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Research paper

Scheduling with the Probabilistic Coupling Method III (PTCM III) – minimising the duration of a project

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Abstract: The time required for construction processes is closely related to the complexity of the project and its specific nature (variable impact factors). A new scheduling method with a probabilistic approach has been developed – Probabilistic Time Couplings Method III (PTCM III). PTCM III is based on the assumptions of Time Couplings Method III (TCM III), which has been improved by using the predictive Multivariate Method of Statistical Models (MMSM) and construction process standard deviations. PTCM III enables the time-cost optimisation of a construction project while taking into account the risks and uncertainties of construction processes. The priority of the method is to minimise the execution time of the project, with the possibility of downtime of work sectors or workers. The paper presents presents the formulas and calculation methodology, based on algorithmisation. In order to best present the capabilities and effects of PTCM III, a case study was carried out in the paper, in which the results of the calculations were compared with other variants of time coupling methods in probabilistic terms. The result of the PTCM III calculations is a range of the duration of a construction project together with the probability of its realisation. The most pessimistic completion time was calculated to be 412.7 working days, the most optimistic was calculated to be 388.7 working days and the 50% completion probability was determined to be 400.7 working days. This allows for more flexible construction scheduling and the adoption of lead times based on the contractor's capabilities and the decision-maker's assessment.

Keywords: duration forecasting, planning, Probabilistic Time Coupling Method III (PTCM III), scheduling, variable construction conditions

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1. Introduction

Nowadays, the effective management of the investment process is a key element of any construction project. This is mainly due to the pressure of the investor contract. The speed of execution often determines the profitability of an investment, which means that the planning of the investment process has to be particularly thorough. As a result, contractors are taking more and more risks in an attempt to optimise the work schedule. However, even the most precise plans cannot take into account all potential complications that may arise during the project [1]. Uncertainty about the exact course of the investment process therefore remains inevitable [2–4].

Scheduling methods are divided by the type of project [5] into: unique projects (complex operations type) and repeatable projects. The first group includes projects of a unique nature, known as complex operations ventures, which are characterised by unique operations. The second group includes projects of a repetitive nature, which are implemented according to the principle of uniform or flow-shop work. A flow-shop work system [5] is characterised by structural clarity and the assignment of work teams to carry out individual processes. This makes it possible to make optimum use of the planned work capacity by: maintaining a constant quality of the work performed (repetition of the same work on individual sectors – experience of the workers).

One method of flow-shop work is the Time Coupling Method (TCM). The time coupling method is based on deterministic lead times of construction processes [6–8]. Scheduling construction projects with the Time Couplings Method (TCM) allows construction project scheduling to be carried out taking into account technological and organisational constraints. Due to the algorithmic nature of the calculations, the TCM method is used in modern scientific solutions. The Time Coupling Method was developed by Professor V. Afanasyev [9, 10]. The continuators of Professor Afanasyev's concept included: J. Mrozowicz [6, 11], Z. Hejducki [7, 12], M. Podolski [8].

Time couplings used in TCMs are the internal temporal links between construction processes and work plots (sectors) [6, 7, 9, 10]. Time couplings are defined between the earliest and latest start and end dates of individual construction processes or work tasks [13]. These couplings can be obligatory (the time between activities is then defined) or conditional (when a minimum time gap is defined between activities).

According to data presented in the literature [14], only 2.5% of construction companies completed 100% of projects in the planned time. Due to the variable nature of construction processes (impact factors: technological, organisational, risk), estimating their duration poses difficulties [1, 15, 16]. Risk analysis is an indispensable part of scheduling [17]. Consequently, the risks and uncertainties associated with a project need to be assessed in order to increase its success (while ensuring that the work is carried out according to the developed schedule). Many techniques, models and programmes have been developed to assist in risk analysis. The most common are the Critical Path Method (CPM) [18], Programme Evaluation and Review Technique (PERT) [19], Critical Chain Method [20], among others. Most of the methods for creating network models and schedules use deterministic estimation. Hulett argues that this is the wrong approach [21]. The design assumptions that are made during deterministic scheduling are estimates that often over-optimise the lead time. A solution to this problem may be the use of probabilistic data, based on forecasts of the lead times of individual construction processes, taking into account their standard deviations.

The paper demonstrates that it is possible to schedule construction processes using time coupling methods (TCM) in a probabilistic approach, which takes into account technical, technological and organisational factors under specific realisation conditions as well as uncertainty and risk. By combining the time coupling method (TCM) and Multivariate Method of Statistical Models (MMSM), it is possible to determine the minimum, most probable and maximum execution time of a project.

2. Methodology

An upgrade of the Time Couplings Method III (TCM III) is the Probabilistic Time Couplings Method III (PTCM III). In the PTCM III method, computational algorithms were developed by using standard deviations and probabilistic input data. A computational application has been developed for the PTCM III method, which is a continuation of the work carried out in [15, 16] and enables the automation of calculations.

