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Research paper

Scheduling with the Probabilistic Coupling Method II (PTCM II) – assuming continuity of work on the working sectors

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Abstract: Effective planning is crucial in the construction sector to ensure projects are completed on time and on budget. However, the construction industry faces various challenges that can complicate the planning process. There are often delays, exceedances of the baseline and increases in investment costs. One planning method is Time Couplings Methods (TCM), which can be improved using predictive multivariate statistical model method (MMSM) construction process times and standard deviations. A new scheduling method in the probabilistic approach was developed – Probabilistic Time Couplings Method II (PTCM II). In PTCM II, the priority is to maintain the continuity of work on working sectors, because sector downtime is unfavorable and extends the investment implementation time. The work presents a case study and compares it with other planning methods and with the real time of the considered investment. he results clearly indicate that the developed methodology is correct, provides good mapping and can be successfully used in planning construction works.

Keywords: construction project management, schedule, Probabilistic Coupling Method II (PTCM II), Multivariate Method of Statistical Models

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1. Introduction

Effective scheduling is crucial in the construction sector to ensure projects are completed on time and within budget. However, the construction industry faces various challenges that can hinder the scheduling process. Scheduling problems in the construction sector refer to the difficulties faced in planning and organizing project activities to meet project deadlines [1]. Construction projects are complex and involve multiple tasks, resources, and stakeholders. Managing these elements effectively is essential for successful project execution [2–4].

Scheduling is vital in construction projects for several reasons. It helps in optimizing resource allocation, ensuring timely completion of tasks, and minimizing project delays. A well-planned schedule also improves productivity, reduces costs, and enhances client satisfaction. Therefore, addressing scheduling problems is crucial for the overall success of construction projects. The construction sector faces several scheduling challenges that can impact project timelines and outcomes. Some of the common challenges include [5, 6]:

- Construction projects often face constraints in terms of resources and manpower. Limited availability of skilled labor, equipment, and materials can lead to scheduling conflicts and delays.
- Unforeseen delays and disruptions. Construction projects are susceptible to unforeseen delays and disruptions such as adverse weather conditions, site accidents, or supply chain issues. These unexpected events can disrupt the project schedule and require adjustments to be made.
- Construction projects involve numerous interdependent tasks and activities. Delays or changes in one activity can have a cascading effect on the entire project schedule, making it challenging to maintain continuity and meet deadlines.
- Changing project requirements. Construction projects are dynamic, and project requirements may change during the course of the project. Changes in design, scope, or client preferences can impact the schedule and require adjustments to be made.

Scheduling problems in the construction sector can have significant consequences on project outcomes. Some of the impacts include [4, 6]:

- Increased project duration and costs. Scheduling problems can lead to project delays, resulting in increased project duration and costs. Delays can lead to additional expenses, such as extended labor and equipment rental, which can significantly impact the project budget.
- Reduced productivity and efficiency. Inefficient scheduling can result in poor resource utilization and reduced productivity. Overlapping tasks, idle time, and inefficient allocation of resources can lead to wasted time and effort, negatively impacting project efficiency.
- Poor resource utilization. Inadequate scheduling can result in underutilization or overutilization of resources. Underutilization leads to wasted resources, while overutilization can cause burnout and decreased productivity among workers.
- Client dissatisfaction. Scheduling problems can lead to delays in project completion, which can result in client dissatisfaction. Clients may lose confidence in the project team's ability to deliver on time, leading to strained relationships and potential legal disputes.

In complex projects, maintaining continuity of work on the working sectors becomes a challenge. Continuity of work on the working plots refers to the uninterrupted progress of activities in a project [4]. It is crucial for maintaining productivity and avoiding delays. When there is a break in the work sequence, it can lead to inefficiencies and disruptions in the project schedule [7]. Therefore, ensuring continuity of work is essential for successful project execution. Without proper planning and scheduling, it is difficult to ensure a smooth flow of work and avoid interruptions.

