Magazine of Civil Engineering

ISSN 2712-8172

journal homepage: http://engstroy.spbstu.ru/

DOI: 10.34910/MCE.101.11

Stochastic model of the construction process implemented with application of sliding formwork

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Keywords: construction, sliding formwork, concrete layer, concrete maturing, concrete pouring, stochastic model

Abstract. The paper covers issues connected to the determination of most preferred values for the parameters of construction processes implemented with application of sliding formwork and defined by the factors of stochastic nature. On the basis of the review of different literature sources connected to the modeling of mentioned above processes it has been concluded that existing scientific developments provide relatively low adequacy of the results due to the simplified mathematical models that do not take into account stochastic factors. That circumstance has determined the necessity for creation of stochastic model for the construction process implemented with sliding formwork. The initial data for the model include baseline duration of the wall construction process, wall height, concrete layer thickness, characteristics of stochastic values of the concrete layer's pouring and maturing duration (mathematical expectation and mean-square deviation), etc.; parameters to be determined are the sliding formwork's panel height and movement base (average) speed. The created model has been implemented on the practical example – wall construction process as the element of the project "Arctic NLG 2". On the basis of the received results the conclusion has been made about high practical significance of the developed tool.

1. Introduction

Modern conditions of the construction industry's development are defined by the increase of requirements for the time and cost parameters of the technological processes assumed by construction projects, increase of the complexity of works performed and implementation of structurally modified innovative materials. In that conditions the issues connected to the determination of the most preferred values for the parameters of technological processes based on different factors of stochastic nature – especially, wall construction with application of sliding formwork technology – gain particular importance as mentioned factors have significant influence on the duration and cost of the works performed in accordance with construction project. This circumstance has determined the necessity for conduction of the research which object is a construction process implemented with application of sliding formwork; corresponding subject is determined by the parameters of the mentioned processed that are connected to the factors of stochastic nature.

Sliding formwork technology is one of the modern technologies applied for building of reinforced concrete structures. A feature of the technology is connected to the application of specific equipment providing continuous movement of the formwork during its pouring with concrete in layers and, as sequence, continuity of the concreting pouring. As the formwork slowly and continuously rises, reinforcing and concrete pouring goes on the upper level and the fresh surface processing on the level below (see Fig. 1).

Matskina, M.M., Petrochenko, M.V., Radaev, A.E. Stochastic model of the construction process implemented with application of sliding formwork. Magazine of Civil Engineering. 2021. 101(1). Article No. 10111. DOI: 10.34910/MCE.101.11

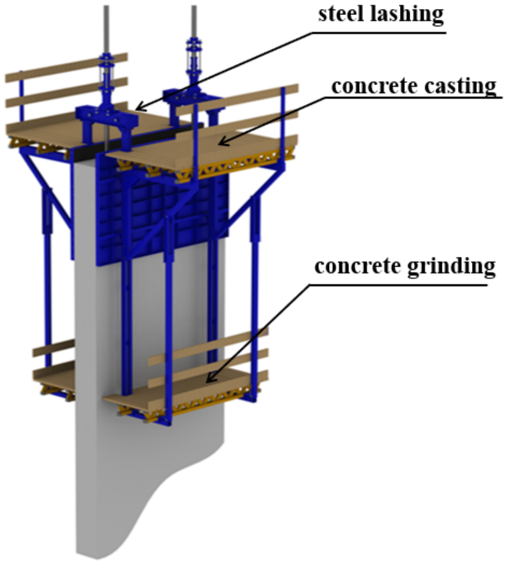

Figure 1. Sliding formwork's general view.

At the initial stage of the research the general analysis of the object under consideration and the review of the scientific developments connected to the modeling of construction processes implemented with application of sliding formwork have been carried out. On the basis of the corresponding results the following conclusions have been made:

1. The literature sources connected to the technology described above can be divided into the following categories:

1.1 Works connected to the comparative analysis of the sliding formwork technology with other technologies of concreting pouring [1–4]. That works contain description of both main advantages of the sliding formwork technology – including relatively high speed of work and the tightness of the finished structure (no joints during continuous concreting) and its disadvantages – increase of operational costs connected to the use of more complex mechanized or automated equipment, a significant impact on the accuracy of formwork positioning on the quality of work performed, etc.

1.2 Works connected to the analysis of the influence of different factors on the aggregate indicators (duration, cost, quality) of the works performed [5–9], including the following studies:

– influence of the formwork occupancy (the level concrete poured in the height of the formwork) on the quality of works performed [5–7]; on the one hand, increase of the formwork volume used for concreting pouring within one continuous operation determines increase of technological process's reliability in terms of possible intervals of technological idle time; on the other hand, ensuring empty volume within the framework provides flexibility of technological process in terms of framework's movement speed regulation in accordance with the dynamics of the concrete hardening or as the adjustment to different events in internal (connected to the technological resources involved) or external environment; researchers have formulated the practical recommendations connected to the formwork occupancy – particularly, the height of the empty volume within the formwork should be equal to the value that 2–3 times higher than concrete pouring level thickness (in case the thickness is 10–15 cm, the mentioned empty volume height is 30–40 cm);

– influence of the thickness of the poured layer on the sliding formwork's movement speed and quality of the concreting pouring [8]; the experimental data showed that with the layer thickness increase the maximum temperature arising during its hardening also increases but with decreasing rate; researchers conclude that in conditions of layer-by-layer casting it is much easier to control thermal cracking in comparison with the block-casting method.

1.3 Works connected to the creation of mathematical models for the construction process implemented with application of sliding formwork [10–21], including the following scientific developments:

– developments connected to the determination of the formwork's technological parameters with application of Building Information Modeling (BIM) for the provision of synchronized scheduling tool [10–14]; those developments are not directly connected to the mathematical modeling as corresponding scientific works include description of different block schemes describing connection between implemented technological process and corresponding BIM models;

– developments connected to the formwork method selection with application of artificial neural networks [15–17], fuzzy logic algorithms [18], multi-criteria decision making [19] and analytical approach [20–22]; the corresponding scientific results – models and algorithms – provide determination of optimal combination of values for unknown characteristics of formwork technology but don't take into account the stochastic nature of different parameters describing technological process under consideration;

– developments connected to the determination of aggregate indicators of the technological process implemented with application of the formwork on the basis of simulation modeling methods [23, 24] – corresponding models don't take into account features of sliding formwork technology and connected with high laboriousness for provision of relatively high adequacy of the results;

– developments connected to the analysis of the physical processes connected to pouring of a concrete into the formwork with different technical characteristics of pumping equipment [25–27] – corresponding models can be used for optimization of the formwork filling process during the design phase but the corresponding factors taken into account don't have significant influence on the technological process's duration that depends also on the time characteristics of other processes (including formwork movement, reinforcement dressing, etc.).

2. Most of existing scientific developments are based on a deterministic (not stochastic) nature of the parameters of construction process implemented with application of sliding formwork and therefore do not correspond to the real conditions of technological process's implementation and, as a sequence, have relatively small practical significance.

On the basis of all mentioned above the general description of the research has been formulated in terms of the following elements:

- research aim – development of the tool for justification of parameters of the construction process implemented with application of sliding formwork.
- research tasks:

1. Creation of the stochastic model of the construction process implemented with application of sliding formwork – in terms of main provisions, initial data and calculated characteristics.

2. Implementation of the stochastic model on a practical example for objective estimation of the practical significance of the created model.

The detailed description of the corresponding structural elements of the research is presented in the following sections of the work.

2. Methods

During the next stage of the research the stochastic model for determination of the most preferred values for parameters of construction process implemented with application of sliding formwork has been created. The main provisions of the created mathematical model are the following:

1. The object under consideration is the technological process of the wall erection performed with application of sliding formwork within a limited time interval (determined by the construction project forecast characteristics).

2. The technological process of the wall erection with sliding formwork includes the following main steps:

2.1. Panels installation in its lowest position; sequential laying (pouring) of concrete layers in an amount that takes into account the legal limit concrete level in the formwork height and the height of one layer with simultaneous control of the layer maturing dynamics.

2.2. Formwork lifting is performed starting from the latest of the following events: development of sufficient strength of the lower layer; the end of the filling of the last stationary formwork (located in the lowest position).

2.3. The movement of the formwork is carried out at a stationary speed within the thickness of one layer of concrete pouring; the movement speed is determined by the standard (most preferred) value, as well as the maximum relative deviation that determines the range of speed values in the case of a relatively low or high speed of next concrete layer maturing.

2.4. The processes described in paragraphs 2.2 and 2.3 are repeated until the formwork reaches the upper extreme position while the process of layer-by-layer concrete pouring will continue until the formwork height is filled.