2.1. Time Couplings Method III – TCM III

The TCM III method aims to minimise the execution time of the entire project, which is a key organisational feature in most cases. This method is often used because of its ability to effectively manage available resources and contribute to the economics of projects. The achievement of the assumed optimisation criterion (minimum time), comes at the expense of downtime for the working brigades on the different fronts [22]. This is due to the assumption of the possibility of downtime in the working groups and waiting on the fronts. This condition makes it possible to eliminate the influence of the continuity of works on the extension of the execution time of the work complex.

The elementary calculation segment of the TCM III method designated for the P_j process and the S_i sector is detailed in Figure 1.

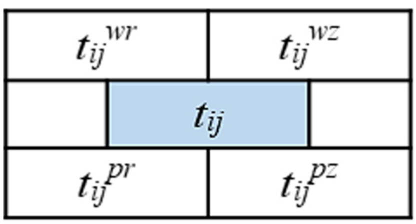

Fig. 1. A single calculation segment of the TCM III method on the basis of the work [6, 7, 15, 16]

Where:
t_{ij} – calculated duration of the construction process j on the sector i,
t_{ij}^{wr} – calculated time of early commencement of the construction process j on the sector i,

t_{ij}^{wz} – calculated time of early completion of the construction process j on the sector i,
t_{ij}^{pr} – calculated time of the late start of the construction process j on the sector i,
t_{ij}^{pz} – calculated time of late completion of the construction process j on the sector i.

2.2. Input data – Multivariate Method of Statistical Models (MMSM)

When creating construction schedules, input data is a very important factor. Traditionally, schedules are created based on deterministic data. When planning investment projects with a high degree of uncertainty, it seems more correct to use probabilistic data. The Multivariate Method of Statistical Models (MMSM) developed by Rogalska [23] is renowned for its precise mapping of investment implementation time. This method employs multi-factor modelling based on real data and influencing variables, making it suitable for a wide range of construction processes.

Collecting and analysing the data collected is a very time-consuming stage of forecasting work. The data collected must have a measurable value. Numerical and linguistic data can be used in the calculations. Linguistic data are given numerical values in the form of codes.

Once the problem has been defined and the dependent variable and independent variables have been determined, the collection of data for the calculation is undertaken. The computational data are obtained:

– via the experimental method, by means of field work and measurements carried out under real conditions,
– from construction company databases,
– from the databases of the Central Statistical Office,
– from publicly available information on the timing and conditions of construction processes.

Data is collected in the form of spreadsheets, e.g. from the STATISTICA programme. Spreadsheets in STATISTICA can contain millions of data. The individual columns of the spreadsheet correspond to dependent and independent variables, while the rows correspond to successive cases, e.g. measured values.

Labour productivity and construction process times, respectively, were determined using the parametric-regression method – MMSM – by modelling them multifactorially from real data. The dependent variable (e.g. employee productivity or construction time) and the independent variables – factors that influence the dependent variable – are defined. The larger the base of measurements to be used for analysis, the more accurately the model will be able to predict the value of the dependent variable. The MMSM uses predictive methods, including [23]: multivariate regression, multivariate adaptive regression with glued functions, generalised additive models, simulated neural networks, support vectors and integrated autoregression. After modelling the dependent variable, the results are subjected to a comparative assessment of the forecast error based on mean absolute percentage error as well as the autocorrelation of series residuals and the autocorrelation of partial series residuals. It is possible to obtain several correctly forecasting models, in which case the one with the smallest MAPE error is selected for further calculations.

2.3. Standard deviations

Standard deviation is an important tool in data analysis and forecasting. The standard deviation is a measure of the dispersion of the data around the mean, which tells you how much the data differs from its mean value. Standard deviation values are always positive, and the higher the deviation, the greater the dispersion of the data.

To calculate the standard deviation, the arithmetic mean of all values is calculated. Then, for each value, the difference between that value and the mean is calculated, after which the difference in values is squared. The arithmetic mean of the squares of the differences and the square root of the result are then calculated.

To adequately factor in standard deviations in the calculation sheet, it is imperative to utilize the formula for summing the standard deviations of two independent random variables [15, 16].

2.4. Probabilistic Time Couplings Method III (PTCM III)

The PTCM III method is a modern approach to the subject of scheduling. PTCM III is based on the calculation algorithms of TCM III [6, 7, 9, 10, 24], which have been suitably modified to take into account the possibility of using additional data, such as standard deviations and data derived from MMSM. Like PTCM I and PTCM II, the PTCM III method allows construction scheduling under different organisational assumptions and using probabilistic data.

The elementary calculation segment of the PTCM III method designated for the P_j process and the S_i sector is detailed in Figure 2.