An important problem when planning construction works, the completion date of which is difficult to predict, is the use of deterministic data [3]. The development of technology, the increase in computer computing power and data analysis methods based on artificial intelligence create opportunities to modernize scheduling methods [8–10]. An important development of the scheduling technique is the use of probabilistic data on the execution times of individual processes and various constraints enabled by new PTCM methods. A variant of the PTCM Method is PTCM II, in which the priority is to preserve work on working sectors.

The Probabilistic Coupling Method II (PTCM II) is a scheduling technique that takes into account the probabilistic nature of project activities [4]. It is based on the concept of coupling, which refers to the relationship between two activities that require the same resources or have dependencies. In PTCM II, scheduling involves determining the sequence of activities and allocating resources in a way that minimizes project duration and maximizes resource utilization. The goal is to create a schedule that is both feasible and efficient. The assumption of continuity of work on the working plots is an important aspect of scheduling in PTCM II.

PTCM II offers several benefits when it comes to scheduling, especially in projects where continuity of work is crucial. By considering the probability of coupling between activities, PTCM II can help identify potential disruptions and plan accordingly. It allows for better resource allocation and optimization, leading to improved project efficiency and reduced delays. The Probabilistic Coupling Method II (PTCM II) is a powerful tool that can be used to address this challenge and optimize scheduling. This article will explore the concept of scheduling with PTCM II, focusing on the assumption of continuity of work on the working sectors.

2. Methodology

The Probabilistic Time Couplings Method II (PTCM II) is an advanced approach to scheduling TCM II construction projects by incorporating probabilistic elements. PTCM II utilizes modern forecasting techniques for construction processes and considers standard deviations in the implementation times of each process. By conducting computational calculations within the PTCM II framework, a user-friendly application has been developed to facilitate the method's practical application.

2.1. Time Couplings Method II – TCM II

Time Coupling Methods (TCM) present a unique methodology for planning construction projects, taking into account various constraints such as technological, technical, organizational, time-related, structural, or sequential factors [7, 11, 12]

These methods significantly differ from network scheduling methods primarily developed in North America. The fundamental concept behind TCM methods is the notion of temporal couplings, which refer to the time intervals between individual tasks or processes. These time couplings play a crucial role in the development of different TCM organizational strategies. The following types of time couplings have been identified [4, 13, 14]:

- between working fronts (working plots/sectors),
- between the means of implementation (resources),
- diagonal, bind various types of works in neighboring types of works,
- reverse diagonal.

The simplest single calculation segment of the TCM method assigned to the *Pj* process and the *Si* sector contains the following information (Figure 1):

- 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.

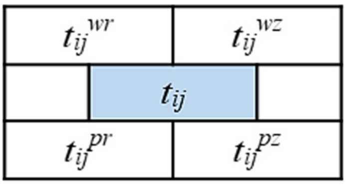


Fig. 1. A single calculation segment of the TCM method [4, 14]

There are several variants of the TCM method, including [7, 11, 12]

- TCM I (the work was planned to eliminate employee downtime),
- TCM II (works were planned to eliminate downtime in sectors),
- TCM III (the work was planned to achieve the minimum duration of the construction work).

The TCM methodology has been extensively documented in various publications [7, 11, 12, 14], and it enjoys widespread recognition within the academic and engineering community, particularly in the realm of scheduling construction processes. Taking into account the requirement of continuous work on working sectors, the authors focused exclusively on the TCM II method.

2.2. Input data – time of construction processes

The duration of construction processes in the schedules can be determined using various methods. After analyzing existing forecasting techniques for estimating construction work durations, it has been found that the Multivariate Method of Statistical Models (MMSM) developed by Rogalska [3, 15, 16] demonstrates excellent accuracy in mapping the actual implementation time of investments. This method employs a multi-factor approach to model the duration of construction works based on real data and the variables that influence them. It is a versatile methodology suitable for both simple and complex processes, as well as linear and cubature works.