3. It is necessary to determine the structural parameters of the formwork – the height of the panel and the nominal speed of its movement – to ensure minimal operational costs and the duration of the wall erection should not exceeding the maximum allowable values in conditions when the durations of laying and maturing of the next layer of concrete are stochastic values corresponding to the normal distribution.

It is important to note that stochastic nature of the duration parameters for laying and maturing of the concrete layer is caused by the influence of big amount of factors on the characteristics of corresponding technological processes. In the case of concrete laying, the mentioned factors are connected to the qualifications of the worker manipulating the trunk of a concrete pumping unit, the amount of preparatory work determined by the configuration of the reinforcement, the state of the previous layer, etc. In the case of concrete maturing, the mentioned factors are connected to the physical and mechanical properties of concrete, the impossibility of enduring of the fixed thickness of concrete layer, etc. The spread of the values of the corresponding time parameters is not critical in the case of the use of standard technologies for the construction of reinforced concrete structures, however, in the case of the sliding formwork technology, which is based mainly on ensuring the continuity and synchronization of the operations of concrete laying and maturing, as well as the movement of the formwork, the specified spread gets much larger significance.

Developed model is based in the initial data specified in Table 1 and assumes carrying out of calculations of individual quantitative characteristics presented in Table 2 (the sequence of calculations is determined by the order of characteristics' numbering in the last specified table). The model's connection to the real conditions is determined by the correspondence of the duration of repeated technological operations to the normal probability distribution. The proposed calculation formulas are based on the probability theory elements.

Table 1. Initial data for created mathematical model.

№	Characteristic name	Designation	Meas. unit
1	**General initial data**		
1.1	**Parameters of the alternative solutions set**		
1.1.1	Number of sliding formwork's panel height alternative values	units	m
1.1.2	Number of sliding formwork's movement speed alternative base values	units	n
1.2	**Time parameters**		
1.2.1	Baseline duration of the wall construction process	hours	$T^{\Sigma\max}$
1.2.2	Mathematical expectation of the one layer pouring duration	hours	$\bar{T}_{\mathrm{m}}$
1.2.3	Mean-square deviation of the one layer pouring duration	hours	σ_{m}
1.2.4	Mathematical expectation of the one layer maturing duration	hours	$\bar{T}_{\mathrm{c}}$
1.2.5	Mean-square deviation of the one layer maturing duration	hours	σ_{c}
1.3	**Design parameters**		
1.3.1	Wall height	m	H^{Σ}
1.3.2	The height of the top gape area	m	Δh^{e}
1.3.3	Thickness of the concrete layer	m	h
1.3.4	Maximal deviation from the sliding formwork's movement base speed	-	Δ_{υ}
1.4	**Probabilistic parameters**		
1.4.1	The minimal probability that the layer maturing duration will not exceed the total layers pouring duration within the valid formwork occupancy height	-	$P_{\mathrm{cm}}^{\min}$
1.4.2	The minimal probability that the layer maturing duration will not exceed the duration of the minimum speed formwork movement to the valid formwork occupancy height	-	$P_{\mathrm{h-}}^{\min}$
1.4.3	The minimal probability that the layer pouring duration will exceed the duration of the minimum speed formwork movement to the one layer height	-	$P_{\mathrm{t-}}^{\min}$
1.4.4	The minimal probability that the layer pouring duration will not exceed the duration of the maximum speed formwork movement to the one layer height	-	$P_{\mathrm{t+}}^{\min}$
1.5	**Cost parameters**		
1.5.1	Unit costs per sliding formwork's panel height unit	CU/m	c^{H}
1.5.2	Unit costs per sliding formwork's movement base speed unit	CU / (m/hour)	c^{υ}
2	**Indexes**		
2.1	Index of the sliding formwork's panel height alternative value	-	$i = 1, 2, ..., m$
2.2	Index of the sliding formwork's movement speed alternative base value	-	$j = 1, 2, ..., n$

№	Characteristic name	Designation	Meas. unit
3	**Parameters for each alternative value *i* (*i* = 1, 2,…, *m*) of sliding formwork's panel height**		
3.1	Sliding formwork's panel height alternative value	m	H_i
4	**Parameters for each alternative base value *j* (*j* = 1, 2,…, *n*) of sliding formwork's movement speed**		
4.1	Sliding formwork's panel height alternative base value	m/hour	υ_j

Table 2. Calculated characteristics for created mathematical model.

№	Characteristic name	Meas. unit	Formula
1	**Characteristics calculated for each alternative value *i* (*i* = 1, 2,…, *m*) of sliding formwork's panel height**		
1.1	Number of layers inside the formwork	units	$z_i^{\mathrm{H}} = \dfrac{H_i - \Delta h^{\mathrm{e}}}{h}$
1.2	Number of formwork movements	hours	$z_i^{\mathrm{H}\Sigma} = \dfrac{H^{\Sigma}}{z_i^{\mathrm{H}} \cdot h}$
1.3	Mathematical expectation of the layers pouring duration within the formwork's panel height (without technological time between the layers)(1)	hours	$M_{\mathrm{H}i} = \overline{T}_{\mathrm{m}} \cdot z_i^{\mathrm{H}}$
1.4	Mean-square deviation of the layers pouring duration within the formwork's panel height (without technological time between the layers)(2)	hours	$\sigma_{\mathrm{H}i} = \sigma_{\mathrm{m}} \cdot \sqrt{z_i^{\mathrm{H}}}$
1.5	Actual probability that the layer maturing duration will not exceed the total layers pouring duration within the valid formwork occupancy height(3)(4)	-	$P_{\mathrm{cm}i} = \Phi'\left(\dfrac{M_{\mathrm{H}i} - \overline{T}_{\mathrm{c}}}{\sqrt{\sigma_{\mathrm{H}i}^2 + \sigma_{\mathrm{c}}^2}}\right)$
1.6	Total costs per formwork height	CU	$C_i^{\mathrm{H}} = c^{\mathrm{H}} \cdot H_i$
2	**Characteristics performed for each alternative base value *j* (*j* = 1, 2,…, *n*) of sliding formwork's movement speed**		
2.1	Duration of the formwork movement via the layer thickness at minimum speed	hour	$t_{\mathrm{h}\,j}^{\min} = \dfrac{h}{\upsilon_j \cdot (1 - \Delta_{\upsilon})}$
2.2	Duration of the formwork movement via the layer thickness at base (average) speed	hour	$t_{\mathrm{h}\,j}^{\mathrm{aver}} = \dfrac{h}{\upsilon_j}$
2.3	Duration of the formwork movement via the layer thickness at maximum speed	hour	$t_{\mathrm{h}\,j}^{\max} = \dfrac{h}{\upsilon_j \cdot (1 - \Delta_{\upsilon})}$
2.4	Actual probability that the layer pouring duration will exceed the duration of the minimum speed formwork movement to the one layer height(3)(5)	-	$P_{\mathrm{t}-j} = 1 - \Phi'\left(\dfrac{t_{\mathrm{h}\,j}^{\min} - \overline{T}_{\mathrm{m}}}{\sigma_{\mathrm{m}}}\right)$
2.5	Actual probability that the layer pouring duration will not exceed the duration of the maximum speed formwork movement to the one layer height(3)(5)	-	$P_{\mathrm{t}+j} = \Phi'\left(\dfrac{t_{\mathrm{h}\,j}^{\max} - \overline{T}_{\mathrm{m}}}{\sigma_{\mathrm{m}}}\right)$
2.6	Total costs determined by formwork base speed	CU	$C_j^{\upsilon} = c^{\upsilon} \cdot \upsilon_j$
3	**Characteristics calculated for each alternative value *i* (*i* = 1, 2,…, *m*) of sliding formwork's panel height and for each alternative base value *j* (*j* = 1, 2,…, *n*) of sliding formwork's movement speed**		
3.1	Duration of the minimum speed formwork movement via the valid formwork occupancy height	hour	$t_{\mathrm{H}ij} = \dfrac{H_i - \Delta h^{\mathrm{e}}}{\upsilon_j \cdot (1 - \Delta_{\upsilon})}$
3.2	Actual probability that the layer maturing duration will not exceed the duration of the minimum speed formwork movement to the valid formwork occupancy height(3)(5)	hour	$P_{\mathrm{h}-ij} = \Phi'\left(\dfrac{t_{\mathrm{H}ij} - \overline{T}_{\mathrm{c}}}{\sigma_{\mathrm{c}}}\right)$