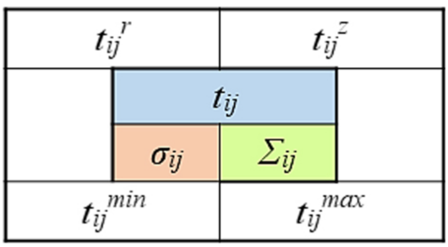

Fig. 2. Single PTCM III calculation segment developed on the basis of the work [6, 7, 15, 16]

Where:

t_{ij} – calculated duration of the construction process j on the sector i,

σ_{ij} – standard deviation of the duration of the construction process j on the sector i,

$\sum_{ij}$ – sum of standard deviations of independent random variables of works preceding the construction process j on the sector i, also taking into account $\sigma(t_{ij})$ of the current work,

t_{ij}^r – prognostic start time of the construction process j on the sector i,

t_{ij}^z – prognostic time of early completion of the construction process j on the sector i (most likely),

$t_{ij}^{\min}$ – minimum prognostic time for completion of the construction process j on the sector i (the most optimistic),

$t_{ij}^{\max}$ – prognostic time of the maximum completion of the construction process j on the sector i (most pessimistic).

The number of calculation segments in the PTCM III sheet is contingent upon the designated number of sectors and processes at the construction site and can vary [24]. Each segment corresponds to the work of a single working brigade (P_j) on a specific working plot (S_i).

The calculation formulas of the PTCM III method are outlined below (Eq. (2.1) – Eq. (2.15)):

– Sector S_1 and process P_1:

$$t^r_{1,1} = \begin{cases} 0 \\ \text{or given initial value} \end{cases} \tag{2.1}$$

$$t^z_{1,1} = t^r_{1,1} + t_{1,1} \tag{2.2}$$

$$\sum_{1,1} = \sigma_{1,1} \tag{2.3}$$

$$t^{\min}_{1,1} = t^z_{1,1} - \sum_{1,1} \tag{2.4}$$

$$t^{\max}_{1,1} = t^z_{1,1} + \sum_{1,1} \tag{2.5}$$

– Sector S_i and process P_1:

$$t^r_{i,1} = t^z_{(i-1),1} \tag{2.6}$$

$$t^z_{i,1} = t^r_{i,1} + t_{i,1} \tag{2.7}$$

$$\sum_{i,1} = \sqrt{\sum_{(i-1),j}^{2} + \sigma^2_{i,1}} \tag{2.8}$$

$$t^{\min}_{i,1} = t^z_{i,1} - \sum_{i,1} \tag{2.9}$$

$$t^{\max}_{i,1} = t^z_{i,1} + \sum_{i,1} \tag{2.10}$$

– Sector S_i and process P_j:

$$t^r_{i,j} = \max \begin{cases} t^z_{i,(j-1)} \\ t^z_{(i-1),j} \end{cases} \tag{2.11}$$

$$t^z_{i,j} = t^r_{i,j} + t_{i,j} \tag{2.12}$$

$$\sum_{i,j} = \sqrt{\sigma^2_{i,j} + \max \begin{cases} t^z_{i,(j-1)} \Rightarrow \sum_{i,(j-1)}^{2} \\ t^z_{(i-1),j} \Rightarrow \sum_{(i-1),j}^{2} \end{cases}} \tag{2.13}$$

$$t_{i,j}^{\min} = t_{i,j}^{z} - \sum_{i,j} \tag{2.14}$$

$$t_{i,j}^{\max} = t_{i,j}^{z} + \sum_{i,j} \tag{2.15}$$

where: $t_{1,1}$; $t_{i,1}$; $t_{i,j}$; $\sigma_{1,1}$; $\sigma_{i,1}$; $\sigma_{i,j}$ – mathematically calculated data.

In order to popularise PTCM, a calculation application based on the Microsoft Excel environment was developed. With its user-friendly interface and algorithmic calculations, the application can be used in practice, even by low-skilled construction workers. The PTCM application simplifies and significantly speeds up calculations based on different variants of the PTCM method.

2.5. Graphical representation of schedules – cyclographs

The analytical part of the schedules is not readable and transparent, so it is accepted practice to represent them graphically. Graphical representation is usually done using dependency networks, graphs, line graphs, diagrams and cyclic lines. In this article, cyclograms are used to reflect the basic parameters of the works resulting from the calculations. A cyclogram is a model of the production process flow that shows the cycle of production of a specific product in calendar terms.

3. Case study

This article considers the case in which a construction project is divided into 5 processes and 10 work plots. Analogous construction processes are carried out on each annual plot: earthworks (P1), masonry works and ceilings (P2), roof truss and roof covering (P3), construction of a closed shell and insulation (P4) and finishing works (P5). The case study was extensively described for PTCM I [15] and PTCM II [16]. This project represents a further development of the PTCM methodologies, utilizing the same computational case for comparative analysis.

