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OPTIMIZATION OF THE TECHNOLOGY FOR FORMING MONOLITHIC VERTICAL ELEMENTS USING MOVING BELT FORMWORK SYSTEMS

This article develops a comprehensive methodological framework for the structural and operational optimization of technologies used to form monolithic vertical building elements through the application of vertically movable belt-type formwork systems. The proposed approach is based on a detailed decomposition of the construction process into nine standardized microelement matrices that represent the full operational cycle: installation of guide frames, placement of reinforcement, suspension of modular units, multilayer concrete placing, regulated curing, vertical lifting of modules, adjustment operations, and subsequent dismantling procedures. Such decomposition makes it possible to quantify labor intensity, assess the technological sequence, and determine the dominant factors influencing productivity.

A key feature of the investigated system is the flexible forming strip, tensioned on drive and bypass rollers, which ensures tangential detachment from the concrete surface during lifting. This mechanism substantially decreases adhesion forces, reduces mechanical resistance, and minimizes risk to the integrity of the freshly formed concrete layer. Compared with conventional panel formwork, belt-type systems demonstrate significantly lower energy demands, reduced labor consumption, and improved turnover rates. The study presents analytical dependencies for evaluating cycle duration, conformity coefficients, turnover ratios, and required operational resources.

The research substantiates the advantages of using mechanized group configurations of belt modules, which enable synchronized lifting, stable geometric accuracy, and continuity of concreting cycles within accelerated construction schedules. Moreover, the methodological framework provides a foundation for digital integration, supporting the application of BIM-based planning tools, SCADA monitoring solutions, and predictive analytics for process optimization.

The results confirm that vertically movable belt formwork systems represent a technologically and economically efficient alternative to traditional formwork approaches. Their implementation leads to measurable improvements in labor productivity, material utilization, cycle stability, and the quality of concrete surfaces. The proposed methodology also creates opportunities for future development of digital twins, *automated control algorithms, and advanced rationalization models for modern monolithic construction..*

Keywords: belt formwork, vertically movable module, panel formwork, concrete adhesion, labor intensity, technological cycle, monolithic structures.

Introduction. Monolithic construction technology is one of the most intensively developed areas of modern construction technology. In urban conditions, where the demand for fast and efficient construction of multi-storey buildings is increasing, the issue of optimizing the technology for forming vertical structures is particularly acute.

Traditional panel formwork systems, which are widely used for concreting walls and pylons, have a number of known drawbacks: significant weight and complexity of installation, the need for crane operations, high tear-off forces during dismantling and the dependence of the quality of the concrete surface on manual technological techniques.

In response to these limitations, mechanized and automated formwork systems of a new generation are being developed. One of such solutions is a vertically movable strip formwork module, in which the forming surface is made in the form of a flexible strip stretched on rollers. When the module is moved, the strip is separated from the concrete surface along the tangent in the lower zone of the formwork, which ensures minimization of tear-off forces and increases the turnover of the form.

Experimental studies show that the tangential separation of the strip forms a low local contact interaction zone, which fundamentally changes the distribution of tangential stresses compared to the panel formwork. Due to this, the technological cycle is significantly accelerated, and the quality of the concrete surface is improved.

Analysis of recent studies and publications. The study of the development of the issue of the use of movable strip-type formwork systems is devoted to works [1-10].

In particular, the effectiveness of the use of such systems as part of the technological process of erecting monolithic structures is determined. In work [11], a constructive solution of the formwork strip module is presented, which, in addition to the low-energy process of separating the formwork module from the building structure, allows to improve the technological rate of concreting structures.

Problem statement. To improve the technology of forming monolithic vertical elements, it is necessary to evaluate the effectiveness of the use of modern technical solutions.

The purpose of this publication is to develop and substantiate a methodology for assessing the technological efficiency of a vertically movable strip formwork system based on structured analysis of operations, microelement rationing, determination of labor intensity, and modeling of technological cycle parameters.

Presentation of the main material.

To determine the ways of optimization, we will compile a methodology for structural and operational analysis of the technological process of erecting vertical monolithic structures using vertically movable strip formwork modules.