№	Characteristic name	Meas. unit	Formula
3.3	Expected estimated duration of wall construction process	days	$T_{ij}^{\Sigma} = \left(P_{\mathrm{cm}\,i} \cdot P_{\mathrm{h}-ij} \times \times\left(P_{\mathrm{t}-j} \cdot P_{\mathrm{t}+j} \cdot z_i^{\mathrm{H}} \cdot t_{\mathrm{h}\,j}^{\mathrm{aver}} + +\left(1-P_{\mathrm{t}-j}\right)\cdot P_{\mathrm{t}+j} \cdot z_i^{\mathrm{H}} \cdot t_{\mathrm{h}\,j}^{\min}\right) + +P_{\mathrm{cm}\,i} \cdot \left(P_{\mathrm{h}-ij} \cdot \left(1-P_{\mathrm{t}+j}\right) + +\left(1-P_{\mathrm{h}-ij}\right)\right) \cdot z_i^{\mathrm{H}} \cdot \overline{T}_{\mathrm{m}} + +\left(1-P_{\mathrm{cm}\,i}\right)\cdot \overline{T}_{\mathrm{c}}\right) \cdot z_i^{\mathrm{H}\Sigma}$
3.4	Total costs	CU	$C_{ij}^{\Sigma} = C_i^{\mathrm{H}} + C_j^{\upsilon}$
3.5	The indicated value of the total costs with taking into account of acceptable solutions area	CU	$C_{ij}'^{\Sigma} = \begin{cases} C_{ij}^{\Sigma}, \text{ if } T_{ij}^{\Sigma} \le T^{\Sigma\max}, \\ \quad P_{\mathrm{cm}\,i} \ge P_{\mathrm{cm}}^{\min}, \\ \quad P_{\mathrm{h}-ij} \ge P_{\mathrm{h}-}^{\min}, \\ \quad P_{\mathrm{t}-j} \ge P_{\mathrm{t}-}^{\min}, \\ \quad P_{\mathrm{t}+j} \ge P_{\mathrm{t}+}^{\min}; \\ \textbf{null} \text{ otherwise} \end{cases}$
3.6	Indicator of the option feasibility for various formwork moving forms	-	$y_{ij} = \begin{cases} 1, \text{ if } i, j: \\ \quad C_{ij}'^{\Sigma} = \min\limits_{i'}\left\{\min\limits_{j'}\left\{C_{i'j'}^{\Sigma}\right\}\right\}, \\ 0 \text{ otherwise} \end{cases}$
4	**Aggregate calculated characteristics**		
4.1	**Design characteristics**		
4.1.1	Sliding formwork's panel height actual value	m	$H = \sum_{i=1}^{m}\left(H_i \cdot \sum_{j=1}^{n} y_{ij}\right)$
4.1.2	Sliding formwork's movement speed actual base value	m/hour	$\upsilon = \sum_{j=1}^{n}\left(\upsilon_j \cdot \sum_{i=1}^{m} y_{ij}\right)$
4.2	**Probabilistic characteristics**		
4.2.1	The actual value of probability that the another layer maturing time will not exceed the duration of the formwork's movement within thickness of one layer with base speed	-	$P_{\mathrm{cm}} = \sum_{i=1}^{m}\left(P_{\mathrm{cm}\,i} \cdot \sum_{j=1}^{n} y_{ij}\right)$
4.2.2	The actual value of probability that the another layer maturing time will not exceed the duration of the formwork's movement within thickness of one layer with minimal speed	-	$P_{\mathrm{h}-} = \sum_{i=1}^{m}\sum_{j=1}^{n} P_{\mathrm{h}-ij} \cdot y_{ij}$
4.2.3	The actual value of probability that the layers maturing time inside the formwork will not exceed the maximal reserve of technological time	-	$P_{\mathrm{t}-} = \sum_{j=1}^{n}\left(P_{\mathrm{t}-j} \cdot \sum_{i=1}^{m} y_{ij}\right)$
4.2.4	The actual value of probability that the actual duration of the wall construction will not exceed the planned value	-	$P_{\mathrm{t}+} = \sum_{j=1}^{n}\left(P_{\mathrm{t}+j} \cdot \sum_{i=1}^{m} y_{ij}\right)$
4.3	**Time characteristics**		
4.3.1	The actual value of the expected estimated duration of wall construction	hours	$T^{\Sigma} = \sum_{i=1}^{m}\sum_{j=1}^{n} T_{ij}^{\Sigma} \cdot y_{ij}$
4.4	**Cost characteristics**		
4.4.1	The actual costs for pouring into layers of a certain thickness	CU	$C^{\mathrm{H}} = c^{\mathrm{H}} \cdot \sum_{i=1}^{m}\left(H_i \cdot \sum_{j=1}^{n} y_{ij}\right)$
4.4.2	The actual costs due to formwork movement speed changes	CU	$C^{\upsilon} = c^{\upsilon} \cdot \sum_{j=1}^{n}\left(\upsilon_j \cdot \sum_{i=1}^{m} y_{ij}\right)$

№	Characteristic name	Meas. unit	Formula
4.4.3	The actual total costs	CU	$C^{\Sigma} = C^{H} + C^{\upsilon}$

Note:

(1) characteristic is calculated with the correspondence the summation rule for the stochastic values' mathematical expectations;

(2) characteristic is calculated with the correspondence the summation rule for the stochastic values' mean-square deviations;

(3) designation Φ' (in the calculated expression) defines the inverse Laplace function, which provides a probability determination based on the initially known normalized deviation (argument);

(4) characteristic is calculated on the basis of the formulas for estimation of the probabilistic parameters for the comparison of random variables corresponding to the normal distribution;

(5) characteristic is calculated on the basis of the dependence between probabilistic parameters and values of a random variable for a function of standard normal distribution.

3. Results and Discussions

At the last stage of the research created mathematical model has been implemented on a practical example – technological process connected to the wall construction in accordance with the project "Arctic NLG 2" (construction of production unit for liquefied natural gas located on the Gydan Peninsula in the Yamal-Nenets Autonomous Area) – with application of Microsoft Excel software. The general view of the corresponding worksheet (including initial data and calculation results) is presented in Fig. 2–4. The principles of the worksheet's fulfillment with the data connected to the task are presented in Table 3. The most preferred values for the initially unknown parameters of the technological process under consideration are the following: sliding formwork's panel height – 1.5 meters, corresponding movement base (average) speed – 1.2 meters per day.

Table 1. Initial data

No.	Characteristic name	Designation	Meas. unit	Value
1	**Time parameters**			
1.1	Baseline duration of the wall construction process	$T^{\Sigma\max}$	hours	480
1.2	Mathematical expectation of the one layer pouring duration	T^{-}_{m}	hours	2
1.3	Mean-square deviation of the one layer pouring duration	σ_m	hours	0.3
1.4	Mathematical expectation of the one layer maturing duration	T^{-}_{c}	hours	25
1.5	Mean-square deviation of the one layer maturing duration	σ_c	hours	5
2	**Design parameters**			
2.1	Wall height	H^{Σ}	m	10
2.2	The height of the top gape area	Δh^{c}	m	0.2
2.3	Thickness of the concrete layer	h	m	0.1
2.4	Maximal deviation from the sliding formwork's movement base speed	Δ_{υ}	-	0.1
3	**Probabilistic parameters**			
3.1	The minimal probability that the layer maturing duration will not exceed the total layers pouring duration within the valid formwork occupancy height	$P^{\min}_{cm}$	-	0.5
3.2	The minimal probability that the layer maturing duration will not exceed the duration of the minimum speed formwork movement to the valid formwork occupancy height	$P^{\min}_{h-}$	-	0.5
3.3	The minimal probability that the layer pouring duration will exceed the duration of the minimum speed formwork movement to the one layer height	$P^{\min}_{t-}$	-	0.2
3.4	The minimal probability that the layer pouring duration will not exceed the duration of the maximum speed formwork movement to the one layer height	$P^{\min}_{t}$	-	0.2
4	**Cost parameters**			
4.1	Unit costs per sliding formwork's panel height unit	c^{H}	CU/m	2.25
4.2	Unit costs per sliding formwork's movement base speed unit	c^{υ}	CU/(m/hour)	2.5

Table 3. Aggregate calculated characteristics

No.	Characteristic name	Designation	Meas. unit	Value
1	**Design characteristics**			
1.1	Sliding formwork's panel height actual value	H	hour	1.5
1.2	Sliding formwork's movement speed actual base value	υ	m/hour	0.049679
2	**Probabilistic characteristics**			
2.1	The actual value of probability that the another layer maturing time will not exceed the duration of the formwork's movement within thickness of one layer with base speed	P_{cm}	-	0.577491
2.2	The actual value of probability that the another layer maturing time will not exceed the duration of the formwork's movement within thickness of one layer with minimal speed	P_{h-}	-	0.792479
2.3	The actual value of probability that the layers maturing time inside the formwork will not exceed the maximal reserve of technological time	P_{t}	-	0.215193
2.4	The actual value of probability that the actual duration of the wall construction will not exceed the planned value	P_{t-}	-	0.285371
3	**Time characteristics**			
3.1	The actual value of the expected estimated duration of wall construction	T^{Σ}	hours	199.2108
4	**Cost characteristics**			
4.1	The actual costs for pouring into layers of a certain thickness	C^{H}	CU	3.375
4.2	The actual costs due to formwork movement speed changes	C^{υ}	CU	2.980769
4.3	The actual total costs	C^{Σ}	CU	6.355769

Figure 2. General view of the Microsoft Excel worksheet created during the implementation of elaborated model on a practical example (beginning).

