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REDUCING THE DURATION OF THE FLOW-LINE CONSTRUCTION IN PARALLEL USING EXISTING TEAMS

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In this article, a matrix model (ones (rank organization of types of work matrix (ROTW)) is used to determine the location and connection in space and time of the main and additional parallel grippers. The main works are used to calculate the values of grippers by a sequential parallel method for technologically similar processes, and additional ones – by a parallel method to increase the amount of resource. The mathematical model includes the research objective and parameters that affect the construction time. The optimal solution is achieved by the parallel method in stages: by reducing the periods and duration of flow-lines, initial and final values of grips and critical works. There has been no study of a sequential method of reducing the construction period using only existing crews. The effectiveness of the phased method of reducing the construction period is determined in comparison with the method of using additional parallel flow-lines

Key words: periods of deployment and convolution of flow-lines; serial-parallel and parallel method; variant design; technologically similar works; rank matrix with priority on the work front; Critical Path Method.

Introduction

For energy-saving technologies of building construction, rational constructive, organisational and technological solutions (COTS) should be introduced on the basis of variant design, which will allow the introduction of resource-saving technological and constructive solutions for the construction of the building (Hrihorovskyi P. Ye., 2022; Mudrjy I., 2011; Hicks S. J., 2004; Using modern, 2005). Variant design for the organization of work allows to reduce construction time by introducing additional labour resources and redistributing workloads between related processes. In non-rhythmic flow-lines, this condition can be achieved by the parallel and parallel-serial methods, with the solution of the issue of reducing the deployment(convolution) periods of flow-lines (Ivaneiko I., 2022; Ivaneiko I., 2023) and the duration of processes. In general, no such study has been conducted.

Construction experience shows that there is a need to accelerate the completion of the facility (The construction, 2020). Reducing the construction duration is achieved by applying industrial labour methods (consolidated assembly, high factory readiness of building products, structures and equipment) using high-performance and energy-saving machines and mechanisms of various types (Marcinkowski R., 2020; Ivaneiko I. D., 2020), in-line methods, increasing the number of workers and shift work, several parallel streams, etc (Shumakov I. V., 2015; Mudryy I., 2017).

Reducing the construction time on non-rhythmic flows was carried out by using parallel crews to achieve a rhythmic flow, introducing an even number of flows on the most labour-intensive works, and searching for and changing the duration of critical works in grid planning (Ivaneiko I., 2023). To calculate the construction period, the Critical Path Method (Kelley, 1959) or optimization methods (Brucker, 2007; Tanaev, 1989; Lazarev, 2011; Pinedo, 2012; Gross, 2006; Cormen, 2007; Jason Chao-Hsien Pan, 2002; Schaller J., 2005) are applied using parallel or sequentially parallel linkage methods with the use of new teams and flow-lines (Afanasiev, 1990; Maj T., 2007; Ushatsky S. A., 2007).

A study conducted at Lviv Polytechnic National University showed that there are many factors in flow-line design and grid planning that cause uneven deviations in labour intensity and timing of work on the grippers. These deviations increase the period of deployment and convolution of the flow-line (labour reserve) and increase the duration and number of people on site. A partial solution to the problem of reducing the duration of ongoing construction has been achieved by the sequential parallel method on technologically similar works within the available labour resource (Ivaneiko I., 2022; Ivaneiko I., 2023) and there is a need for their further study by using parallel works (with additional resources).

To develop and improve the model and theory of current irregular construction to reduce the periods of deployment (convolution) of the flow-line and the construction period by introducing parallel methods without changing the number of teams.

Materials and Methods

Parallel methods in the current organisation of works are used to reduce the construction period, which is achieved by redistributing labour resources between the teams using the sequential-parallel and parallel methods. This balancing of processes is intensive and extensive in nature and uses the labour resources available at the site or additional resources. A mathematical model has been developed to use additional parallel resources within existing teams. The calculation is carried out in stages and includes: balancing the duration of several technologically similar processes; reducing deployment periods, flow-line durations and critical work by an additional resource. The methodology uses schedules of the number of workers as well as ordinary (with continuous development of the OTW front) and rank (with continuous use of the ROTW resource) matrices.