Due to the computational extensiveness of the MMSM, this article presents one selected construction process – the roof truss and roof covering (P3). The remaining processes (P1, P2, P4, P5) were computed similarly, and their final results are documented in the paper (Table 3). For process P3, the "roof truss and roof covering" in m^2/h was considered the dependent variable (v1), influenced by a range of independent variables, like (Table 1): average employee experience (v3), roof shape (v4), roof truss type (v5), roofing material (v6), roof dimensions (v7, v8) and weather conditions (v9, v10).

The calculations and analyses were based on historical data from similar construction processes (obtained from publicly available data, published e.g. on the websites of city or municipal authorities, as well as in cooperation with construction companies) and empirical surveys carried out on construction sites between 2017 and 2022. The data obtained served as input data for the calculation of construction process times using the MMSM method and then the PTCM III.

Table 1. Dependent and independent variables used in the MMSM method

No.	Variable	Variable description	Units
1	v1	Roof works	[m^2/h]
2	v2	Duration of works	[h]
3	v3	Average employee experience	[years]
4	v4	Roof shape	-
5	v5	Roof truss type	-
6	v6	Roofing material	-
7	v7	Roof length	[m]
8	v8	Roof width	[m]
9	v9	Temperature	[°C]
10	v10	Rainfall/humidity	[%]
11	v11	Employee absenteeism	[%]

Thirty-two instances of baseline data were collected, obtained through experimental work on site. Using the baseline input data, calculations were carried out using the MMSM method. The subsequent calculation steps of the MMSM are [23]:

– Checking the normality of the distributions of the individual variables (the distribution of the variables was tested using the Shapiro-Wilk test. Not all independent variables showed a normal distribution);
– Checking for correlations between variables (it was determined that in most cases there are moderate or weak correlations. The presence of strong correlations will be a basis for rejecting one of the highly correlated variables from the forecasting calculations of some methods);
– Carry out forecasting calculations using: Multiple Regression (MR), Generalized Additive Methods (GAM), Multivariate Adaptive Regression Splines (MARSplines), Support Vector Machine (SVM), Simulated Neural Networks (SNN);
– Comparison of the values obtained in the projections with the baseline values obtained experimentally and calculation of the MAPE error;
– Check for significant autocorrelation of residuals and significant partial autocorrelation of residuals;
– Selection of the model with the smallest error of prediction.

2 of the 5 modelling exercises carried out are correct and can be used in the data forecasting. As a lower MAPE error was achieved by the model obtained using Simulated Neural Networks (SNN), it was used in further calculations.

The results of the forecasting models are summarized in Table 2.

Table 2. Summary of prognostic models for the variable v1

The prognostic method	Whether significant residual autocorrelations exist	Whether significant partial autocorrelations of residuals exist	MAPE error value [%]	The model is correct
MR	Yes – 2 pos.	Yes – 2 pos.	6,34	Not correct
GAM	No	No	2,65	Correct
MARS	Yes – 4 pos.	Yes – 4 pos.	7.51	Not correct
SVM	Yes – 3 pos.	Yes – 3 pos.	9.72	Not correct
SNN	No	No	1.80	Correct

Using a Simulated Neural Networks (SNN) dependency network, after the introduction of new independent variables related to the new construction, which is a case study, the execution time of the P3 process on each sector was obtained. The summary of the calculation results is presented in Table 3. The data presented in Table 3 were already used during the calculations with PTCM I [15] and PTCM II [16]. However, it is necessary to use these data for PTCM III calculations in order to obtain a proper comparison of the resulting times.

Table 3. Summary of the forecast duration of P1-P5 processes in S1-S10 sectors for a new investment – PTCM III [15, 16]

Time t_{ij} [days]		**Processes**				
		P1	**P2**	**P3**	**P4**	**P5**
Sectors	S1	10.0	22.4	20.2	18.6	33.0
	S2	8.1	25.6	22.0	20.5	30.8
	S3	8.1	20.2	20.1	24.2	35.4
	S4	9.2	23.0	21.5	21.5	31.0
	S5	9.4	22.1	23.0	19.3	35.1
	S6	10.5	22.4	20.9	18.6	33.9
	S7	8.9	25.0	22.0	20.9	30.8
	S8	8.1	20.2	19.0	24.2	33.4
	S9	8.0	23.2	21.5	22.0	31.0
	S10	9.9	22.1	23.0	19.3	35.1

4. PTCM III – results and discussion

Figures 3 and 4 show the cyclogram for the case study stage. The execution times of the individual construction processes were determined using the MMSM method, and the standard deviations for these processes were based on calculations of analogous processes in the past.

The realisation times of the individual processes in the plots shown in Table 3, as well as their standard deviations, are the input data for the calculations carried out through PTCM III. The organisation of the construction processes in the PTCM III method focuses on minimising the duration of the project, and as the results show, these assumptions were achieved. PTCM II and PTCM III achieved almost identical results, which means that the work is divided up and arranged in such a way that there is hardly any downtime in the sectors.