Table 2. Calculated characteristics for alternative variants

Row	M: Variant number	N: Sliding formwork panel height	O: Amount of layers inside the formwork	P: Number of formwork movements	Q–R	S	T	U	V	W	X	Y	Z	AA	AB	AC	AD	AE	AF	AG	AH	AI: Total value
2–3								The indicator of the feasibility of selection of the alternative variant (j)														
4					Variant number	j	-	1	2	3	4	5	6	7	8	9	10	11	12	13	14	
5					Alternative base value of formwork speed	υ_j	m/day	0.5	0.6	0.7	0.8	1.0	1.1	1.2	1.3	1.4	1.5	1.7	1.8	1.9	2	
6							m/hour	0.021	0.026	0.030	0.035	0.040	0.045	0.050	0.054	0.059	0.064	0.069	0.074	0.079	0.083	
7																						
8	i	H_i	z^{H}_j	$z^{H\Sigma}_i$	-	-	-	$y_{ij\ 1}$	$y_{ij\ 2}$	$y_{ij\ 3}$	$y_{ij\ 4}$	$y_{ij\ 5}$	$y_{ij\ 6}$	$y_{ij\ 7}$	$y_{ij\ 8}$	$y_{ij\ 9}$	$y_{ij\ 10}$	$y_{ij\ 11}$	$y_{ij\ 12}$	$y_{ij\ 13}$	$y_{ij\ 14}$	$\Sigma_j y_{ij}$
9	-	m	units	hours	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
10	1	1.2	10	10	-	-	-	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
11	2	1.3	11	9.090909	-	-	-	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
12	3	1.4	12	8.333333	-	-	-	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
13	4	1.5	13	7.692308	-	-	-	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1
14	5	1.6	14	7.142857	-	-	-	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
15	6	1.7	15	6.666667	-	-	-	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
16	7	1.8	16	6.25	-	-	-	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
17	8	1.9	17	5.882353	-	-	-	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
18	9	2	18	5.555556	-	-	-	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
19	10	2.1	19	5.263158	-	-	-	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
20	11	2.2	20	5	-	-	-	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
21	12	2.3	21	4.761905	-	-	-	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
22	13	2.4	22	4.545455	-	-	-	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
23	14	2.5	23	4.347826	-	-	-	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
24	Total value					$\Sigma_i y_{ij}$	-	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1

Row	AJ–AK: Layers pouring duration within the formwork's panel height (without technological time between the layers): Mathematical expectation	AL–AM: Mean-square deviation	AN–AQ: Actual probability that the layer maturing duration will not exceed the total layers pouring duration within the valid formwork occupancy height	AR–AS: Total costs per formwork height
8	M_{Hi}	$\sigma_{\Pi i}$	$P_{cm\ i}$	C^{H}_i
9	hours	hours	-	д.е.
10	20	0.948683	0.162934	2.7
11	22	0.994987	0.278111	2.925
12	24	1.03923	0.422377	3.15
13	26	1.081665	0.577491	3.375
14	28	1.122497	0.72087	3.6
15	30	1.161895	0.834983	3.825
16	32	1.2	0.913297	4.05
17	34	1.236932	0.95971	4.275
18	36	1.272792	0.983497	4.5
19	38	1.30767	0.994055	4.725
20	40	1.341641	0.998119	4.95
21	42	1.374773	0.999478	5.175
22	44	1.407125	0.999873	5.4
23	46	1.438749	0.999973	5.625

					1	2	3	4	5	6	7	8	9	10	11	12	13	14
25	Duration of the formwork movement via the layer thickness: at minimum speed		$t^{min}_{h\ j}$	hour	5.333	4.333	3.649	3.152	2.773	2.476	2.237	2.039	1.874	1.733	1.612	1.507	1.415	1.333
26	at base (average) speed		$t^{aver}_{h\ j}$	hour	4.8	3.9	3.284	2.836	2.496	2.229	2.013	1.835	1.686	1.56	1.451	1.357	1.273	1.2
27	at maximum speed		$t^{max}_{h\ j}$	hour	4.364	3.545	2.986	2.579	2.269	2.026	1.83	1.668	1.533	1.418	1.319	1.233	1.158	1.091
28	Duration of the minimum speed formwork movement via the valid formwork occupancy height for the sliding formwork's panel height alternative value (i)	1	$t_{H\ i=1,j}$	hour	53.33	43.33	36.49	31.52	27.73	24.76	22.37	20.39	18.74	17.33	16.12	15.07	14.15	13.33
29		2	$t_{H\ i=2,j}$	hour	58.67	47.67	40.14	34.67	30.51	27.24	24.6	22.43	20.61	19.07	17.74	16.58	15.56	14.67
30		3	$t_{H\ i=3,j}$	hour	64	52	43.79	37.82	33.28	29.71	26.84	24.47	22.49	20.8	19.35	18.09	16.98	16
31		4	$t_{H\ i=4,j}$	hour	69.33	56.33	47.44	40.97	36.05	32.19	29.08	26.51	24.36	22.53	20.96	19.59	18.39	17.33
32		5	$t_{H\ i=5,j}$	hour	74.67	60.67	51.09	44.12	38.83	34.67	31.31	28.55	26.23	24.27	22.57	21.1	19.81	18.67
33		6	$t_{H\ i=6,j}$	hour	80	65	54.74	47.27	41.6	37.14	33.55	30.59	28.11	26	24.19	22.61	21.22	20
34		7	$t_{H\ i=7,j}$	hour	85.33	69.33	58.39	50.42	44.37	39.62	35.78	32.63	29.98	27.73	25.8	24.12	22.64	21.33
35		8	$t_{H\ i=8,j}$	hour	90.67	73.67	62.04	53.58	47.15	42.1	38.02	34.67	31.86	29.47	27.41	25.62	24.05	22.67
36		9	$t_{H\ i=9,j}$	hour	96	78	65.68	56.73	49.92	44.57	40.26	36.71	33.73	31.2	29.02	27.13	25.47	24
37		10	$t_{H\ i=10,j}$	hour	101.3	82.33	69.33	59.88	52.69	47.05	42.49	38.75	35.6	32.93	30.64	28.64	26.88	25.33
38		11	$t_{H\ i=11,j}$	hour	106.7	86.67	72.98	63.03	55.47	49.52	44.73	40.78	37.48	34.67	32.25	30.14	28.3	26.67
39		12	$t_{H\ i=12,j}$	hour	112	91	76.63	66.18	58.24	52	46.97	42.82	39.35	36.4	33.86	31.65	29.71	28
40		13	$t_{H\ i=13,j}$	hour	117.3	95.33	80.28	69.33	61.01	54.48	49.2	44.86	41.23	38.13	35.47	33.16	31.13	29.33
41		14	$t_{H\ i=14,j}$	hour	122.7	99.67	83.93	72.48	63.79	56.95	51.44	46.9	43.1	39.87	37.09	34.67	32.54	30.67
42	Actual probability that the layer maturing duration will not exceed the duration of the minimum speed formwork movement to the valid formwork occupancy height for the sliding formwork's panel height alternative value (i)	1	$P_{h-\ i=1,j}$	hour	1	1	0.989	0.904	0.708	0.481	0.299	0.178	0.105	0.063	0.038	0.024	0.015	0.01
43		2	$P_{h-\ i=2,j}$	hour	1	1	0.999	0.973	0.865	0.673	0.468	0.304	0.19	0.118	0.073	0.046	0.03	0.019
44		3	$P_{h-\ i=3,j}$	hour	1	1	1	0.995	0.951	0.827	0.643	0.458	0.308	0.2	0.129	0.083	0.054	0.036
45		4	$P_{h-\ i=4,j}$	hour	1	1	1	0.999	0.986	0.925	0.792	0.619	0.449	0.311	0.21	0.14	0.093	0.063
46		5	$P_{h-\ i=5,j}$	hour	1	1	1	1	0.997	0.973	0.897	0.761	0.597	0.442	0.314	0.218	0.15	0.103
47		6	$P_{h-\ i=6,j}$	hour	1	1	1	1	1	0.992	0.956	0.868	0.733	0.579	0.435	0.316	0.225	0.159
48		7	$P_{h-\ i=7,j}$	hour	1	1	1	1	1	0.998	0.984	0.936	0.84	0.708	0.563	0.43	0.318	0.232
49		8	$P_{h-\ i=8,j}$	hour	1	1	1	1	1	1	0.995	0.973	0.915	0.814	0.685	0.55	0.425	0.32
50		9	$P_{h-\ i=9,j}$	hour	1	1	1	1	1	1	0.999	0.99	0.96	0.893	0.789	0.665	0.537	0.421
51		10	$P_{h-\ i=10,j}$	hour	1	1	1	1	1	1	1	0.997	0.983	0.944	0.87	0.767	0.647	0.527
52		11	$P_{h-\ i=11,j}$	hour	1	1	1	1	1	1	1	0.999	0.994	0.973	0.926	0.848	0.745	0.631
53		12	$P_{h-\ i=12,j}$	hour	1	1	1	1	1	1	1	1	0.998	0.989	0.962	0.908	0.827	0.726
54		13	$P_{h-\ i=13,j}$	hour	1	1	1	1	1	1	1	1	0.999	0.996	0.982	0.949	0.89	0.807
55		14	$P_{h-\ i=14,j}$	hour	1	1	1	1	1	1	1	1	1	0.999	0.992	0.973	0.934	0.871
56–58	Actual probability that the layer pouring duration will exceed the duration of the minimum speed formwork movement to the one layer height		P_{t-j}	-	0	4E-15	2E-08	6E-05	0.005	0.056	0.215	0.448	0.663	0.813	0.902	0.95	0.974	0.987

