiring similar labour *R*, materials *M*, and equipment operation *S*;

- is necessary to create a workstation and assure work area;
- is usually entrusted to one team to execute a consecutive work forming a separate whole.

Work areas analysed below have been labelled as i, $i = 1, 2, \ldots, n$ and described with a set $i \in I$.

In other works, in the case of the *PR* method, the building facility is divided into n – work areas with similar *RMS* outlays, or in the case of n – repeatable smaller facilities, each one is treated as a work area. Usually, one work area is entrusted to one team who carry out a particular process during the 'rhythm' – r, or its multiplicity. A team carries out the same work process while moving consecutively along all work areas, from the first to the last one. After completing a particular process, each area is taken over by the next team who, after completing their work, hand it over to a team executing the next process (according to the construction technology). In such a way, each area, in the technological order, undergoes all processes j, $j = 1, 2, \ldots, m$ described with the set $i \in I$, consecutively from the first $j = 1$, to the last $j = m$.

In the deterministic approach, with the assumption of constant times for executing each process at work area during rhythm r, execution of a set of all m – processes at one, e.g. the first area, lasts for the time $t = mr$. Processes at each consecutive area commence at rhythmic intervals, hence their completion occurs, respectively, a rhythm r later. Therefore, completion of the execution of a process at area n – the last area occurs later than at the first area by $r(n-1)$.

The period t^{PR} – of work execution cycle using the *PR* method thus totals:

$$t^{PR} = t + r(n-1), \tag{1}$$

or

$$t^{PR} = r(m+n-1), \tag{1a}$$

$$r = \text{const.}$$

In the case of the balanced workload method, and when we can perfectly predict the above times for the execution of each process in the work area during rhythm r, it is very favourable to have t_{pc}^{PR} – continuous working time of any team on the task, which is n times greater than the period of rhythm r (as it is repeated on execution of a particular process at all areas) totalling:

$$t_{pc}^{PR} = nr, r = \text{const.} \tag{2}$$

In actual conditions at the construction site, particular execution times t_{ij}, at work areas i, of processes j are undetermined, but are characterised with random values, with significant dispersion against the central tendency. Using the example below, the impact of the random process duration on the execution cycle of the entire task is analysed.

3. Example

On each storey of the building, four work areas are defined, with the width of facility projection, in the other direction (along the building) limited with axes 1÷4, 4÷7 with core I, 7÷9 with core II, and 9÷11. Due to the building structure, the first and second work areas are larger than work areas 3 and 4.

According to actual execution works, $m = 8$ processes have been differentiated:

1) formwork, pole reinforcement;
2) concrete pouring of poles;
3) formwork, reinforcement of core of the buildings and elevators;
4) concrete laying for core of the buildings and elevators;
5) formwork of joists, beams, lintels and floors;
6) reinforcement of joists, beams, lintels and floors;
7) concrete laying of joists, beams, lintels and floors;
8) formwork, reinforcement and concrete laying of stairs.

Formwork and reinforcement of poles, and the other processes of concrete laying of poles, were executed in the same work areas.

Formwork and reinforcement of walls in core I of the building and elevator shafts, and the other processes of concrete laying of walls in core I of the building and elevator shafts, were carried out in parallel with pole execution on work areas $1k$ and $2k$ (k – refers to storey of the building). Analogically, execution of core II and the elevator shafts was performed in parallel with pole execution on work areas $3k$ and $4k$.

Formwork of joists, beams, lintels and floors, was executed in advance of one work area against reinforcement of joists, beams, lintels and floors, and one work area against concrete laying for such elements. The last process involved formwork, reinforcement and concrete laying for stairs.

3.1. Task execution cycles and stoppages of teams and work areas

Following the analysis of process execution times at the construction in question, it was determined that average time totalled $t_m = 3.125$ work shifts with a standard deviation of particular measurement results $\sigma = 1.287$. Therefore, the relative standard deviation is very high, totalling as much as $\delta\sigma = 41.18\%$. Distribution of process execution times ranged from $t_{min} = 2.5$ shift to $t_{max} = 6.5$ work shift.

In further analysis, the average time $t_m = 3.125$ work shift has been identified with one time unit: 1 t.u. = 3.125 shift.