PTCM III		Proceses									
		P1		P2		P3		P4		P5	
Sectors	S1	0.0	10.0	10.0	32.4	32.4	52.6	52.6	71.2	71.2	104.2
		10.0		22.4		20.2		18.6		33.0	
		1.1	1.1	2.5	2.7	2.2	3.5	2.0	4.1	3.6	5.4
		8.9	11.1	29.7	35.1	49.1	56.1	67.1	75.3	98.8	109.6
	S2	10.0	18.1	32.4	58.0	58.0	80.0	80.0	100.5	104.2	135.0
		8.1		25.6		22.0		20.5		30.8	
		0.9	1.4	2.8	3.9	2.4	4.6	2.3	5.1	3.4	6.1
		16.7	19.5	54.1	61.9	75.4	84.6	95.4	105.6	128.9	141.1
	S3	18.1	26.2	58.0	78.2	80.0	100.1	100.5	124.7	135.0	170.4
		8.1		20.2		20.1		24.2		35.4	
		0.9	1.7	2.2	4.5	2.2	5.1	2.7	5.8	3.9	7.3
		24.5	27.9	73.7	82.7	95.0	105.2	118.9	130.5	163.1	177.7
	S4	26.2	35.4	78.2	101.2	101.2	122.7	124.7	146.2	170.4	201.4
		9.2		23.0		21.5		21.5		31.0	
		1.0	2.0	2.5	5.2	2.4	5.6	2.4	6.1	3.4	8.0
		33.4	37.4	96.0	106.4	117.1	128.3	140.1	152.3	193.4	209.4
	S5	35.4	44.8	101.2	123.3	123.3	146.3	146.3	165.6	201.4	236.5
		9.4		22.1		23.0		19.3		35.1	
		1.0	2.2	2.4	5.7	2.5	6.2	2.1	6.5	3.9	8.9
		42.6	47.0	117.6	129.0	140.1	152.5	159.1	172.1	227.6	245.4
	S6	44.8	55.3	123.3	145.7	146.3	167.2	167.2	185.8	236.5	270.4
		10.5		22.4		20.9		18.6		33.9	
		1.2	2.5	2.5	6.2	2.3	6.6	2.0	6.8	3.7	9.7
		52.8	57.8	139.5	151.9	160.6	173.8	179.0	192.6	260.7	280.1
	S7	55.3	64.2	145.7	170.7	170.7	192.7	192.7	213.6	270.4	301.2
		8.9		25.0		22.0		20.9		30.8	
		1.0	2.7	2.8	6.8	2.4	7.0	2.3	7.4	3.4	10.2
		61.5	66.9	163.9	177.5	185.7	199.7	206.2	221.0	291.0	311.4
	S8	64.2	72.3	170.7	190.9	192.7	211.7	213.6	237.8	301.2	334.6
		8.1		20.2		19.0		24.2		33.4	
		0.9	2.8	2.2	7.1	2.1	7.3	2.7	7.8	3.7	10.9
		69.5	75.1	183.8	198.0	204.4	219.0	230.0	245.6	323.7	345.5
	S9	72.3	80.3	190.9	214.1	214.1	235.6	237.8	259.8	334.6	365.6
		8.0		23.2		21.5		22.0		31.0	
		0.9	3.0	2.6	7.6	2.4	7.7	2.4	8.1	3.4	11.4
		77.3	83.3	206.5	221.7	227.9	243.3	251.7	267.9	354.2	377.0
	S10	80.3	90.2	214.1	236.2	236.2	259.2	259.8	279.1	365.6	400.7
		9.9		22.1		23.0		19.3		35.1	
		1.1	3.2	2.4	8.0	2.5	8.1	2.1	8.3	3.9	12.0
		87.0	93.4	228.2	244.2	251.1	267.3	270.8	287.4	388.7	412.7