The methodology includes the following elements:

1. Decomposition of the technological process

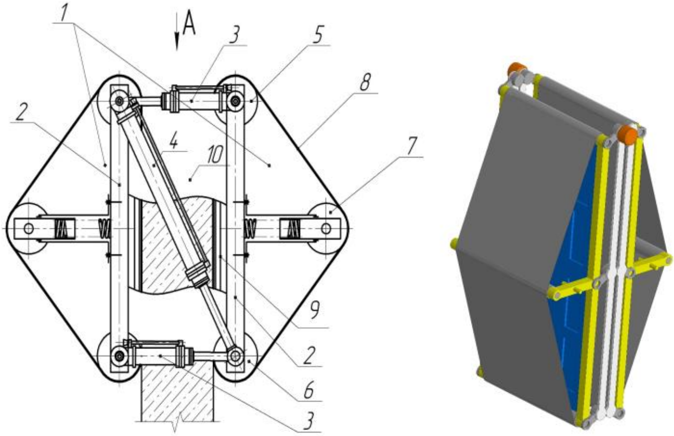
The technological process is divided into blocks, each of which describes a structural operation - installation of the guide frame, installation of reinforcement, hanging of modules, laying of concrete, care for concrete, lifting of modules, lifting of guides, dismantling of modules and dismantling of the frame.

2. Construction of matrices of microelement standardization

For each operation, the following are determined: the number of actions Ni; standard time for each action; labor costs in man-minutes; compliance coefficients; labor intensity in man-hours.

3. Technological model of the operation of the strip formwork module

The module includes: a guide frame that moves in discrete steps (1.5 m); a forming strip stretched on rollers; lifting mechanism; working zone of local tangential separation (Fig. 1).



a b

Figure 1. Belt formwork module: a – general view; b – 3D model of the module: 1 – half-frame; 2 – frame; 3 – limiting crossbars; 4 – diagonal ties; 5 – drive rollers; 6 – bypass rollers; 7 – tension rollers; 8 – belt; 9 – forming shield; 10 – guides

The separation of the tape from the concrete occurs tangentially at the lower point of the roller, which:

• minimizes the separation force;
• reduces the risk of damage to the fresh concrete surface;
• allows to increase the lifting frequency;
• provides high turnover of forms.

The developed technological system belongs to continuous mechanized technologies of concreting vertical elements, in which the process of forming and hardening occurs synchronously with the vertical movement of the formwork.

It implements the principle of technological sequence with modular coordination, i.e. each module performs the functions of an independent technological unit, which can be integrated into the general construction system according to the modular principle.

The organizational scheme provides for three levels of process control:

1. Local - regulation of the operation of a separate module (lifting speed, tape tension, clamping forces).

2. Group - synchronization of the operation of several modules that form a common section (pylon, wall or core).

3. Process - control of the cycle of concrete mix supply, reinforcement, aging and movement to the next tier.

As shown in the works [8], technological efficiency in continuous processes is determined by the coordination of the concrete hardening rate with the kinematics of the formwork movement.

Therefore, for each type of concrete (C25/30 - C40/50), an optimal lifting speed of 10–25 mm/min is set, which ensures a balance between hydrostatic pressure and the strength of the contact layer.

To quantitatively assess the efficiency of the work process of the developed system, the method of microelement normalization [8] was used, supplemented by analytical coefficients.

The methodology is based on dividing the process of concreting pylons into nine operational stages (Table 1), which cover the entire cycle: from the installation of the guide frame to the dismantling of the formwork after the completion of concreting (Fig. 2).

Table 1

Decomposition of the technological process

Code	Process name	Characteristic	Average labor intensity, person-hours
O1	installation of the guide frame	Installing guide elements, checking verticality	2,23
O2	installation of the reinforcing frame	Fastening on anchor supports, connecting the hydraulic system	1,95
O3	hanging of form modules	Fitting the reinforcement, checking its position	3,10
O4	concreting	Mixture feeding, vibration, compaction control	0,58 at 1 м³
O5	Exposure and curing control	Preparing for the climb	0,40
O6	Module lift	Hydraulic drive operation, synchronism control	0,88
O7	Self-cleaning tape	Cleaning from sticking, checking tension	0,25
O8	Adjusting parameters	Adjusting the pylon width and tilt angle	0,30
O9	Dismantling the system	Disconnecting modules, moving to a new section	1,85

The expanded decomposition of the technological process of erecting vertical monolithic structures will look like this.

Process structure O1 – installation of the guide frame:

$O_{1.1}$ – moving pallets by trolleys to the next grab;

$O_{1.2}$ – installation and fastening of the support frame 1;

$O_{1.3}$ – installation and fastening of vertical guides 2;

$O_{1.4}$ – installation of scaffolding;

$O_{1.5}$ – installation and fastening of the upper beam 3;

$O_{1.6}$ – verification of guides;

$O_{1.7}$ – control of geometric dimensions and verticality of guides.

