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# OPTIMIZATION OF DEPLOYMENT PERIODS OF NON-RHYTHMIC FLOW-LINES BY COMPLEX MECHANIZED MACHINES

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**The article proposes to balance processes with non-rhythmic flow-lines according to the period of works execution with the use of complex mechanized machines (CMM).**

**An increase in the period of deployment in the flow-line and downtime of non-critical works calculated by the Critical Path Method requires the development of optimization methods to reduce the construction period. We proposed a hypothesis to equalize work rhythms due to the redistribution of work volumes on interdependent divisions (ID) between CMMs.**

**A typical matrix model is used to compare the period of works execution. The calculation formulas are given for determining the execution time on the ID, the deployment period of the flow-line, the brigade and the building.**

**There is a new method of optimizing the flow-line deployment period with the parallel use of complex mechanized machines proposed in the article. This method shortens the construction period.**

**Keywords: non-rhythmic flow-lines, Critical Path Method, complex mechanized machines, interdependent divisions, matrix method of flow-lines calculation, optimization of flow-lines deployment periods.**

## Introduction

For energy-saving building construction technologies, harmoniously balanced systems should be introduced by adopting rational constructive, organizational and technological decisions (COTD) based on variant design. This task can be solved both for the system as a whole and by connecting individual elements (Ivaneiko, Oleksiv, 2015; Ivaneiko, Mudryi, Oleksiv, 2015; Ivaneiko, Ivaneiko, 2020; Shatrova, 2006; Radkevich, 2006). This article deals with the issue of providing an option to reduce the deployment period of the flow-lines with the linking of organizational and technological solutions (OTS) (Shumakov I., 2015) using complex mechanized machines and the effectiveness of its application (Determination of the duration of construction, DSTU, 2014).

## Analysis of research and publications

Today, with the limitation of energy resources, effective OTS should be introduced to construct preschool education institutions in a short period to increase the working population. Solving the problem in non-rhythmic flow-lines is achieved by choosing the optimal methods of performing work with a change in the sequence of development of work fronts, choosing the intensity of work, number resources in the process (Kanyuka, Rezunyk, Novatskyi, 1977; Afanasiev, 1990; Shumakov, 2018). The main problem of optimization methods is the lack of a mathematical solution to this problem, which is partially solved in the works of S. M. Johnson (Jason Chao-Hsien Pan, Jen-Shiang Chen, Chii-Ming Chao, 2002; Schaller J. 2005). The balancing of processes according to the rhythm of work performance is studied in the works (Ivaneiko, Oleksiv, 2015; Ivaneiko, Ivaneiko, 2020). Therefore, in order to reduce costs for the construction of the object, effective means of mechanization should be used according to the volume and performance characteristics, weight and load moment (Ivaneiko, Mudryi, Oleksiv, 2015; Zavadskas, 1991; Shumakov, 2015). Due to the unevenness of the work rhythms within the processes on non-rhythmic flow-lines, there are significant gaps in terms of execution due to the increase in the period of flow-lines deployment (Ivaneiko, Oleksiv, 2016; Ushatsky, Sheiko, Triger, 2007).

The primary method of reducing the construction period is executing works according to a grid schedule using the Critical Path Method developed in the USA in 1959 by J.E. Kelly and M.R. Walker (Kelly, Walker, 1959). The disadvantage of this method is the downtime of resources during work execution (non-critical work). The flow-line method of construction developed at the Kyiv Engineering and Construction Institute by professor M.S. Budnikov allows reducing the resource downtime. At the same time, this method can increase the construction period compared to the Critical Path Method due to the increase in the deployment period in non-rhythmic flow lines (Ivaneiko, Oleksiv, 2016). One of the ways to reduce the period of flow lines deployment is to reduce labour productivity to obtain the effective intensity of work (Afanasiev, 1990). At the same time, the author concluded that this proposal is economically inefficient.

Method of reducing flow-line deployment periods has been developed to shorten the construction period (Ivaneiko, Oleksiv, 2016). From the calculations of the deployment periods, flow lines with an increased period are determined, which require an increase in the construction period by using this resource for the performance of the previous work. The studies showed that using the resource in the previous work reduces the flow-line deployment period and the construction period without involving additional resources. At the same time, the means of mechanization, the methods of organizing parallel execution of works on the previous division, the means of mechanization, and the interdependent divisions are not fully defined in the calculations (Ivaneiko, Ivaneiko, 2020). In this method machines are used in parallel as necessary on the division to balance the differences in the terms of work. In addition, such machines are necessary for implementing the resource of non-critical work Critical Path Method on other processes. The performers must have professional training, and the machines must be adapted according to their technical characteristics to perform these works.