Fig. 3. PTCM III schedule

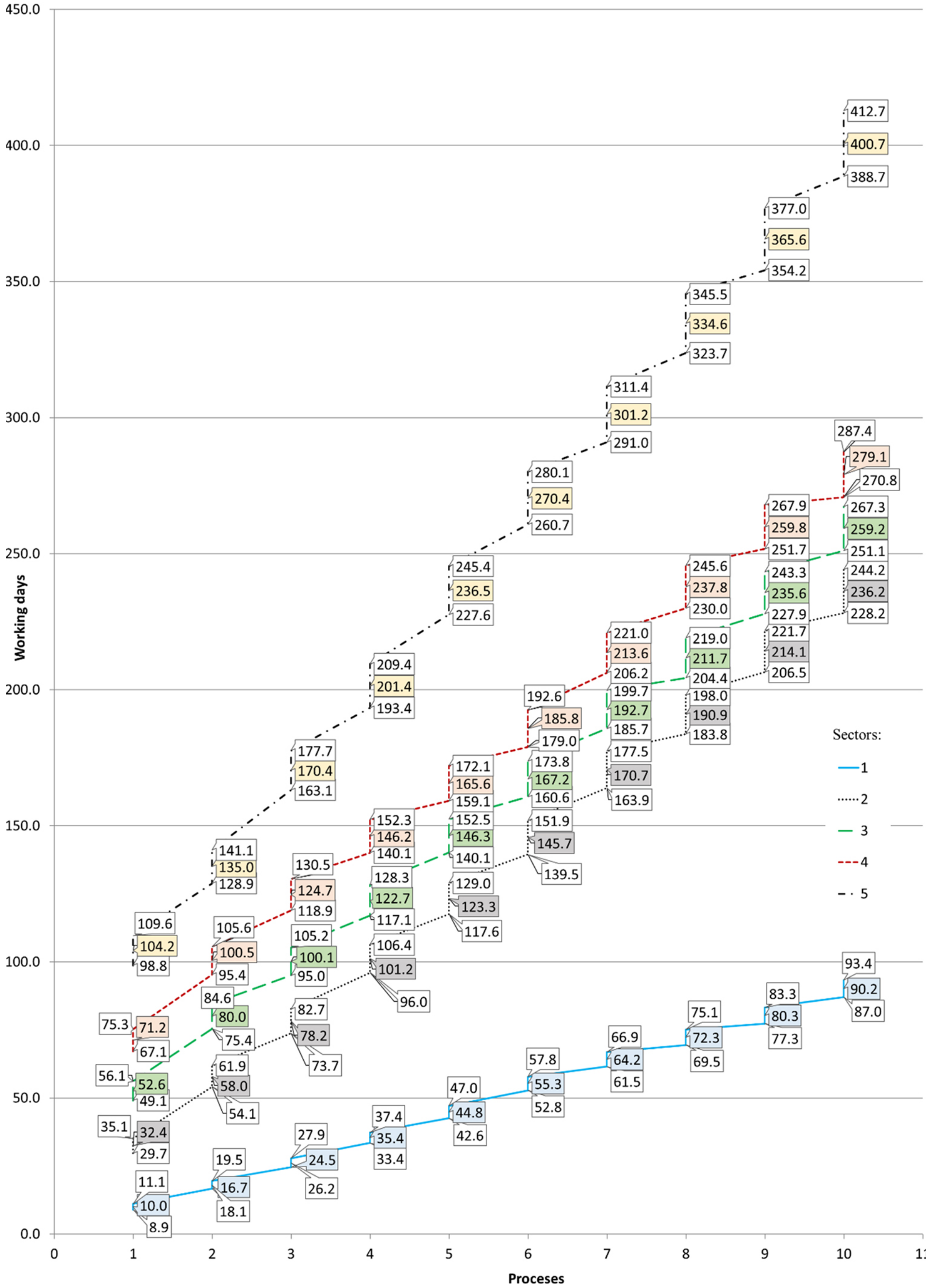

Fig. 4. The PTCM III cyclogram

Table 4 summarises and compares the results obtained with all three variants of the PTCM method.

Table 4. Summary of the forecast and a comparison with the results of PTCM I [15] and PTCM II [16]

The method of determining the schedule	**The total duration of the investment [working – days]**
PTCM III	Minimal: 388.7 Most likely: 400.7 Maximum: 412.7
PTCM II	Minimal: 388.6 Most likely: 400.7 Maximum: 412.8
PTCM I	Minimal: 409.6 Most likely: 421.1 Maximum: 432.6

Analyzing the results obtained in the PTCM III method (Table 4, Figures 3 and 4), the most pessimistic completion time for the entire project was 412.7 working days, the most optimistic was 388.7 working days and there was a 50% probability of completion within 400.7 working days. Traditionally, schedules are prepared based on deterministic data, but with the high uncertainty associated with the schedule, this is not a good approach. This study proposes preparing a schedule based on probabilistic data, which will result in a certain range of completion times. The project developer, in consultation with the developer, will be able to determine the lead time depending on his resources and the calculated probability of implementation. If a shorter execution time is chosen, the contractor runs the risk of not meeting this deadline. On the other hand, by choosing a time close to the longest time (with the highest probability), the contractor runs the risk of being at a disadvantage compared with the competition.

The results of the PTCM II and PTCM III scheduling calculations may show similarities, as both methods are based on similar principles of creating a task network and determining the critical path that determines the shortest possible project time. Time coupling in both methods determines how tasks are interdependent, i.e. which tasks must be completed before others can begin. The durations of individual processes can be arranged in such a way that the results of different variants of the PTCM method will be similar. This is the case when, between consecutive processes, there are large differences in their execution times.

Traditional TCMs use plot order optimisation, so that results between TCM variants vary. The use of plot order optimisation is not always possible and in PTCMs this has not yet been implemented and may be a further research area.