The described method allows for the incorporation of any number of factors that may impact the duration of the work, whether they are numerical or descriptive (linguistic) in nature. The method utilizes computational analysis generated from prognostic methods, including multiple regression, multivariate adaptive regression with spline functions, generalized additive models, simulated neural networks, support vectors, and integrated autoregression. The outcome of these calculations is a set of prognostic models that determine the duration of construction works through regression equations. To identify the most accurate regression equations that closely reflect the specific construction process under examination, a comparative assessment is conducted. This assessment considers the forecast error (MAPE), as well as the autocorrelation of series residuals and the autocorrelation of partial series residuals.

2.3. Standard deviations

To incorporate the risk of deadline failure and the uncertainty of construction processes into the calculations, a standard deviation is utilized. The standard deviation serves multiple purposes, including measuring investment risk, determining the coefficient of variation, and assessing the typical range of variability. It represents the average deviation of measurements from the norm or arithmetic mean. It is important to note that a higher standard deviation indicates a greater investment risk. To accurately account for standard deviations in the calculation sheet, the formula (2.1) for the sum of standard deviations of two independent random variables is applied. This formula allows for the consideration of the combined variability resulting from multiple factors.

$$\sum \tau = \sqrt{\sigma_x^2 + \sigma_y^2} \tag{2.1}$$

where:

σ_x– standard deviation of an independent random variable X;

σ_y– standard deviation of an independent random variable Y.

Therefore, each assigned task duration will include information regarding the potential deviation from the planned value. For the final task, it will encompass the total duration of all subsequent work that concludes the task, as well as the potential deviation from the scheduled plan. This approach ensures that the calculations account for the inherent uncertainties and potential variations in the construction processes, allowing for a more comprehensive and accurate assessment of the project timeline.

2.4. Probabilistic Time Couplings Method II (PTCM II)

The calculation segment of the PTCM II method has been expanded compared to the TCM II method to incorporate additional data. This includes the standard deviation of a specific process, the sum of standard deviations of all preceding processes (considering the standard deviation of the current work), the minimum time forecast for completing the work (optimistic estimate), and the maximum time forecast (pessimistic estimate) for completing the work. Figure 2 illustrates the calculation segment of the PTCM II method for the *Pj* process and the Si sector, which encompasses the following information. [4, 14]:

- 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).

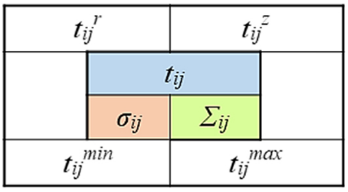


Fig. 2. Single PTCM II calculation segment [14]

The assumption of the PTCM II method is that a segment corresponds to the work of one work brigade (*Pj*) in one work sector (*Si*). The number of plots/work sections and the work carried out on them can be any, although practice shows that as the size and complexity of the project increases, the number of sectors and processes increases. The number of calculation segments of the PTCM II spreadsheet can be any.

General calculation formulas of the PTCM II method are presented below (Eq. (2.2)–(2.16)) and the full description of the PTCM II method is described in [4]:

- Sector S_1 i process P_1:

$$t_{1,1}^r = \begin{cases} 0 \\ \text{or given initial value} \end{cases} \tag{2.2}$$

$$t_{1,1}^z = t_{1,1}^r + t_{1,1} \tag{2.3}$$

$$\sum_{1,1} = \sigma_{1,1} \tag{2.4}$$

$$t_{1,1}^{\min} = t_{1,1}^{z} - \sum_{1,1} \tag{2.5}$$

$$t_{1,1}^{\max} = t_{1,1}^{z} + \sum_{1,1} \tag{2.6}$$

– Sector S_i i process P_1:

$$t_{i,1}^{r} = t_{(i-1),1}^{r} + \max \begin{cases} t_{(i-1),1} \\ t_{(i-1),1} + t_{(i-1),2} - t_{i,1} \\ \ldots \\ t_{(i-1),1} + t_{(i-1),2} + \ldots + t_{(i-1),n} - t_{i,1} - t_{i,2} - \ldots - t_{i,(n-1)} \end{cases} \tag{2.7}$$

$$t_{i,1}^{z} = t_{i,1}^{r} + t_{i,1} \tag{2.8}$$

$$\sum_{i,1} = \sqrt{\Sigma_{(i-1),j}^{2} + \max \begin{cases} t_{(i-1),1} \Rightarrow \sigma_{(i-1),1}^{2} \\ t_{(i-1),1} + t_{(i-1),2} - t_{i,1} \Rightarrow \sigma_{(i-1),1}^{2} + \sigma_{(i-1),2}^{2} - \sigma_{i,1}^{2} \\ \ldots \\ t_{(i-1),1} + t_{(i-1),2} + \ldots + t_{(i-1),n} - t_{i,1} - t_{i,2} - \ldots - t_{i,(n-1)} \\ \Rightarrow \sigma_{(i-1),1}^{2} + \sigma_{(i-1),2}^{2} + \ldots + \sigma_{(i-1),n}^{2} - \sigma_{i,1}^{2} - \sigma_{i,2}^{2} - \ldots - \sigma_{i,(n-1)}^{2} \end{cases}} \tag{2.9}$$

$$t_{i,1}^{\min} = t_{i,1}^{z} - \sum_{i,1} \tag{2.10}$$

$$t_{i,1}^{\max} = t_{i,1}^{z} + \sum_{i,1} \tag{2.11}$$

– Sector S_i i process P_j:

$$t_{i,j}^{r} = \max \begin{cases} t_{i,(j-1)}^{z} \\ t_{(i-1),j}^{z} \end{cases} \tag{2.12}$$

$$t_{i,j}^{z} = t_{i,j}^{r} + t_{i,j} \tag{2.13}$$

$$\sum_{i,j} = \sqrt{\sigma_{i,j}^{2} + \max \begin{cases} t_{i,(j-1)}^{z} \Rightarrow \Sigma_{i,(j-1)}^{2} \\ t_{(i-1),j}^{z} \Rightarrow \Sigma_{(i-1),j}^{2} \end{cases}} \tag{2.14}$$

$$t_{i,j}^{\min} = t_{i,j}^{z} - \sum_{i,j} \tag{2.15}$$

$$t_{i,j}^{\max} = t_{i,j}^{z} + \sum_{i,j} \tag{2.16}$$

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 speed up work related to scheduling using the PTCM II method, a computational application in Microsoft Excel was created. Excel is a popular program, universal and intuitive to use. The computational application has been prepared so that as many calculations as possible are performed automatically, and the application user's work is limited only to entering input data.

2.5. Graphical representation of schedules – cyclographs

Schedules often cause problems with reading them, which is why they are additionally reproduced graphically. The most popular graphic scheduling methods include cyclograms and Gantt charts. The work uses cyclograms that can be quickly and easily read by a person even without experience.

3. Case study

The work will present a case study for an investment involving the construction of a single-family house estate. There are 10 working sectors, each sector corresponding to one house. Similar construction processes are carried out on individual plots, from which 5 main works have been distinguished: earthworks (P1), wall and ceiling works (P2), roof trusses and roofing (P3), construction of the closed shell and insulation (P4) and works finishing (P5). The case study was described in more detail in [14] for the PTCM I method, for which the priority is to maintain continuity of work by work teams. This work is a further development of the TCM and PTCM methodologies and the same computational case was intentionally used so that the results could be put together and compared. In [14], earthworks (P1) were considered in detail, and the current work shows wall and ceiling works (P2) in order not to repeat some of the calculations.