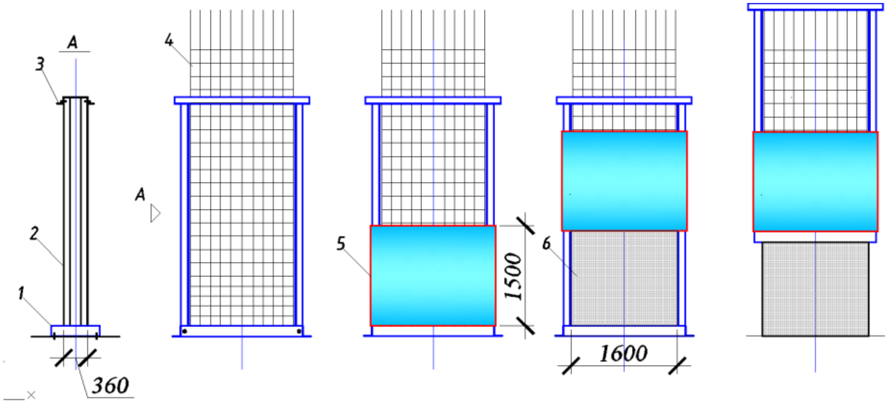


Figure 2. Scheme of concreting a vertical building structure with a module: 1 – support frame; 2 – vertical guides; 3 – upper beam; 4 – reinforcement frame; 5 – formwork module; 6 – building structure

Process structure O2 – installation of the reinforcing frame:
$O_{2.1}$ – feeding the frame with a crane;
$O_{2.2}$ – lowering the frame;
$O_{2.3}$ – joining the frame rods with the reinforcement outlets;
$O_{2.4}$ – unslinging;
$O_{2.5}$ – fastening of the protective layer clamps;
$O_{2.6}$ – control of the geometric parameters of the frame.
Process structure O3 – hanging of form modules:
$O_{1.1}$ – moving pallets with trolleys to the next grab;
$O_{3.2}$ – hanging of form modules;
$O_{3.3}$ – fixing of form modules;
$O_{3.4}$ – checking the operability of the formwork;
$O_{3.5}$ – lubrication of the working surface of the formwork;
$O_{3.6}$ – quality control.
Process structure O4 – placing of concrete:
$O_{4.1}$ – feeding concrete into the bucket by crane;
$O_{4.2}$ – leveling and compacting concrete in layers 0.5 m high;
$O_{4.3}$ – lowering of the empty bucket;
$O_{4.4}$ – quality control.
Process structure O5 – curing and care of concrete:
$O_{5.1}$ – moistening of exposed concrete surfaces;
$O_{5.2}$ – covering exposed concrete surfaces with a film.
Process structure O6 – lifting the module-form:
$O_{6.1}$ – preparing the modules for lifting;
$O_{6.2}$ – lifting the module-form to the next tier (1.5 m);
$O_{1.4}$ – installing scaffolding;
$O_{3.4}$ – checking the operability of the formwork;
$O_{6.3}$ – cleaning the working surface of the formwork from contamination;
$O_{3.5}$ – lubricating the working surface of the formwork;

$O_{3.6}$ – quality control.

O_4 – Placing the second tier of concrete (see structure above).

O_5 – curing and care for the concrete (see structure above).

Process structure O7 – lifting and securing the guides:

$O_{7.1}$ – detaching the lower frame of the guides from the support;

$O_{7.2}$ – fixing the module-forms from movement;

$O_{7.3}$ – lifting the guide frame by one step (1.5 m);

$O_{7.4}$ – fixing the guide frame to the concrete with dowels;

$O_{7.5}$ – checking the geometric parameters and reliability of fixing.

Process structure O8 – dismantling the formwork modules:

$O_{8.1}$ – lowering the formwork modules onto the floor;

$O_{8.2}$ – unhooking the formwork modules from the guides;

$O_{6.3}$ – cleaning the working surface of the formwork from contamination;

$O_{8.3}$ – storing the formwork modules on pallets;

$O_{1.1}$ – moving the pallets with trolleys to the next grab.