5. Conclusion

The scheduling of construction work is an important issue due to the significant time and financial savings that compliance with pre-imposed time standards by construction contractors enables. With schedules, resources can be better allocated and tasks prioritised, which increases productivity. In addition, schedules make it possible to monitor progress towards long-term projects and goals, which is important for evaluating performance and planning future activities. For this reason, the development of scheduling methods is important and is constantly being pursued in research work.

The research and calculation work resulted in a schedule that aimed to minimise the duration of construction work. The most pessimistic completion time was calculated as 412.7 working days, the most optimistic as 388.7 working days and the 50% probability of completion was determined as 400.7 working days. These times are very close to the results obtained with the PTCM II method, which means that the organisation of the work and the layout of the work plots allow for minimal downtime on them. The literature, as well as our own observations [24], show that usually a project is completed at 70–80% probability.

The results of the forecasting of process and project execution times calculated using the PTCM method, compared to the traditionally used approach (based on Tangible Expenditure Catalogues and the average productivity of construction workers), are more precise and create real opportunities for construction planning with very good results. The PTCM method can be successfully used to forecast construction project lead times in probabilistic terms and shows potential for practical applications).

The developed PTCM computational application allows the creation of schedules with different organisational variants of the work and a quick comparison of results between these variants. However, the authors recognise a limitation of the PTCM application, namely that it does not optimise the sequence of work plots. Optimisation of the sequence of work plots may contribute to better results and will be the subject of further work by the authors.

References

[1] Z.T. Kosztyan, "An exact algorithm for the flexible multilevel project scheduling problem", *Expert Systems with Applications*, vol. 158, no. 15, art. no. 113485, 2020, doi: 10.1016/j.eswa.2020.113485.

[2] J.R.S. Cristóbal, "The S-curve envelope as a tool for monitoring and control of projects", *Procedia Computer Science*, vol. 121, pp. 756–761, 2017, doi: 10.1016/j.procs.2017.11.097.

[3] B.K. Sovacool, A. Gilbert, and D. Nugent, "An international comparative assessment of construction cost overruns for electricity infrastructure", *Energy Research and Social Science*, vol. 3, pp. 152–160, 2014, doi: 10.1016/j.erss.2014.07.016.

[4] R. Atkinson, "Project Management: cost, time and quality, two best guesses and a phenomenon, it's [its] time to accept other success criteria", *International Journal of Project Management*, vol. 17, no. 6, pp. 337–342, 1999, doi: 10.1016/S0263-7863(98)00069-6.

[5] K.M. Jaworski, *Podstawy organizacji budowy*. Warszawa: Wydawnictwo Naukowe PWN, 2004.

[6] J. Mrozowicz, *Metody organizacji procesów budowlanych uwzględniające sprzężenia czasowe*. Wrocław: Dolnośląskie Wyd. Edukacyjne, 1997.

[7] Z. Hejducki, *Sprzężenia czasowe w metodach organizacji złożonych procesów budowlanych. Prace Naukowe Instytutu Budownictwa Politechniki Wrocławskiej. Monografie*, nr 34, 2000.

[8] M. Podolski, „Analiza nowych zastosowań teorii szeregowania zadań w organizacji robót budowlanych", PhD. thesis, Politechnika Wrocławska, 2008.

[9] V.A. Afanasev, *Algoritmy formirovania rascieta i optimizacji metod organizacji rabot*. Leningrad: Ucziebnoje pasobije, 1980.

[10] V.A. Afanasev and A.V. Afanasev, *Paralelno – potočnaja organizacja stroitelstva*. Leningrad, 1985.

[11] J. Mrozowicz, *Potokowe metody organizacji procesów budowlanych o charakterze deterministycznym*. Wydawnictwo Politechniki Wrocławskiej, 1982.

[12] Z. Hejducki, *Zarządzanie czasem w procesach budowlanych z zastosowaniem modeli macierzowych*. Wydawnictwo Politechniki Wrocławskiej, 2004.

[13] R. Marcinkowski, "Modelowanie ograniczeń w metodzie pracy potokowej", *Przegląd Naukowy – Inżynieria i Kształtowanie Środowiska*, vol. 26, no. 2, pp. 210–218, 2017.

[14] R. Assaad, I.H. El-Adaway, and I.S. Abotaleb, "Predicting Project Performance in the Construction Industry", *Journal of Construction Engineering and Management*, vol. 146, no. 5, 2020, doi: 10.1061/(ASCE)CO.1943-7862.0001797.

[15] P. Kostrzewa-Demczuk and M. Rogalska, "Scheduling with the Probabilistic Coupling Method I (PTCM I) – assuming the continuity of work of working teams", *Archives of Civil Engineering*, vol. 69, no. 2, pp. 455–469, 2023, doi: 10.24425/ace.2023.145278.

[16] P. Kostrzewa-Demczuk and M. Rogalska, "Scheduling with the Probabilistic Coupling Method II (PTCM II) – assuming continuity of work on the working sectors", *Archives of Civil Engineering*, vol. 70, no. 4, 2024, pp. 505–520, doi: 10.24425/ace.2024.151906.