For the adopted values of rhythm time $r = 1$ t.u., $m = 8$ processes and $n = 4 \cdot 12 = 48$ work areas (4 work areas on each of the 12 storeys) task execution time using the balanced workload method totals $t^{PR} = 55$ t.u.

Based on numerical calculations using a network model with a deterministic *see above note* structure and meeting the conditions of the technological order of execution of works and as above with random process duration characteristics, after carrying out 10,000 simulations, obtained average values, namely values occurring with the probability of 50%, have been presented in Table 1 and Fig. 1.

Table 1. Task execution periods and summary waiting times of teams at work areas

Process execution period t_m	Task execution cycle t^{PR}	Task execution time t_{los}	Absolute cycle elongation Δ_c	Relative cycle elongation δ_c	Work area waiting time τ_d	Team waiting time τ_b
[t.u.]	[t.u.]	[t.u.]	[t.u.]	[%]	[t.u.]	[t.u.]
1.0	55.000	61.146	6.146	11.17	156. 32	24.141
0.897	49.335	55.000	5.665	11.48	142.043	18.771

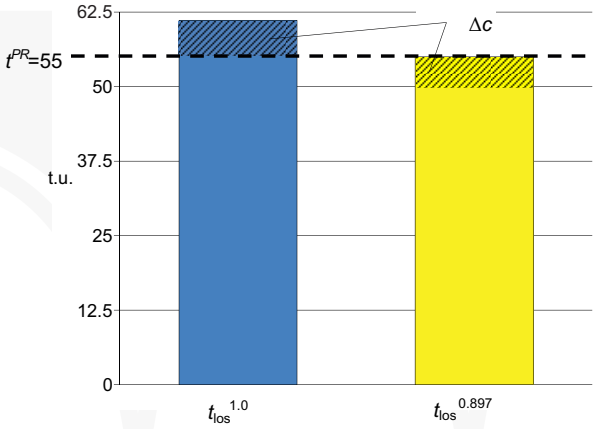

Fig. 1. Task execution times $t_{los}^{1.0}$, $t_{los}^{0.897}$ considering random process duration, respectively for t_m = 1.0 t.u. and t_m = 0.897 t.u. and Δ_c – execution of task execution time against the cycle t^{PR}

Following the results of numerical calculations, while considering random duration of particular processes, task execution time is elongated, in absolute terms by Δ_c = 6.15 t.u., while in relative terms by δ_c = 11.17% as compared to the cycle t^{PR} = 55 t.u. calculated according to the balanced workload method.

In turn, in order to ensure that task execution time is equal to the calculated t^{PR} = 55 t.u., it is necessary to ensure a smaller value of rhythm duration by 0.103*r*, specifically, the process duration to be applied should be t_m = 0.897 t.u.

This problem is very frequent in construction works. Despite process execution times with average values equal to the rhythm *r*, actual random values of such times cause significant prolongation of the task execution period. For example, at the analysed construction site, relative elongation of the execution time amounted to, as above, over 11%. Therefore, in order to preserve the cycle t^{PR}, the planned rhythm duration in the analysed case (with the determined empirical characteristics of processes completed) should be reduced by approximately 10.3%.

As a consequence of the impact of the random duration of particular processes, there are both periodic stoppages in work areas whilst waiting for the start and execution of the next process, and periodic stoppages of teams occurring as a result of failure in making work areas

available by the teams still completing previous processes, Fig. 2. Waiting time in work areas totalled $\tau_d^{1.0}$ = 156.32 t.u. Prolongation of the task execution time amounted to Δ_c = 6.146 t.u.; this prolongation of the task execution is over twenty-five times less than the total waiting time of all work area results from the fact that waiting time refers to forty-eight work areas, at each of which may have been down time for several times (in the special case: 8 times – corresponding to the number of processes executed), or there may have been no stoppages at all.

In turn, summary waiting time of the teams, totalling $\tau_b^{1.0}$ = 24.141 t.u. is about 3.9 times greater than the elongation of task execution time Δ_c.

Similar proportions of stoppages for work areas and teams were observed while applying, in the calculations, of expected process execution time t_m = 0.897 t.u.