Process structure O9 – dismantling the guide frame:

$O_{9.1}$ – unfastening and removing the upper beam 3;

$O_{9.2}$ – unfastening and removing the vertical guides 2;

$O_{6.3}$ – cleaning the working surface of the formwork from contamination;

$O_{9.3}$ – unfastening and removing the support frame 1;

$O_{1.1}$ – moving pallets by trolleys to the next grab.

Thus, for process normalization and model synthesis, nine matrices (O1-O9) should be constructed using the microelement normalization method.

The labor cost rate for each process is determined by the formula [7]:

$$\boldsymbol{H_{hw}} = 0{,}0167\left(\sum_1^n Q_{wi}\right)\frac{K_r}{V_0},$$

where K_r – coefficient that takes into account the needs for free time and the own needs of the process performers, time spent on preparatory and final actions, and possible technological breaks; V_0 – volume of production.

Based on microelement rationing, the total labor intensity of the cycle was determined [7]:

$$T_\Sigma = \sum_{i=1}^{9} T_i,\ \textit{person·hour/module},$$

(for one module per lifting cycle).

To assess the efficiency, the coefficient of conformity of the mechanization process is used [7]:

$$K_R = \frac{t_R}{t_M},$$

де t_R – real-time execution of operations, t_M – standard time for manual method.

An example of modeling the normalization matrix for the concreting process is given in the table 2.

The data is calculated for one formwork station or for 1,6·0,36·1,5=0,864 m3.

For the developed module ($K_R = 1{,}74 \ldots 2{,}5$), which indicates a twofold reduction in labor intensity.

The turnover ratio determines the number of cycles of use of one set:

$$K_O = \frac{N_C}{N_{CH}},$$

where N_C – number of operating cycles during the service life, N_{CH} – average number of changes per object.

Table 2

Example of forming a matrix for normalizing the O4 concreting process

Operations	Number of actions N_i according to the norm of time, $H_{h\ min}$.								T_{wi}, min	N_{wi}, person	Q_{wi}, person-min
	0.5	1	2	3	4	5	6	7			
$O_{4.1}$				1					3	1	3
$O_{4.2}$			3						6	3	18
$O_{4.3}$				1					3	1	3
$O_{4.4}$			1						2	1	2
Labor cost rate – $\boldsymbol{H_{hw}}$ = *0,0167·26·1,15/1 = 0,5 person-hour./1 or 0,58 person-hour / м3* Coefficient of compliance $\boldsymbol{K_{hw}}$ = 2,16											26
Process structure O4 – placing of concrete: $O_{4.1}$ – feeding concrete into the bucket by crane; $O_{4.2}$ – leveling and compacting concrete in layers 0.5 m high; $O_{4.3}$ – lowering of the empty bucket; $O_{4.4}$ – quality control.											

For the developed module $K_O = 80 \dots 100$, which is 1,5–1,8 times higher than similar systems [12].

The duration of one concreting cycle is determined by:

$$T_C = T_{Ct} + T_H + T_{LT} + T_\tau,$$

where T_{Ct} – layer concreting time (≈ 4 hour), T_H – holding time before starting the lift (≈ 3 hour), T_{LT} – module lift time (≈ 2 hour), T_τ – technological breaks (≈ 1 hour). Therefore, T_C = 10 … 12 hour.

This cycle provides a daily rhythm of concreting one tier (1.5 m high) and allows you to organize work according to a continuous two-shift scheme.

The optimal number of sets is determined from the condition of continuity of the technological flow:

$$n = \frac{T_{CD}}{T_C} K_O,$$

where T_{CD} – total construction duration of the section, T_C – duration of one cycle, K_O – turnover ratio.

For the given building scheme with a floor height of 3 m and a section concreting duration of 20 days: $n \approx 0{,}5$.

Therefore, one set of formwork is capable of erecting two sections in parallel, which reduces the need for equipment on site. 40–50 %.

The formation of sets is carried out taking into account: standard size of pylons (1, 1.5, 1.8 m); level of mechanization (single-level or two-level system); concreting mode (continuous or periodic).

Each set includes: two forming modules, a set of guides, a pumping station, a control panel, service platforms and a belt cleaning system.

Building structures of frame-monolithic multi-storey buildings erected using self-elevating formwork with a movable module with a belt should be designed taking into account the specific requirements of concreting technology and structural features of the formwork [7, 8, 17].