Figure 3. General view of the Microsoft Excel worksheet created during the implementation of elaborated model on a practical example (continuation).

	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	AA	AB	AC	AD	AE	AF	AG	AH	AI	AJ	AK	AL	AM	AN	AO	AP	AQ	AR	AS
59	Actual probability that the layer pouring duration will not exceed the						$P_{t\,j}$	-	1	1	0.999	0.973	0.815	0.534	0.285	0.135	0.06	0.026	0.012	0.005	0.002	0.001											
60	duration of the maximum speed formwork movement to the one																																
61	layer height																																
62						1	$T^{\Sigma}_{i=1,j}$	days	296.2	279.9	268.4	258.4	249.1	243.8	242.1	241.8	241.8	241.8	241.8	241.9	241.9	241.9											
63						2	$T^{\Sigma}_{i=2,j}$	days	312.4	284.6	265.5	250	234.8	224.3	220.4	219.6	219.6	219.7	219.7	219.7	219.7	219.7											
64						3	$T^{\Sigma}_{i=3,j}$	days	345.6	303.4	274.4	251.9	230.1	213.4	206.3	204.7	204.6	204.7	204.8	204.8	204.8	204.8											
65						4	$T^{\Sigma}_{i=4,j}$	days	389.2	331.5	291.9	261.4	232.6	209.9	199.2	196.5	196.4	196.6	196.7	196.7	196.7	196.7											
66						5	$T^{\Sigma}_{i=5,j}$	days	434.3	362.2	312.8	274.8	239.3	211.4	197.5	193.6	193.4	193.7	193.9	194	194	194											
67						6	$T^{\Sigma}_{i=6,j}$	days	472.8	389.3	332.1	288.1	247	215	198.8	194	193.6	194	194.3	194.4	194.5	194.5											
68	Expected estimated duration of wall construction process for the sliding formwork's panel height alternative value (*i*)					7	$T^{\Sigma}_{i=7,j}$	days	500.6	409.3	346.7	298.5	253.7	218.7	201	195.6	195.1	195.5	195.9	196.1	196.2	196.2											
69						8	$T^{\Sigma}_{i=8,j}$	days	517.8	421.8	356.1	305.4	258.3	221.6	203	197.2	196.6	197	197.5	197.7	197.8	197.8											
70						9	$T^{\Sigma}_{i=9,j}$	days	526.8	428.5	361.1	309.2	260.9	223.3	204.3	198.3	197.6	198.1	198.5	198.8	198.9	199											
71						10	$T^{\Sigma}_{i=10,j}$	days	530.9	431.5	363.4	311	262.1	224.2	204.9	198.9	198.1	198.6	199.1	199.3	199.5	199.5											
72						11	$T^{\Sigma}_{i=11,j}$	days	532.6	432.8	364.4	311.7	262.7	224.5	205.2	199.2	198.4	198.8	199.3	199.6	199.7	199.8											
73						12	$T^{\Sigma}_{i=12,j}$	days	533.1	433.2	364.7	312	262.8	224.7	205.3	199.3	198.5	198.9	199.4	199.7	199.8	199.9											
74						13	$T^{\Sigma}_{i=13,j}$	days	533.3	433.3	364.8	312	262.9	224.7	205.4	199.3	198.5	198.9	199.4	199.7	199.8	199.9											
75						14	$T^{\Sigma}_{i=14,j}$	days	533.3	433.3	364.8	312	262.9	224.7	205.4	199.3	198.5	198.9	199.4	199.7	199.8	199.9											
76	Total costs determined by formwork base speed						C^{υ}_{j}	CU	1.25	1.538	1.827	2.115	2.404	2.692	2.981	3.269	3.558	3.846	4.135	4.423	4.712	5											
77						1	$C^{\Sigma}_{i=1,j}$	CU	3.95	4.238	4.527	4.815	5.104	5.392	5.681	5.969	6.258	6.546	6.835	7.123	7.412	7.7											
78						2	$C^{\Sigma}_{i=2,j}$	CU	4.175	4.463	4.752	5.04	5.329	5.617	5.906	6.194	6.483	6.771	7.06	7.348	7.637	7.925											
79						3	$C^{\Sigma}_{i=3,j}$	CU	4.4	4.688	4.977	5.265	5.554	5.842	6.131	6.419	6.708	6.996	7.285	7.573	7.862	8.15											
80						4	$C^{\Sigma}_{i=4,j}$	CU	4.625	4.913	5.202	5.49	5.779	6.067	6.356	6.644	6.933	7.221	7.51	7.798	8.087	8.375											
81						5	$C^{\Sigma}_{i=5,j}$	CU	4.85	5.138	5.427	5.715	6.004	6.292	6.581	6.869	7.158	7.446	7.735	8.023	8.312	8.6											
82						6	$C^{\Sigma}_{i=6,j}$	CU	5.075	5.363	5.652	5.94	6.229	6.517	6.806	7.094	7.383	7.671	7.96	8.248	8.537	8.825											
83	Total costs for the sliding formwork's panel height					7	$C^{\Sigma}_{i=7,j}$	CU	5.3	5.588	5.877	6.165	6.454	6.742	7.031	7.319	7.608	7.896	8.185	8.473	8.762	9.05											
84	alternative value (*i*)					8	$C^{\Sigma}_{i=8,j}$	CU	5.525	5.813	6.102	6.39	6.679	6.967	7.256	7.544	7.833	8.121	8.41	8.698	8.987	9.275											
85						9	$C^{\Sigma}_{i=9,j}$	CU	5.75	6.038	6.327	6.615	6.904	7.192	7.481	7.769	8.058	8.346	8.635	8.923	9.212	9.5											
86						10	$C^{\Sigma}_{i=10,j}$	CU	5.975	6.263	6.552	6.84	7.129	7.417	7.706	7.994	8.283	8.571	8.86	9.148	9.437	9.725											
87						11	$C^{\Sigma}_{i=11,j}$	CU	6.2	6.488	6.777	7.065	7.354	7.642	7.931	8.219	8.508	8.796	9.085	9.373	9.662	9.95											
88						12	$C^{\Sigma}_{i=12,j}$	CU	6.425	6.713	7.002	7.29	7.579	7.867	8.156	8.444	8.733	9.021	9.31	9.598	9.887	10.18											
89						13	$C^{\Sigma}_{i=13,j}$	CU	6.65	6.938	7.227	7.515	7.804	8.092	8.381	8.669	8.958	9.246	9.535	9.823	10.11	10.4											
90						14	$C^{\Sigma}_{i=14,j}$	CU	6.875	7.163	7.452	7.74	8.029	8.317	8.606	8.894	9.183	9.471	9.76	10.05	10.34	10.63											
91						1	$C'^{\Sigma}_{i=1,j}$	CU	-	-	-	-	-	-	-	-	-	-	-	-	-	-											
92						2	$C'^{\Sigma}_{i=2,j}$	CU	-	-	-	-	-	-	-	-	-	-	-	-	-	-											
93						3	$C'^{\Sigma}_{i=3,j}$	CU	-	-	-	-	-	-	-	-	-	-	-	-	-	-											
94						4	$C'^{\Sigma}_{i=4,j}$	CU	-	-	-	-	-	-	6.356	-	-	-	-	-	-	-											
95						5	$C^{\Sigma}_{i=5,j}$	CU	-	-	-	-	-	-	6.581	-	-	-	-	-	-	-											
96						6	$C^{\Sigma}_{i=6,j}$	CU	-	-	-	-	-	-	6.806	-	-	-	-	-	-	-											
97	The indicated value of the total costs with taking into account of acceptable solutions area for the sliding formwork's panel height alternative value (*i*)					7	$C^{\Sigma}_{i=7,j}$	CU	-	-	-	-	-	-	7.031	-	-	-	-	-	-	-											
98						8	$C^{\Sigma}_{i=8,j}$	CU	-	-	-	-	-	-	7.256	-	-	-	-	-	-	-											
99						9	$C^{\Sigma}_{i=9,j}$	CU	-	-	-	-	-	-	7.481	-	-	-	-	-	-	-											
100						10	$C^{\Sigma}_{i=10,j}$	CU	-	-	-	-	-	-	7.706	-	-	-	-	-	-	-											
101						11	$C^{\Sigma}_{i=11,j}$	CU	-	-	-	-	-	-	7.931	-	-	-	-	-	-	-											
102						12	$C^{\Sigma}_{i=12,j}$	CU	-	-	-	-	-	-	8.156	-	-	-	-	-	-	-											
103						13	$C^{\Sigma}_{i=13,j}$	CU	-	-	-	-	-	-	8.381	-	-	-	-	-	-	-											
104						14	$C^{\Sigma}_{i=14,j}$	CU	-	-	-	-	-	-	8.606	-	-	-	-	-	-	-											