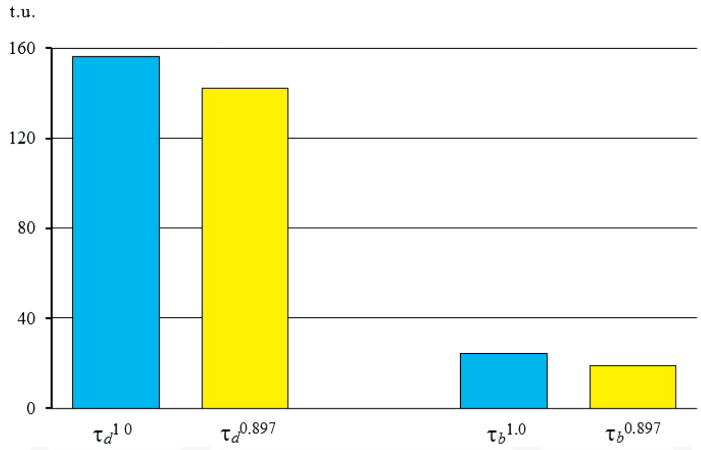

Fig. 2. Waiting times at work areas $\tau_d^{1.0}$, $\tau_d^{0.897}$ and of teams $\tau_b^{1.0}$, $\tau_b^{0.897}$ considering the impact of random process duration, respectively for t_m = 1.0 t.u. and t_m = 0.897 t.u.

3.2. Variability of task execution time and stoppages of teams and work areas

Task execution times t_{los} and summary waiting time of work areas τ_d and of the teams τ_b depending on the number of work areas n where the eight processes are repeated, are presented in Table 2 and Fig. 3.

Table 2. Variability of task execution periods t_{los} and total waiting times of work areas τ_d and teams τ_d, depending on work area number n

n	1	2	4	8	16	32	64	128	256	512	1024	2048
t_{los}	8.3629	9.6551	12.146	16.78	25.727	43.111	77.183	144	276.05	537.75	1057.7	2093.7
t_{los}/n	8.3629	4.8275	3.0365	2.0975	1.6079	1.3472	1.2059	1.125	1.0783	1.0502	1.0329	1.0223
τ_d	0.2834	0.8884	3.0506	9.142	27.672	81.09	242.02	722.48	2101.9	6094.7	17705	50767
τ_d/n	0.2833	0.4442	0.7626	1.1427	1.7295	2.5341	3.7815	5.6443	8.2104	11.903	17.289	24.788
τ_b	1.5874	3.0974	5.1067	8.528	12.849	19.369	29.046	42.291	61.482	89.38	127.99	183.12
τ_b/n	1.5873	1.5487	1.2766	1.066	0.8031	0.6053	0.4538	0.3304	0.2402	0.1745	0.1249	0.0894

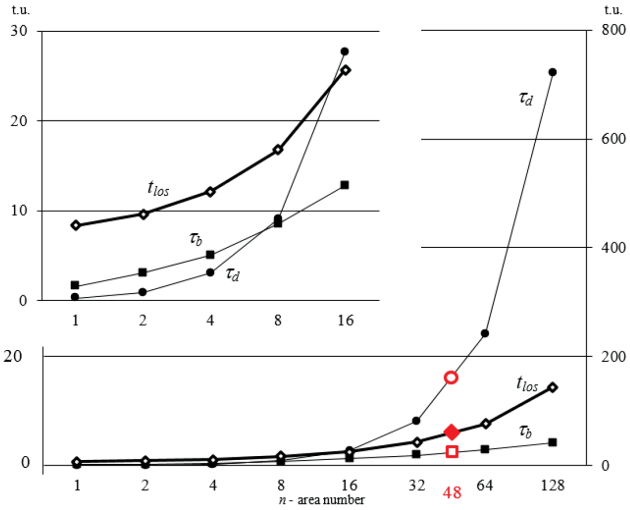

Fig. 3. Task execution times t_{los} and summary waiting times of work areas τ_d and teams τ_b, by work area number n

In the case of increasing the work area number n, for example, as a result of multiplying the number of storeys or extension of the planned facility, the time for process execution tlos is extended. According to the results of calculations (Fig. 1, Table 2), for the analysed values $n = 1, 2, 4, \ldots, 2048$ ($n \in I$), task execution times are greater than the corresponding τ_b – than summary waiting times of the teams:

$$t_{los} > \tau_b,\ n \in I. \tag{3}$$

In the analysed case, for a smaller number of work areas n, from about 15, namely for $n < \sim 15$, summary waiting times of work areas τ_d, similarly as team stoppages, are smaller than task execution times t_{los}. In turn, for a greater number of work areas n, from about 15, namely for $n > \sim 15$, summary waiting times of work areas τ_d are greater than task execution times t_{los}, with the intensively growing discrepancy together with further growth of the value n.