When designing buildings, it is recommended: the pylon grid should be taken as the same on all floors of the building; for pylons located one above the other along the height of the building, the same cross-sectional dimensions should be assigned; it is not allowed to design elements protruding from the pylon structure – their implementation should be provided after the pylon structure is installed. In this case, it is recommended to use prefabricated reinforced concrete and metal structures; pylons should be designed from concrete of class no lower than C20/25 [18]; the protective layer in pylons should be at least 20 mm; for supporting floor slabs, it is necessary to provide for the installation of embedded parts in the pylon structure. In this case, the weakening of the cross-section should be no more than 0.4 of the pylon thickness; it is recommended to perform the joining of vertical reinforcement rods of pylons at a mark where the action of bending moments is minimal; the joints of reinforcing rods in pylons, as a rule, should be designed with an overlap with wire binding without welding; the vertical reinforcement rods of the pylons should not have hooks at the upper ends, and the length of these rods should not exceed 3.5 m; the height of the floor should be set within 2.8-3.3 m.

Conclusions

- A structural and operational description of the full concreting cycle of vertical monolithic structures based on microelement rationing matrices is proposed, which takes into account the use of a vertically movable strip formwork system.
- A model of the mechanized lifting cycle of the formwork module is developed, which takes into account the phased operation of the support frame, guides and working belt with a local tangential separation zone.
- The analysis of labor costs for movable vertical formwork systems is performed thanks to detailed operational decomposition algorithms, which allow for comparative studies with panel systems.
- The concept of the formwork module is developed taking into account their interaction with guides and the lifting frame.
- The proposed approach to the formation of rationing matrices allows for accurate modeling of cycle duration and comparison of different options for technological solutions.
- The vertically movable system significantly increases the turnover of the formwork and reduces dependence on crane equipment, which is critically important for the accelerated construction of multi-story buildings.
- The methodology lays the foundation for further development of digital models, optimization algorithms, and integration with BIM/SCADA systems [19-21].

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Оптимізація технології формування монолітних вертикальних конструкцій з використанням рухомих стрічкових опалубних систем

У статті розроблено комплексну методологічну основу для структурно-операційної оптимізації технології формування монолітних вертикальних елементів будівель із застосуванням вертикально переміщуваних модулів стрічкового типу. Запропонований підхід ґрунтується на детальній декомпозиції будівельного процесу на дев'ять уніфікованих матриць мікроелементного нормування, які охоплюють повний виробничий цикл: монтаж направляючих рам, установлення арматурних каркасів, підвішування модулів, пошарове укладання бетонної суміші, регульований догляд за бетоном, вертикальне переміщення формувальних модулів, виконання коригувальних операцій та подальший демонтаж системи. Така структуризація дає змогу точно визначати трудомісткість, оцінювати технологічну послідовність операцій та виявляти чинники, що найбільше впливають на продуктивність.

Ключовою особливістю досліджуваної системи є гнучка формувальна стрічка, натягнута на приводні та обвідні ролики, що забезпечує тангенціальне відокремлення від поверхні бетону під час підйому модуля. Такий принцип істотно зменшує сили адгезії, знижує механічний опір та мінімізує ризик пошкодження свіжої бетонної поверхні. Порівняно з традиційними панельними системами, стрічкова опалубка демонструє нижчі енерговитрати, меншу трудомісткість і підвищений коефіцієнт оборотності. У роботі сформульовано аналітичні залежності для оцінювання тривалості технологічного циклу, коефіцієнтів відповідності, оборотності та потреб у ресурсах.

Обґрунтовано переваги використання механізованих групових конфігурацій модулів, які забезпечують синхронізований підйом, стабільність геометрії та безперервність бетонування в умовах прискореного будівництва. Методика також створює підґрунтя для цифрової інтеграції технологічного процесу з BIM-плануванням, SCADA-моніторингом та використанням прогнозних алгоритмів оптимізації.

Результати дослідження підтверджують, що вертикально переміщувані стрічкові опалубні системи становлять технологічно та економічно ефективну альтернативу традиційним рішенням. Їх застосування підвищує продуктивність праці, покращує якість бетонних поверхонь і забезпечує більшу стабільність технологічного циклу. Запропонована методологія формує основу для подальшої розробки цифрових моделей, алгоритмів автоматизованого керування та сучасних інструментів раціоналізації процесів монолітного будівництва.

Ключові слова: стрічкова опалубка, вертикальний рухомий модуль, щитова опалубка, зчеплення бетону, трудомісткість, технологічний цикл, монолітні конструкції.