Figure 4. General view of the Microsoft Excel worksheet created during the implementation of elaborated model on a practical example (ending).

Table 4. The contents of the cells within Microsoft Excel worksheet prepared during the implementation of the developed procedure on a practical example.

Worksheet cell addresses*	Content / formula	Structural element of mathematical model
	Table 1	
K5:K9	initial data elements	Table 1, lines 1.2.1–1.2.5
K11:K14	initial data elements	Table 1, lines 1.3.1–1.3.4
K16; K19; K22; K25	initial data elements	Table 1, lines 1.4.1–1.4.4
K29; K31	initial data elements	Table 1, lines 1.5.1, 1.5.2
	Table 2	
N10:N23	initial data elements	Table 1, line 3.1
O10(:O23)	=(N10-$K$12)/$K$13	Table 2, line 1.1
P10(:P23)	=$K$11/(O10*$K$13)	Table 2, line 1.2
U5:AH5	initial data elements	Table 1, line 4.1
U6(:AH6)	=U5/24	-
U10(:AH23)	=IF(AND(NOT(ISERROR(MATCH(MIN($U$91:$AH$104),U$91:U$104,0))),NOT(ISERROR(MATCH(MIN($U$91:$AH$104), $U91:$AH91,0)))),1,0)	Table 2, line 3.6
AI10(:AI23)	=SUM(U10:AH10)	-
AK10(:AK23)	=O10*$K$6	Table 2, line 1.3
AM10(:AM23)	=$K$7*SQRT(O10)	Table 2, line 1.4
AP10(:AP23)	=NORM.S.DIST((AK10-$K$8)/ SQRT($K$9^2+AM10^2),1)	Table 2, line 1.5
AS10(:AS23)	=$K$29*N10	Table 2, line 1.6
U24(:AI24)	=SUM(U10:U23)	-
U25(:AH25)	=$K$13/(U$6*(1-$K$14))	Table 2, line 2.1
U26(:AH26)	=$K$13/U6	Table 2, line 2.2
U27(:AH27)	=$K$13/(U$6*(1+$K$14))	Table 2, line 2.3
U28(:AH41)	=($N10-$K$12)/(U$6*(1-$K$14))	Table 2, line 3.1
U42(:AH55)	=NORM.S.DIST((U28-$K$8)/$K$9,1)	Table 2, line 3.2
U56(:AH56)	=1-NORM.S.DIST((U25-$K$6)/$K$7,1)	Table 2, line 2.4
U59(:AH59)	=NORM.S.DIST((U27-$K$6)/$K$7,1)	Table 2, line 2.5
U62(:AH75)	=($AP10*U42*(U$56*U$59*$O10*U$26+ (1-U$56)* U$59*$O10*U$25)+$AP10*(U42* (1-U$59)+(1-U42))* $O10*$K$6+(1-$AP10)* $K$8)*$P10	Table 2, line 3.3
U76(:AH76)	=U$5*$K$31	Table 2, line 2.6
U77(:AH90)	=$AS10+U$76	Table 2, line 3.4
U91(:AH104)	=IF(AND(U62<=$K$5,$AP10>=$K$16,U42>= $K$19, U$56>=$K$22,U$59>=$K$25),U77,"-")	Table 2, line 3.5
	Table 3	
K39	=SUMPRODUCT(N10:N23,AI10:AI23)	Table 2, line 4.1.1
K40	=SUMPRODUCT(U6:AH6,U24:AH24)	Table 2, line 4.1.2
K42	=SUMPRODUCT(AP10:AP23,AI10:AI23)	Table 2, line 4.2.1
K45	=SUMPRODUCT(U10:AH23,U42:AH55)	Table 2, line 4.2.2
K48	=SUMPRODUCT(U24:AH24,U56:AH56)	Table 2, line 4.2.3
K51	=SUMPRODUCT(U24:AH24,U59:AH59)	Table 2, line 4.2.4
K55	=SUMPRODUCT(U62:AH75,U10:AH23)	Table 2, line 4.3.1
K57	=K29*SUMPRODUCT(N10:N23,AI10:AI23)	Table 2, line 4.4.1
K58	=K31*SUMPRODUCT(U24:AH24,U5:AH5)	Table 2, line 4.4.2
K59	=K57+K58	Table 2, line 4.4.3

Note:

* the abstract designation A1(:B10) means that in the cell A1 you need to enter the formula indicated in the corresponding column of the table, after which "stretch" (copy) the result to cell B10.

For the objective estimation of the practical significance of the created tool the analysis of dependences of different indicators connected to the technological process under consideration on mentioned above parameters has been carried out. The corresponding results are presented in Fig. 5 and 6. On the basis of mentioned results, the following particular conclusions have been made:

– the duration of the movement of the formwork is directly proportional to the height of the formwork and decreases hyperbolically with formwork's movement base speed increase (Fig. 5,*a*), while the range of the duration of the movement of the formwork depending on the formwork's movement base speed rises as the formwork's panel height increases;

– for large values of the height of the shield, the nominal speed of movement practically does not affect the duration of the erection of the wall structure (Fig. 5,*b*). The main reason is that with an increase in the preferred speed of formwork movement, the probability that the maturing time of the layer does not exceed the preferred speed of movement of the formwork asymptotically approaches zero, thereby determining the maturing speed of the concrete layer as a key parameter that affects the duration of the erection of the wall structure;

– the graph shows that the total costs increase monotonously and in direct proportion to the determined parameters – the formwork's panel height and movement base speed – in accordance with the originally specified relationships (Fig. 5,*c*); it is also important to note that in general case an arbitrary dependence can be specified, including a nonlinear one;

– the actual value of probability that the layer maturing duration will not exceed the total layers pouring increases nonlinearly and monotonically with increasing formwork height and has an inflection point corresponding to the probability value $P_{\mathrm{cm}\,i} = 0.5$ and a speed value of approximately $H_i \approx 1.45$ m (Fig. 6,a);

– the actual value of probability that the layer pouring duration will exceed the duration of the minimum speed formwork movement to the one-layer height increases nonlinearly and monotonically with an increase of the formwork's movement base speed and has an inflection point corresponding to the probability value $P_{\mathrm{t}-j} = 0.5$ and the velocity value of approximately $\upsilon_j \approx 1.33$ m/day (Fig. 6,b);

– the actual value of probability that the layer pouring duration will not exceed the duration of the maximum speed formwork movement to the one-layer height decreases non-linearly and monotonically with increasing of the formwork's movement base speed and has an inflection point corresponding to the value of probability $P_{\mathrm{t}+j} = 0.5$ and the value of speed of approximately $\upsilon_j \approx 1.08$ m /day (Fig. 6,*c*);

– the influence (determined by the difference in duration values for the current *j* and previous *j* – 1 alternative values of the duration) of the deviation from the base (average) value of the formwork's movement speed is significant only at relatively low base value of the speed ($\upsilon_j \leq 1.3$ m/day) and ranges from 3.7% to 18.75% of the largest duration value; in case of relatively large base value of the formwork's movement speed ($\upsilon_j > 1.3$ m/day), the mentioned above effect can be considered insignificant.