Mathematical model of the problem. The objective function of our problem can be written in the form:

$$\mathrm{T} \leq \mathrm{T}^{n} \tag{1}$$

where T^{n} – is the normative construction period; T – is the construction period based on the flow-line, which is equal to:

$$\mathrm{T}=\mathrm{T}^{d}+\mathrm{T}_{n}=\mathrm{T}^{c}+\mathrm{T}_{1} \tag{2}$$

where T_1 and T_n – the lead time for the first and last work in the flow-line, excluding additional parallel grippers; T^{d} and T^{c} – the total periods of deployment and convolution of the flow-lines, they are determined by the following formulas:

$$\mathrm{T}^{d}=\sum_{i=2}^{\mathrm{n}} \mathrm{T}_{\mathrm{i}}^{\mathrm{d}} \tag{3}$$

$$\mathrm{T}^{c}=\sum_{i=n-1}^{i=1} \mathrm{T}_{\mathrm{i}}^{c} \tag{4}$$

where $\mathrm{T}_{\mathrm{i}}^{\mathrm{d}}$ and $\mathrm{T}_{\mathrm{i}}^{c}$ – are the periods of deployment and convolution of the *i*-th flow-line, determined by the formulas:

$$\mathrm{T}_{\mathrm{i}}^{d}=\frac{max}{k}\left(\sum_{\mathrm{j}=1}^{\mathrm{k}} t_{j,(i-1)}-\sum_{\mathrm{j}=1}^{\mathrm{k}-1} t_{ji}\right) \qquad 1 \leq \mathrm{k} \leq m \tag{5}$$

$$\mathrm{T}_{i}^{c}=\frac{\max}{k}\left(\sum_{j=m}^{\mathrm{k}} t_{j,i}-\sum_{\mathrm{j}=m}^{\mathrm{k}+1} t_{(j-1)i}\right) \qquad m \geq \mathrm{k} \geq 1 \tag{6}$$

where $t_{ji}-t_{ji}$ – duration of the *i*-th flow-line (work) on the *j*-th front; $1,2,\ldots,j,\ldots,k,\ldots,m$ – partial work fronts; $1,2,\ldots,i,\ldots,n$ – partial flow-lines (work).

To determine the total number of grips on a flow-line construction site, a model was developed that divides them in space and time into main and additional parallel ones (rank organization of types of work matrix (ROTW)) (Table 2). The total number of grippers on a structure is determined by the number of ranks (N_t). Additional parallel quantities (T_{Jr}) are determined by balancing the two processes or are equal to zero. The maximum number of parallel grippers on a work is determined by the formula:

$$N_p = N_t - m \quad , \tag{7}$$

where N_t – is the total number of grippers on the structure; N_p – is the number of parallel grippers on the work; m – is the number of assigned grippers to the work.

Example 1. The output data are included in the matrix in the OTW system (Table 1).

Table 1

OTW matrix for the number of works *n=6* on divisions *m=7*

OTW			Divisions and duration of the work						
			1	2	3	4	5	6	*m*=7
Types of works	A	1	t_{11}	t_{12}	t_{13}	t_{14}	t_{15}	t_{16}	t_{17}
	B	2	t_{21}	t_{22}	t_{23}	t_{24}	t_{25}	t_{26}	t_{27}
	C	3	t_{31}	t_{32}	t_{33}	t_{34}	t_{35}	t_{36}	t_{37}
	D	4	t_{41}	t_{42}	t_{43}	t_{44}	t_{45}	t_{46}	t_{47}
	E	5	t_{51}	t_{52}	t_{53}	t_{54}	t_{55}	t_{56}	t_{57}
	F	n=6	t_{61}	t_{62}	t_{63}	t_{64}	t_{65}	t_{66}	t_{67}

A rank matrix with continuous resource utilisation (ROTW) and with the timing of the main t_{jr} and additional parallel (T_{Jr}) work was developed (Table 2) to create a model without changing the number of teams. The timing of additional work is calculated to balance related processes or is assumed to be zero.