Previous studies have shown that mechanisms with these technical characteristics are special (necessary for two processes) (Ivaneiko, Mudryi, Oleksiv, 2015) and universal machines (Ivaneiko, Ivaneiko, Vyshnevskyi, 2020) and manipulators (Ivaneiko, Oleksiv, 2016) – complex mechanized machines (CMM). In addition, this process can use a machine (CMM) in three shifts with the involvement of labor resources from interdependent divisions (Tadeusz, 2007) – processes with an increased deployment period.

To solve the problem, we offered the hypothesis of equalizing the rhythms of work and the use of the resource of non-critical work by redistributing the volume of work on interdependent division using CMM.

Reduction of the construction term of a building (construction) by reducing the period of deployment of flow-lines and using the resource of non-critical works with the parallel use of complex mechanized machines.

## Materials and Methods

In order to solve the problem of balancing the object according to construction terms, the main types of work (partial flow-lines) in which the periods of deployment of processes increase were determined. To perform the works, complex mechanized machines are used, which are linked in space and time.

Balancing the system with complex mechanized machines (CMM) involves achieving the necessary rhythms of work on interdependent divisions. On the matrix model, for a given task, variants of interdependent divisions are defined to reduce the periods of deployment of flow-lines. When involving CCM from another process, their technical characteristics must be greater or equal for the construction of elements of this process, or the use of machines of this process in the second shift.

Reducing the flow-line deployment periods involves determining the number of processes with the use of complex mechanized machines. Such technological processes can be two adjacent processes with the terms of the flow-line deployment period longer than the duration of the flow-line execution on the first division.

For the object, we create a matrix model (the number of flow-lines (specialized flow-lines) and divisions (work fronts). The model calculates the matrix with continuous use of the resource in the OTW system (organization of types of work). In it, the periods of deployment of flow-lines are determined:

$$\mathrm{T_i^p} = \frac{max}{k}\left(\sum_{j=1}^{k} t_{j,(i-1)} - \sum_{j=1}^{k-1} t_{ji}\right) \le 0; \quad 1 \le k \le n \ , \tag{1}$$

where $\mathrm{T_i^p}$ – deployment period of the *i*-th flow-line; $t_{ji}$ – duration of execution of the *i*-th flow-line on the *j*-th front; $1, 2, ..., j, ..., k, ..., n$ – partial fronts of works; $1, 2, ..., i, ..., m$ – partial flow-lines.

We determine the earliest early start of work on the first division for flow-lines, taking into account parallel work:

$$\mathrm{t_{1(i-1)}} = \frac{max}{h}\left(t_{2(i-r)}\right) , \tag{2}$$

where $h$ – the number of jobs that affect the flow-lines execution $(i-1)$; $\mathrm{t_{1(i-1)}}$ – flow-line execution time $(i-1)$ on the first division; $t_{2(i-r)}$ – flow-line execution time $(i-r)$ linked with the flow-line $(i-1)$ on the second division.

Unbalanced flow-lines are defined for the model – the duration of work, which must be increased:

$$T_i^p > t_{1(i-1)} \tag{3}$$

Each model determines the number of interdependent divisions, which is determined in the ROTW system (rank organization of types of work) (Table 1). To redistribute the term (scope) of work for several processes, the number of interdependent divisions can be determined (n).

*Table 1*

**Interdependent divisions for two processes on the 4×4 matrix**

| ROTW | | Ranks and duration of processes | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
| Processes | A* | $t_{11}$ | $t_{12}$ | $t_{13}$ | $t_{14}$ | – | – | – |
| | B* | – | $t_{21}$ | $t_{22}$ | $t_{23}$ | $t_{24}$ | – | – |
| | C | – | – | $t_{31}$ | $t_{32}$ | $t_{33}$ | $t_{34}$ | – |
| | D | – | – | – | $t_{41}$ | $t_{42}$ | $t_{43}$ | $t_{44}$ |
| *N* | | 1 | 2 | 2 | 2 | 1 | – | – |

Processes A* and B* are interdependent processes.