4. Conclusions

On the basis of conducted research described above the following results have been received:

1. Review of the literature sources connected to the modeling of construction processes. On the basis of the results for corresponding procedure it has been concluded that existing scientific developments don't take into account the factors of stochastic nature and therefore can not ensure the high adequacy of the calculated results.

2. Stochastic model of the construction process implemented with application of sliding formwork has been created. The model ensures determination of the most preferred values for technological parameters describing sliding formwork's panel height and base (average) movement speed on the basis of wall height, baseline duration of the wall construction process and characteristics of the stochastic values of concrete layer's pouring and maturing duration.

3. Created stochastic model has been implemented on a practical example for the wall construction process assumed by the construction project "Arctic LNG 2". Results of the calculation satisfied the conditions of construction processes' implementation and became the basis for the conclusion about high practical significance of the developed tool.

It is necessary to note that due to the absence of the scientific developments connected directly the application of stochastic modeling tools to the construction process implemented with using of sliding formwork it is impossible to compare received results of the research with the data obtained by other researchers. Therefore the practical significance of the developed model described in the work has been estimated on the basis of the degree of correspondence of calculation results to the real conditions for implementation of the construction process under consideration.

It is also should be emphasized that the created model can be used not only for the wall construction with application of sliding formwork, but for any technological process connected to the erection of buildings and structures (including installation of ceiling and wall structures, separation partitions, etc.) in the area of civil, industrial and road construction that has following features:

- unknown parameters are independent from each other (the number of the parameters can be not only two, but three and more) and have influence on economic indicator (for example, operational costs) to be minimized or maximized;

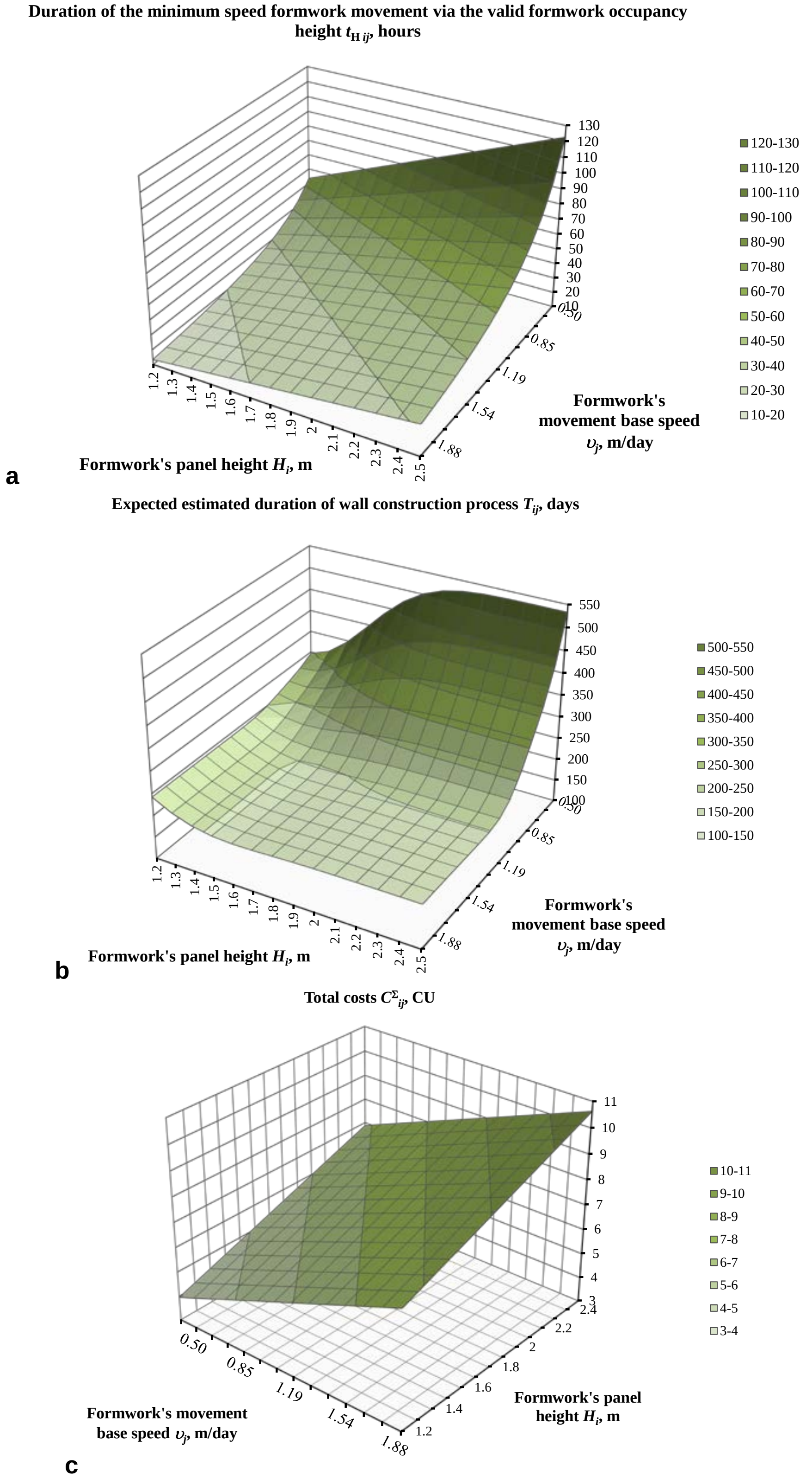

Figure 5. Dependences of different indicators connected to the technological process under consideration on technological parameters (beginning).

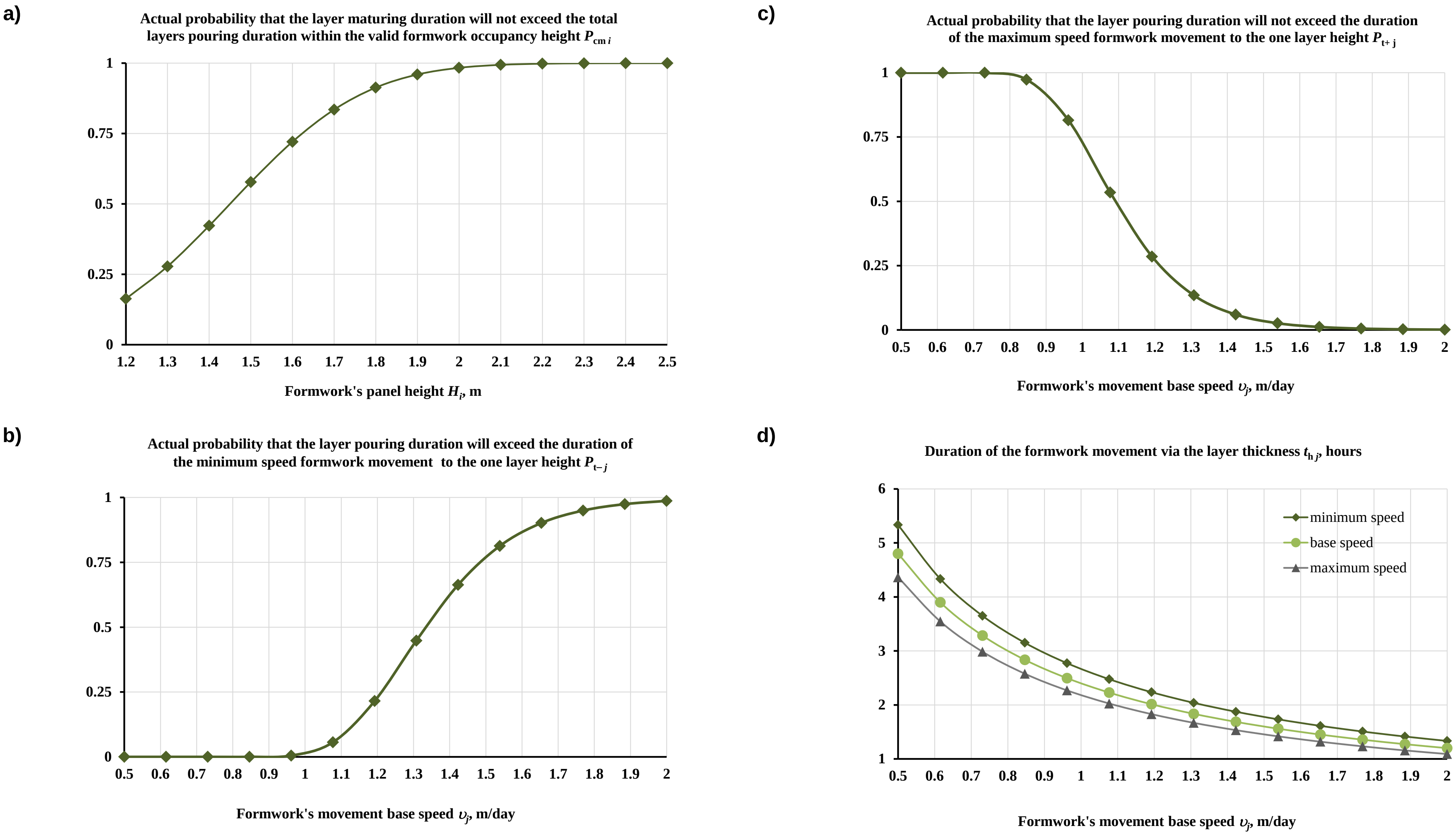

Figure 6. Dependences of different indicators connected to the technological process under consideration on technological parameters (ending).