Table 2

The ROTW matrix model *n* m=6*7* with additional parallel work

ROTW*			Ranks and duration of work											
			1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**p=12**
Types of works	A	1	t_{11}	t_{12}	t_{13}	t_{14}	t_{15}	t_{16}	t_{17}	T_{18}	T_{19}	T_{110}	T_{111}	T_{112}
	B	2*	T_{21}	t_{22}	t_{23}	t_{24}	t_{25}	t_{26}	t_{27}	t_{28}	T_{29}	T_{210}	T_{211}	T_{212}
	C	**3***	T_{31}	T_{32}	t_{33}	t_{34}	t_{35}	t_{36}	t_{37}	t_{38}	t_{39}	T_{310}	T_{311}	T_{312}
	D	4*	T_{51}	T_{52}	T_{53}	t_{44}	t_{45}	t_{46}	t_{47}	t_{48}	t_{49}	t_{410}	T_{411}	T_{412}
	E	5*	T_{51}	T_{52}	T_{53}	T_{54}	t_{55}	t_{56}	t_{57}	t_{58}	t_{59}	t_{510}	t_{511}	T_{512}
	F	n=6	T_{61}	T_{62}	T_{63}	T_{64}	T_{65}	t_{66}	t_{67}	t_{68}	t_{69}	t_{610}	t_{611}	t_{612}

* The amount of work $n = 6$ on the grippers $m = 7$; the timing of the main t_{jr} and additional parallel T_{Jr} grippers.

Methodology for solving the problem of reducing the construction period:

1. Reducing the time of technologically similar processes.
2. Additional parallel works to reduce the periods of deployment and convolution of flow-lines.

3. Alignment of the labour schedule with parallel work.
4. Reducing the duration of critical activities to further shortening of the construction period (matrix for the Critical Path Method).

Results and discussion

The output data (Table 3) and the variant for comparing the construction period reduction by additional parallel flow-lines (Afanasiev, 1990) are presented in Table 4. The calculation was performed using the branch-and-boundary algorithm, and includes 6 brigades, with the maximum use of three brigades on the schedule (average number of workers N_{avg}=2.43). The construction duration is reduced from 54 to 37 days.

Table 3

Input data

OTW		Divisions, duration of work			
		I	II	III	IV
Types of works	A	4	8	10	6
	B	2	5	2	3
	C	7	4	9	1
	D	4	5	7	6

Table 4

Matrix for reducing construction time by parallel flow-lines

OTW		Divisions, duration of work			
		I	IV	III	II
Types of works	A1	$^{0}4^{4}$	0	$^{4}10^{14}$	0
	A2	0	$^{1}9^{10}$	0	$^{11}12^{23}$
	B	$^{4}2^{6}$	$^{10}3^{13}$	$^{14}2^{16}$	$^{23}5^{28}$
	C	$^{6}7^{13}$	$^{13}1^{14}$	$^{16}9^{25}$	$^{28}4^{32}$
	D1	$^{13}4^{17}$	0	$^{25}7^{32}$	$^{32}5^{37}$
	D2	0	$^{14}6^{20}$	0	0

Example 2. Reduction of the construction period by the sequential-parallel and parallel construction method based on option 2 (Ivaneiko I., 2022) (Table 5).

Table 5

Matrix of current calculation with continuous use of the resource

OTW		Divisions and duration of work				Option 1			Option 2		
						Output data			A+B		
		I	II	III	IV	T_1^p	T_{fl1}	$\frac{T_1^s}{T_1^f}$	T_2^p	T_{fl2}	$\frac{T_2^s}{T_2^f}$
Types of works	A	4 $^{0}4^{4}$	8 $^{4}5^{9}$	10 $^{9}7^{16}$	6 $^{16}4^{20}$	19	28	0 28	4	20	0 27
	B	2 $^{4}5^{9}$	5 $^{9}8^{17}$	2 $^{17}4^{21}$	3 $^{21}3^{24}$		12	19 31		20	4 24
	C	7 $^{10}7^{17}$	4 $^{17}4^{21}$	9 $^{21}9^{30}$	1 $^{30}1^{31}$	2	21	21 42	6	21	10 31
	D	4 $^{21}4^{25}$	5 $^{25}5^{30}$	7 $^{30}7^{37}$	6 $^{37}6^{43}$	11	22	32 54	11	22	21 43
Deployment period						32			21		