Therefore:

$$t_{los} > \tau_d,\ n < \sim 15, \tag{4}$$

$$t_{los} < \tau_d,\ n > \sim 15. \tag{5}$$

In cases where the work area number is smaller than 8, namely for $n < m$ (where m means the number of teams, here $m = 8$) the total waiting times of work areas is smaller than the summary team stoppages, while in cases with a greater number of work areas – work area stoppages are greater than team stoppages, with the intensively growing discrepancy with the further increasing number of work areas:

$$\tau_d < \tau_b,\ n < m, \tag{6}$$

$$\tau_d > \tau_b,\ n > m. \tag{7}$$

Fig. 4 and Table 2 present the variability of task execution periods t_{los} and total waiting times of work areas τ_d and teams τ_d, depending on work area number n where the processes are repeated.

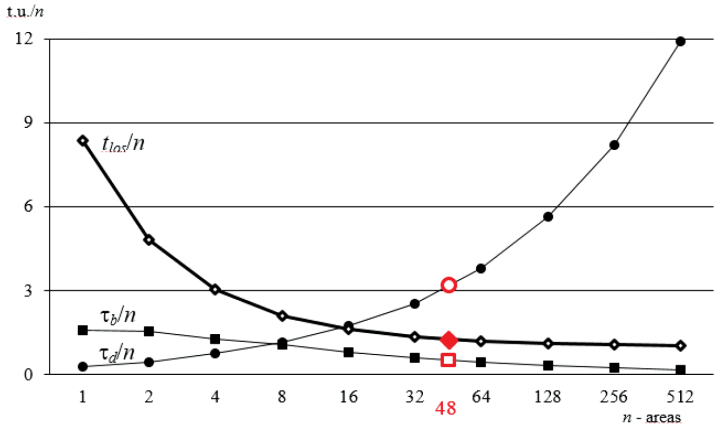

Fig. 4. Variability of the proportions between task execution periods t_{los} and summary waiting times of work areas τ_d and teams τ_d, depending on work area number n

The proportion of task execution time t_{los} to the number of work areas n where processes are repeated, with n growing from 1 to 2048, suggest that with further increasing of the value $n \to \infty$, there is a correlation of proportion value to 1. In turn, the proportions of summary team stoppage times τ_b to the number of work areas n, also in the case of n growing from 1 to 2048, suggest that in the case of increasing the value n as above, there is a correlation of proportion results to 0. In the case of work area number also growing from 1 to 2048, the proportions of summary waiting times of work areas τ_d to their number n indicate that for $n \to \infty$ there is a discrepancy of proportion results to the infinity.

4. Conclusion

The analysed actual process execution times while executing the building shell were characterised with average duration t_m = 3.1 shift, a high standard deviation of σ = 1.3, a large distribution of process execution times, with minimum time t_{min} = 2.5 shift, and t_{max} = 6.5 shift.

On the basis of numerical calculations, with the application of model distributions compatible with the actual characteristics at the site, it is determined that random times of particular process duration has caused, among other factors, long waiting times of particular teams for their work areas. Team stoppages totalled approximately 39%, against the task cycle time. In turn, the total work area waiting time (at 48 work areas) lasted over 2.5 times longer than the average task execution cycle t^{los} = 191 shifts.

As compared to the task execution period calculated using the deterministic method as the total of average process duration, the actual task execution cycle, accounting for random

conditions at the site, is longer by over 11%, and keeping the deadline with 50% certainty requires the application of over 10% shorter times of particular process execution.

The performed analyses allow for pointing to the interdependence where if the n – work area is smaller than m – number of teams (processes), summary waiting times of work areas τ_d are smaller than summary team stoppage times τ_b. Therefore, $\tau_d < \tau_b$ for $n < m$, and the contrary correlation $\tau_d > \tau_b$ at $n > m$.

The characteristic large distributions of particular process execution times that were actually observed at the site, are a significant cause for stoppages of teams and work areas, and cause significant prolongation of the task execution cycle, hence the need to account for their impact.

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