[17] J.C. Teixeria, J. Kulejewski, M. Krzemiński, and J. Zawistowski, *Zarządzanie ryzykiem w budownictwie*. Warszawa, Poland: Wydawnictwo Guimaraes, 2011.

[18] A. Grześ, "Wykres gantta a metoda ścieżki krytycznej (CPM)", *Optimum. Studia Ekonomiczne*, no. 6(72), pp. 195–216, 2014, doi: 10.15290/ose.2014.06.72.14.

[19] M. Trocki and P. Wyrozębski, *Planowanie przebiegu projektów*. Oficyna Wydawnicza SGH, 2015.

[20] E.M. Goldratt, *Critical Chain*. Great Barrington, MA: The North River Press, 1997.

[21] D. Hulett, *Practical Schedule Risk Analysis*. Abingdon, Oxon, GBr.: Ashgate Publishing Group, 2009.

[22] Z. Hejducki and M. Rogalska, *Flow Shop scheduling of construction prosesses using time coupling methods*. Lublin, Poland: Politechnika Lubelska, 2021.

[23] M. Rogalska, *Wieloczynnikowe modele w prognozowaniu czasu procesów budowlanych*. Lublin, Poland: Politechnika Lubelska, 2016.

[24] P. Kostrzewa-Demczuk, "Construction Schedule versus Various Constraints and Risks", *Applied Sciences,* vol. 14, no. 1, art. no. 196, 2024, doi: 10.3390/app14010196.

Harmonogramowanie Probabilistyczną Metodą Sprzężeń Czasowych III (PTCM III) – minimalizacja czasu realizacji projektu

Słowa kluczowe: Probabilistyczna Metoda Sprzężeń Czasowych III (PTCM III), planowanie, prognozowanie czasu, harmonogram, zmienne warunki realizacyjne

Streszczenie:

Czas realizacji procesów budowlanych jest ściśle związany ze złożonością projektu oraz ze spefyficznymi dla każdej budowy warunkami realizacyjnymi (zmiennymi czynnikami wpływu). Badania przeprowadzone na złożonych projektach budowlanych na całym świecie dostarczyły statystycznych dowodów potwierdzających występowanie odchyleń w realizacji projektów w porównaniu do planowanych kosztów i czasu trwania. Jest to powodem poszukiwań nowych, lepszych metod planowania i kontroli harmonogramów. Opracowano nową metodę planowania harmonogramów o podejściu probabilistycznym – Probabilistic Time Couplings Method III (PTCM III). PTCM III bazuje na założeniach metody sprzężeń czasowych III (TCM III), która została udoskonalona poprzez zastosowanie predykcyjnej Metody Wieloczynnikowego Prognozowania Czasu Procesów Budowlanych (MMSM) i odchyleń standardowych procesu budowlanego. PTCM III umożliwia optymalizację czasowo-koszową przedsięwzięcia budowlanego przy jednoczesnym uwzględnieniu rysyka i niepewności procesów budowlanych. Priorytetem w tej metodzie jest minimalizacja czasu realizacji przedsięwzięcia, przy możliwości występowania przestojów sektorów roboczych bądź pracowników. W pracy przedstawiono podstawy i założenia metody

PTCM III, zaprezentowano wzory i metodykę obliczeniową, opartą na algorytmizacji. W celu jak najlepszej prezentacji możliwości i efektów PTCM III, w pracy przeprowadzono studium przypadku, w którym wyniki obliczeń porównano z innymi wariantami metod spsrzężeń czasowych w ujęciu probabilistycznym. Efektem obliczeń PTCM III jest zakres czasu trwania inwestycji budowlanej wraz z prawdopodobieństwem jego realizacji. Najbardziej pesymistyczny czas realizacji został obliczony na 412,7 dni roboczych, najbardziej optymistyczny na 388,7 dni roboczych, a 50% prawdopodobieństwo realizacji zostało określone na 400,7 dni roboczych. Zaletą metody PTCM III jest to, że prognoza czasu zakończenia inwestycji jest określana przez zakres szacowanych dat, a nie jako dokładna data. Tradycyjne podejście do harmonogramowania opiera się na wartościach średnich (czasach normowych), które z założenia powinny być aktualizowane wraz z rozwojem technologii budowlanej, sprzętu i narzędzi. Praktyka budowlana pokazuje jednak, że założenie to jest dalekie od rzeczywistości. Procesy budowlane są bardzo wrażliwe na zmiany czynników, od których zależą. Dlatego też preferowaną metodą harmonogramowania może być prognozowanie, które określa najbardziej prawdopodobny czas prac budowlanych oraz jego prognostyczną wartość minimalną i maksymalną – PTCM. PTCM III wykazuje potencjał do zastosowań praktycznych i dalszych rozwinięć.

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