Determining the timing of the last and penultimate work gives the time of reduction of the last work (works):

$$t^1_{47}/2 = 3 \le T^2_{37} \le t^s_{47} - t^e_{36} = 37 - 31 = 6$$

where t^1_{47} – is the duration of the main work 47 (Table 6); T^2_{37} .– is an additional parallel work to the main work 47(Table 6); t^s_{47} i t^e_{36} – early start 47 and late finish 36 (Table 5).

To realise the unused resource, additional technologically similar parallel works are introduced, starting from the end:

$$T^2_{37} = t^1_{47}/2 = 6/2 = 3$$

$$T^2_{36} = (t^1_{46} - t^1_{36})/2 = (7-1)/2 = +3$$

where $t^1_{46} - t^1_{36}$ – the difference between the works performed on one gripper.

$$T^2_{36} + T^2_{37} = 3 + 3 = 6$$

To reduce the duration of the first work (t^2_{11}) additional parallel grippers of the same type are introduced, equal to $T^2_{21} \le t^1_{11} = 4/2 = 2$ (located on the same rank of the ROTW matrix):

$$t^2_{11} = t^1_{11} - T^2_{21} = 4 - 2 = 2$$

In this case, the work is performed by 4 teams in 35 days, with the maximum use of three teams on the schedule (average number of workers N_{avg}=2.57).

Table 6

Matrix for redistributing the timing of work by the parallel method

OTW			Ranks and duration of work							Option 2			Option 3		
										A+B			A+B/paralel		
			1	2	3	4	5	6	7	T_1^p	T_{fl2}	$\frac{T_1^s}{T_1^f}$	T_2^p	T_{fl3}	$\frac{T_2^s}{T_2^f}$
Types of works	A	1	4 2	8 5	10 7	6 4	0 0	0 0	0 0	4	20	0 20	2	18	0 18
	B	2	0 2	2 5	5 8	2 4	3 3	0 0	0 0		20	4 24		20	2 22
	C	3	0 0	0 0	7 7	4 4	9 9	1 1+3	0 3	6	21	10 31	6	21	8 29
	D	4	0 0	0 0	0 0	4 4	5 5	7 4	6 3	11	22	21 43	11	16	19 35
Deployment period										21			19		

Additional parallel work is not taken into account when calculating the deployment periods and duration of work: $T^2_{21} = 2$; $T^2_{36} = +3$; $T^2_{37} = 3$.

The Critical Path Method calculation matrix is used to further shorten the construction period (Table 7).

It is possible to reduce the time of work t^2_{35} and construction by four days with the Critical Path Method by introducing additional parallel work with a total construction period of 31 days. In this case, the work is performed by 4 teams, with the maximum use of four teams on the schedule (average number of workers N_{avg}=2.9).

Table 7

Critical Path Method calculation matrix

OTW		Divisions, duration of work			
		I	II	III	IV
Types of works	A	${}^{0}_{0}2^{2}_{2}$	${}^{2}_{2}5^{7}_{7}$	${}^{7}_{8}7^{14}_{15}$	${}^{14}_{24}4^{18}_{28}$
	B	${}^{2}_{2}5^{7}_{7}$	${}^{7}_{7}8^{15}_{15}$	${}^{15}_{15}4^{19}_{19}$	${}^{19}_{28}3^{22}_{31}$
	C	${}^{7}_{8}7^{14}_{15}$	${}^{15}_{15}4^{19}_{19}$	${}^{19}_{19}9^{28}_{28}$	${}^{28}_{31}1^{29}_{32}$
	D	${}^{14}_{19}4^{18}_{23}$	${}^{19}_{23}5^{24}_{28}$	${}^{28}_{28}4^{32}_{32}$	${}^{32}_{32}3^{35}_{35}$

Example 3. Calculation of the example which is performed with a reduced number of grippers (Table 8 and 9).