For the execution of parallel works, delivery of execution of brigades (CMM) can be carried out within the limits of the division or (and) in time.

When linking elements in space, the number of brigades (CMM) on the division is determined from the condition:

$$N = \frac{A}{S} , \tag{4}$$

where $S$ – unit measurement of the area (volume) for placement of the CMM on the area taking into account safety techniques (determined by regulatory documents or a safety engineer), ($m^2$; $m^3$); $A$ – total area (volume) of division, ($m^2$; $m^3$).

When linking elements in time, the number of brigades (CMM) on the division is determined by a condition:

$$N = \frac{P}{y}, \tag{5}$$

where P=24 hours – day duration; $y$ – shift duration.

Each of the methods has advantages and disadvantages that should be further investigated.

The total duration of interdependent division is determined:

$$T_{id} = \sum_{1}^{n} T_f, \tag{6}$$

and the average value for the execution of the flow-lines:

$$t_{id}^{av} = \frac{T_{id}}{n}. \tag{7}$$

The average value must be an integer and the sum equal to the total duration of interdependent divisions. With a non-integer average value, later flow-lines are rounded up, and initial flow-lines are rounded down. In the work (Ivaneiko, Oleksiv, 2016), other distributions of the duration of work on interdependent divisions are given.

## Results and discussion

To compare the terms of work performance, the matrix model proposed (Ivaneiko, Ivaneiko, 2020) was taken (Table 2).

*Table 2*

**Output data**

| OTW | | Divisions, duration of the process | | | |
|---|---|---|---|---|---|
| | | I | II | III | IV |
| Processes | A | 4 | 8 | 10 | 6 |
| | B | 2 | 5 | 2 | 3 |
| | C | 7 | 4 | 9 | 1 |
| | D | 4 | 5 | 7 | 6 |

The calculation is carried out in the OTW matrix using the Critical Path Method (Table 4) and flow-line with continuous use of the resource (Table 3). According to the deviation of the work execution terms of the flow-line method from the Critical Path Method, it is necessary to optimize the flow-line as a whole.

Optimization is performed by the method of reducing deployment periods for processes:

$T_B^p = 19 > t_{11} = 4$ – unbalanced,

$T_C^p = 2 = t_{21} = 2$ – balanced,

$T_D^p = 11 > t_{31} = 7$ – unbalanced.

For an unbalanced process A, there are interdependent divisions at work A+B, and for D – C+D (+- designation of works on interdependent divisions). Optimization can be performed for processes by variants: A+B; C+D; A+B i C+D. One option may not be implemented – due to the lack of highly qualified workers for other work, the impossibility of CMM application in the second shift or other circumstances. In our version, we reduce the deployment period only for processes A+B in the OTW matrix (Table 4).

*Table 3*

**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 | $T_1^p$ | $T_{fl1}$ | $\frac{T_1^s}{T_1^f}$ | $T_2^p$ | $T_{fl2}$ | $\frac{T_2^s}{T_2^f}$ |
| Processes | A | 4<br>4 | 8<br>5 | 10<br>7 | 6<br>4 | 19 | 28 | 0<br>28 | 4 | 20 | 0<br>27 |
| | B | 2<br>5 | 5<br>8 | 2<br>4 | 3<br>3 | | 12 | 19<br>31 | | 20 | 4<br>24 |
| | C | 7 | 4 | 9 | 1 | 2 | 21 | 21<br>42 | 6 | 21 | 10<br>31 |
| | D | 4 | 5 | 7 | 6 | 11 | 22 | 32<br>54 | 11 | 22 | 21<br>43 |
| ∑ | | | | | | 32 | 83 | | 21 | 83 | |