– structure of technological process can be described as the sequence of elemental processes (implemented one after another) each of which is described by a stochastic time parameter corresponding to normal distribution.

– baseline duration of the whole technological process is known.

The analysis of possibilities for application of the created model for the different categories of technological processes in the area of construction will be carried out at the further stages of the research activity.

References

1. Daukšys, M. Productivity analysis of concrete slab construction by using different types of formwork. Journal of Sustainable Architecture and Civil Engineering. 2016. 2. Pp. 38–46. DOI: 10.5755/j01.sace.15.2.15789.
2. Golafshani, E. M., Talatahari, S. Predicting the climbing rate of slip formwork systems using linear biogeography-based programming. Applied Soft Computing Journal. 2018. 70. Pp. 263–278. DOI: 10.1016/j.asoc.2018.05.036.
3. Bulgakov A., Kruglova T., Sayfeddine D. Simulation Mathematical Model of Mechatronic Sliding Formwork for Monolithic Tower with Variable Cross Section. Advanced Construction and Building Technology for Society. 2016. Pp. 8-14.
4. Heiza, K., Abo El enen, N., Mahdi, I. Value methodology of vertical slip form construction system in high rise buildings. The International Conference on Civil and Architecture Engineering. 2016. Pp. 19–21. DOI: 10.21608/iccae.2016.43437.
5. Zayed, T., Sharifi, M.R., Baciu, S., Amer, M. Slip-form application to concrete structures. Journal of Construction Engineering and Management, 2008. 134(3). Pp. 134–142. DOI: 10.1061/(ASCE)0733-9364(2008)134:3(157).
6. Tregger, N., Voigt, T., Shah, S.P. Improving the slipform process via material manipulation. Advances in Construction Materials, 2007. Pp. 539–546. DOI: 10.1007/978-3-540-72448-3_55.
7. Reichverger, Z., Jaegermann, C. Optimal regime in slip form concreting. Matériaux et Constructions. 1980. 13. Pp. 109–113. DOI: 10.1007/BF02473807.
8. Choktaweekarn, P., Tangtermsirikul, S. Effect of aggregate type, casting, thickness and curing condition on restrained strain of mass concrete. Songklanakarin Journal of Science and Technology. 2010. 32(4). Pp. 391–402.
9. Gamayunova, O., Spitsov, D. Technical features of the construction of highrise buildings E3S Web of Conferences. 2020. 164. 08008.
10. Mansuri, D., Chakraborty, D., Elzarka, H., Deshpande, A., Gronseth, T. Building Information Modeling enabled Cascading Formwork Management Tool. Automation in Construction. 2017. 83. Pp. 259–272. DOI: 10.1016/j.autcon.2017.08.016.
11. Lee, J., Park, Y. J., Choi, C. H., Han, C. H. BIM-assisted labor productivity measurement method for structural formwork. Automation in Construction. 2017. 84. Pp. 121–132. DOI: 10.1016/j.autcon.2017.08.009
12. Lu, N., Korman, T. Implementation of Building Information Modeling (BIM) in Modular Construction: Benefits and challenges. Construction Research Congress 2010: Innovation for Reshaping Construction Practice – Proceedings of the 2010 Construction Research Congress. 2010. Pp. 1136–1145. DOI: 10.1061/41109(373)114.
13. Meadati, P., Irizarry, J., Aknoukh, A. BIM and Concrete Formwork Repository. 47th ASC Annual International Conference Proceedings. 2011.
14. Romanovskyi, R., Sanabria Mejia, L., Rezazadeh Azar, E. BIM-based decision support system for concrete formwork design. Proceedings of the 36th International Symposium on Automation and Robotics in Construction, ISARC. 2019. Pp. 1129–1135. DOI: 10.22260/isarc2019/0150.
15. Shin, Y., Kim, T., Cho, H., Kang, K.I. A formwork method selection model based on boosted decision trees in tall building construction. Automation in Construction. 2012. 23. Pp. 47–54. DOI: 10.1016/j.autcon.2011.12.007.
16. Kamarthi, S.V., Sanvido, V.E., & Kumara, S.R.T. Neuroform—neural network system for vertical formwork selection. Journal of Computing in Civil Engineering. 1992. 6(2). Pp. 178–199. DOI: 10.1061/(ASCE)0887-3801(1992)6:2(178).
17. Roe, B. P., Yang, H. J., Zhu, J., Liu, Y., Stancu, I., McGregor, G. Boosted decision trees as an alternative to artificial neural networks for particle identification. Nuclear Instruments and Methods in Physics Research, Section A: Accelerators, Spectrometers, Detectors and Associated Equipment. 2005. 543. Pp. 577–584. DOI: 10.1016/j.nima.2004.12.018.
18. Elbeltagi, E., Hosny, O.A., Elhakeem, A., Abd-Elrazek, M.E., Abdullah, A. Selection of slab formwork system using fuzzy logic. Construction Management and Economics. 2011. 29(7). Pp. 659–670. DOI: 10.1080/01446193.2011.590144.
19. Struková, Z., Kozlovská, M., Kováčová, B. Determination of optimal supporting system of deep foundation pit based on multi-criteria decision analysis. 12th International Multidisciplinary Scientific GeoConference and EXPO – Modern Management of Mine Producing, Geology and Environmental Protection, SGEM. 2012. 2. Pp. 47–54.
20. Baskova, R., Krajnak, M. An analytical approach to optimization of the costs for construction formwork. International Multidisciplinary Scientific GeoConference Surveying Geology and Mining Ecology Management, SGEM. 2013. 2. Pp. 35–40. DOI: 10.5593/SGEM2013/BE5.V2/S21.005.
21. Bolotin, S., Dadar, A., Ptuhina, I. Construction work tasks duration: Pessimistic scenarios based on PERT method. Advanced Materials Research. 2014. 945–949. Pp. 3026–3031. DOI: 10.4028/www.scientific.net/AMR.945-949.3026.
22. Mishakova, A., Vakhrushkina, A., Murgul, V., Sazonova, T. Project Control Based on a Mutual Application of Pert and Earned Value Management Methods. Procedia Engineering. 2016. 165. Pp. 1812–1817. DOI: 10.1016/j.proeng.2016.11.927.
23. Gurmu, A.T., Ongkowijoyo, C.S. Stochastic-Based Model for Setting Formwork-Productivity Baseline. Journal of Construction Engineering and Management. 2020. 146(9). 04020099.
24. Lim, H., Kim, T., Cho, H., Kang, K.I. Simulation-based planning model for table formwork operation in tall building construction. Journal of Asian Architecture and Building Engineering. 2017. 16(1). Pp. 115–122. DOI: 10.3130/jaabe.16.115.
25. Tichko, S., Van De Maele, J., Vanmassenhove, N., De Schutter, G., Vierendeels, J., Verhoeven, R., Troch, P. Numerical simulation of formwork pressure while pumping self-compacting concrete bottom-up. Engineering Structures. 2014. 70. Pp. 218–333. DOI: 10.1016/j.engstruct.2014.04.008.
26. Le, H.D., De Schutter, G., Kadri, E.H., Aggoun, S., Vierendeels, J., Troch, P. Velocity profile of self compacting concrete and traditional concrete flowing in a half open pipe. Concrete Repair, Rehabilitation and Retrofitting III – Proceedings of the 3rd International Conference on Concrete Repair, Rehabilitation and Retrofitting (ICCRRR). 2012. P. 1382–7.
27. Puente, I., Santilli, A., Lopez, A. Lateral pressure over formwork on large dimension concrete blocks. Engineering Structures. 2010. 32(1). Pp. 195–206. DOI: 10.1016/j.engstruct.2009.09.006.

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