Table 8

Output data

Divisions	Types of works			
	A	B	C	D
1	12	7	11	9
2	16	5	10	13

Table 9

Matrix for redistributing the timing of work by the parallel method

ROTW			Ranks and duration of work					Option 1			Option 2		
								Output data			Parallel works		
			1	2	3	4	5	T_1^p	T_{fl1}	$\frac{T_1^s}{T_1^f}$	T_2^p	T_{fl2}	$\frac{T_2^s}{T_2^f}$
Types of works	A	1	12 6	16 8				21	28	0 20	6	14	0 13
	B	2	0 6	7 7	5 5	0 5+2			12	21 24		12	2 22
	C	3		0 8	11 6	10 5	0 6	7	21	10 31	7	11	8 29
	D	4			0 5	9 7	13 7	12	22	40 62	6	14	19 33
Deployment period								40			19		

In this case, the work is performed by 4 teams in 34 days, with the maximum use of three teams on the schedule (average number of workers N_{avg}=2.73).

Conclusions

1. Today, virtually the majority of buildings are completed with delays (77 % of projects are 40 % behind schedule (Optimisation, 2023). To implement an effective BIM technology, it is necessary to optimise costs and time. One of the ways to achieve the required time is to develop effective calculation methods and implement them in production.
2. A mathematical model for calculating the reduction of construction time by parallel methods is proposed.
3. A methodology for solving the problem of reducing the construction period is developed.
4. The proposed method for reducing the construction period by sequential-parallel and parallel methods with irregular flow-lines allows reducing the construction period by 12–18 % compared to the method of parallel flow-lines.

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СКОРОЧЕННЯ ТЕРМІНУ ПОТОЧНОГО БУДІВНИЦТВА ПАРАЛЕЛЬНИМ СПОСОБОМ З ВИКОРИСТАННЯМ НАЯВНИХ БРИГАД

У статті запропоновано зменшити тривалість виконання неритмічних потокових робіт паралельним методом за допомогою наявних бригад.

За неритмічного потокового будівництва існують процеси із запасом невикористаного трудового ресурсу на роботах, які визначаються періодом розгортання потоків. Вони впливають на термін спорудження будівлі. Під час проєктування та виробництва виникають ситуації, коли необхідно зменшити терміни виконання робіт, нормативні або встановлені замовником. Одним із способів вирішення проблеми є уведення додаткового паралельного ресурсу для зменшення календарного терміну будівництва і використання машин.

Скорочення терміну будівництва за допомогою організації робіт досягають паралельним методом – запровадженням додаткових захоплень, потоків і робіт. Оптимізаційні послідовності потоку розраховують способами Critical Path Method, теорії розкладів та алгоритмом гілок і меж.

У статті для розрахунку виконано модель у матриці (рангова матриця з безперервним використанням ресурсу ROTW) для визначення розміщення та зв’язку в просторі та часі основних та додаткових паралельних захваток. Основні роботи використовують для розрахунку значень захоплень послідовно-паралельним методом на технологічно однотипних процесах, а додаткові – паралельним методом зі збільшенням кількості ресурсу. Математична модель охоплює мету дослідження та параметри, що впливають на термін будівництва. Оптимальне рішення досягається паралельним способом поетапно: зменшенням періодів та терміну потоків, початкових та кінцевих значень захоплень та критичних робіт. Дослідження послідовного методу скорочення терміну будівництва з використанням лише наявних бригад загалом не виконувалося. Ефективність поетапного методу зі зменшенням терміну будівництва визначено порівняно з методом використання додаткових паралельних потоків .

Ключові слова: періодів розгортання і згортання потоків; послідовно-паралельний і паралельний метод; варіантне проєктування; технологічно однотипні роботи; рангова матриця з пріоритетом по фронту робіт; Critical Path Method.