*Table 4*

**Critical Path Method calculation matrix**

| OTW | | Divisions and duration of work | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | I | | | II | | | III | | | IV | | |
| Processes | A | 0 | | 4 | 4 | | 12 | 12 | | 22 | 22 | | 28 |
| | | | **4** | | | **8** | | | **10** | | | **6** | |
| | | 0 | | 4 | 4 | | 12 | 12 | | 22 | 30 | | 36 |
| | B | 4 | | 6 | 12 | | 17 | 22 | | 24 | 28 | | 31 |
| | | | **2** | | | **5** | | | **2** | | | **3** | |
| | | 11 | | 13 | 15 | | 20 | 22 | | 24 | 36 | | 39 |
| | C | 6 | | 13 | 17 | | 21 | 24 | | 33 | 33 | | 34 |
| | | | **7** | | | **4** | | | **9** | | | **1** | |
| | | 13 | | 20 | 20 | | 24 | 24 | | 33 | 39 | | 40 |
| | D | 13 | | 17 | 21 | | 26 | 33 | | 40 | 40 | | 46 |
| | | | **4** | | | **5** | | | **7** | | | **6** | |
| | | 24 | | 28 | 28 | | 33 | 33 | | 40 | 40 | | 46 |

For processes A+B we establish interdependent divisions (placed on the same rank) and their number (n) (Table 5). According to the formulas (6) and (7) we determine the total durations of interdependent divisions and new deadlines for work (Table 3, words A, B denominator)

*Table 5*

**Matrix for defining interdependent divisions**

| ROTW | | Ranks and duration of processes | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
| Processes | A* | 4 | 8 | 10 | 6 | | | |
| | B* | | 2 | 5 | 2 | 3 | | |
| | C | | | 7 | 4 | 9 | 1 | |
| | D | | | | 4 | 5 | 7 | 6 |
| n (for A+B) | | 1 | 2 | 2 | 2 | 1 | – | – |

A* and B* interdependent processes.

According to the methods of calculations without changing the labor intensity, the deadlines for the work are established: flow-line – 54 units; Critical Path Method – 46 units; optimization of the flow-line deployment period – 43 units. To implement the method, it is necessary to have specialists on interdependent works at the construction site.

## Conclusions

1. A new method of optimizing the flow-line deployment period with the parallel use of complex mechanized machines is proposed.

2. The method of optimizing the flow-line deployment period allows to:

– shorten the construction period of the building using the flow-line method of construction without involving additional resources;

– apply resources from non-critical works to critical works with a reduction in the construction period calculated by the Critical Path Method.

3. When using complex mechanized machines with additional manipulators, it is necessary to conduct further studies on the costs of construction work.

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## ОПТИМІЗАЦІЯ ПЕРІОДІВ РОЗГОРТАННЯ НЕРИТМІЧНИХ ПОТОКІВ КОМПЛЕКСНО-МЕХАНІЗОВАНИМИ МАШИНАМИ



У статті запропоновано збалансувати процеси з неритмічними потоками за термінами виконання робіт з використанням комплексно-механізованої машини.

Збільшення періоду розгортання у потоці та простої некритичних робіт, розрахованих Critical Path Method, потребують розробки оптимізаційних методів для скорочення терміну будівництва. Для скорочення терміну виконання потокових робіт необхідно гранично наблизити один до одного ритми різних процесів на захватках і зменшити період розгортання.

Ритми робіт на захватках вирівнюються зміною продуктивності праці, збільшенням кількості машин. Ми запропонували гіпотезу: вирівнювати ритми робіт за рахунок перерозподілу обсягів робіт на двох взаємозалежних захватках (ВЗ) між двома механізмами. Для виконання робіт застосовують спеціальні (необхідні для двох процесів), універсальні машини та маніпулятори при паралельному виконання робіт на площині, а також основну машину в другу зміну.

Для потокового методу на матричній моделі встановлено взаємозалежні захватки. В ідеалі різниця термінів виконання для потоків на взаємозалежних захватках не має давати збільшення періоду розгортання.

Для порівняння термінів виконання робіт взято типову матричну модель. Для цієї матриці вказано процеси, які збільшують термін виконання робіт. Для потокового методу на матричній моделі встановлено взаємозалежні захватки. Розроблено оптимізаційний метод скорочення періоду розгортання та наведено формули розрахунку для визначення терміну виконання на ВЗ, періоду розгортання потоку, бригади та зведення будівлі. Надано формули розміщення комплексно-механізованих процесів на площині і в часі.

В статті запропоновано новий метод оптимізації періоду розгортання потоку з паралельним використанням комплексно-механізованих машин, який скорочує термін виконання неритмічних потоків та сіткового планування.

**Ключові слова: неритмічні потоки, Critical Path Method, комплексно-механізовані машини, взаємозалежні захватки, матричний спосіб розрахунку потоків, оптимізація періодів розгортання потоків.**