The calculations and analysis were carried out on the basis of data on the implementation of similar construction processes in the past and through experimental work on construction sites. The acquired data were input data used to calculate the times of construction processes using the MMSM method and then PTCM II. Due to the large number of calculations, the article presents detailed calculation results for wall and ceiling works (P2). The remaining processes (P1, P3–P5) were calculated similarly and their final results are presented in the paper. In the P2 process, “wall and ceiling works” in m^2/h was adopted as the dependent variable (v1). The independent variables influencing the dependent variable include: duration of work, employee experience, aera of window and door openings, type of material used and adopted technology. The variables used for analysis are presented in Table 1.

The calculation results using the MMSM method are summarized in Table 2. The dependent variable “wall and ceiling works” and the independent variables influencing its value are characterized by a normal distribution. The normal distribution is the most common distribution in nature and for some forecasting models it determines the conduct of further calculations. The normality of the distribution was examined using using the Shapiro–Wilk test [17]. The obtained values of the Shapiro–Wilk test coefficient “W” were compared with the critical values of the test. For 32 observed data, Wkr = 0.93.

The next step in the MMSM method is to check the degree of linear correlation – the relationship between variables. The occurrence of correlations between variables may cause distortions in the regression equation and ultimately lead to erroneous results. The basis for eliminating one of the variables between which there is a correlation is a value above 0.8. In the analyzed case, no significant correlations were found and all variables were qualified for calculations.

After determining the data distributions and determining the correlation of variables, you can proceed to forecasting calculations. The MMSM method uses a number of computational

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

No.	Variable	Variable description	Units
1	v1	Wall and ceiling works	[m^2/h]
2	v2	Duration of works	[h]
3	v3	Average employee experience	[years]
4	v4	Area of works carried out	[m^2]
5	v5	Working height	[m]
6	v6	Area of window and door openings	[m^2]
7	v7	Number of corners	[pcs]
8	v8	Type of material used	[linguistic]
9	v9	Temperature	[°C]
10	v10	Equipment failure rate	[%]
11	v11	Adopted technology	[linguistic]

methods to perform calculations and then determine the goodness of fit of the models and the size of the forecast error [3]. Finally, the model with the smallest error is selected, which means the best fit. In the analyzed case, the following methods were used for calculations:

- Multiple Regression (MR),
- Generalized Additive Methods (GAM),
- Multivariate Adaptive Regression Splines (MARSplines),
- Support Vector Machine (SVM),
- Simulated Neural Networks (SNN).

The result of the work was the generation of 4 forecast models. After a detailed analysis of each model and checking its correctness using the MAPE error, autocorrelation of residuals and autocorrelation of partial residuals, it turned out that only two models meet the appropriate conditions (SNN and GAM models). In the rest models, despite the acceptable MAPE error of less than 5%, significant autocorrelations of residuals and partial residuals were detected, which prevents the use of these models for forecasting. No significant autocorrelations of residuals and partial residuals were detected in the SNN and GAM models, but for SNN the MAPE error was smaller than for GAM, so the SNN model was used for further calculations.

In the SNN method, regression patterns are not generated as in GAM. As a result of SNN modeling, we obtain a network of dependencies into which new data (for a new case) is directly introduced in order to calculate its value. The lack of a regression formula (enabling the possibility of wide and quick use of the calculated model) can be described as a modeling disadvantage because, unlike the regression formula, the condition for making a forecast using SNN is to have prior data and a selected neural network. However, the sheet with basic data, the results and the network itself can be exported to files and sent, and another person can quickly conduct modeling in appropriate software based on them.

Using the network of dependencies to determine the v1 variable (P2 process), the implementation time in individual sectors was calculated. The remaining processes were determined using the MMSM method, analogously to the P2 process, for each of the 10 sectors. The summary of calculation results is presented in Table 2.

Table 2. Forecast duration of P1-P5 processes on S1-S10 sectors – PTCM II [14]

Time t_{ij} [days]		**Proceses**				
		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

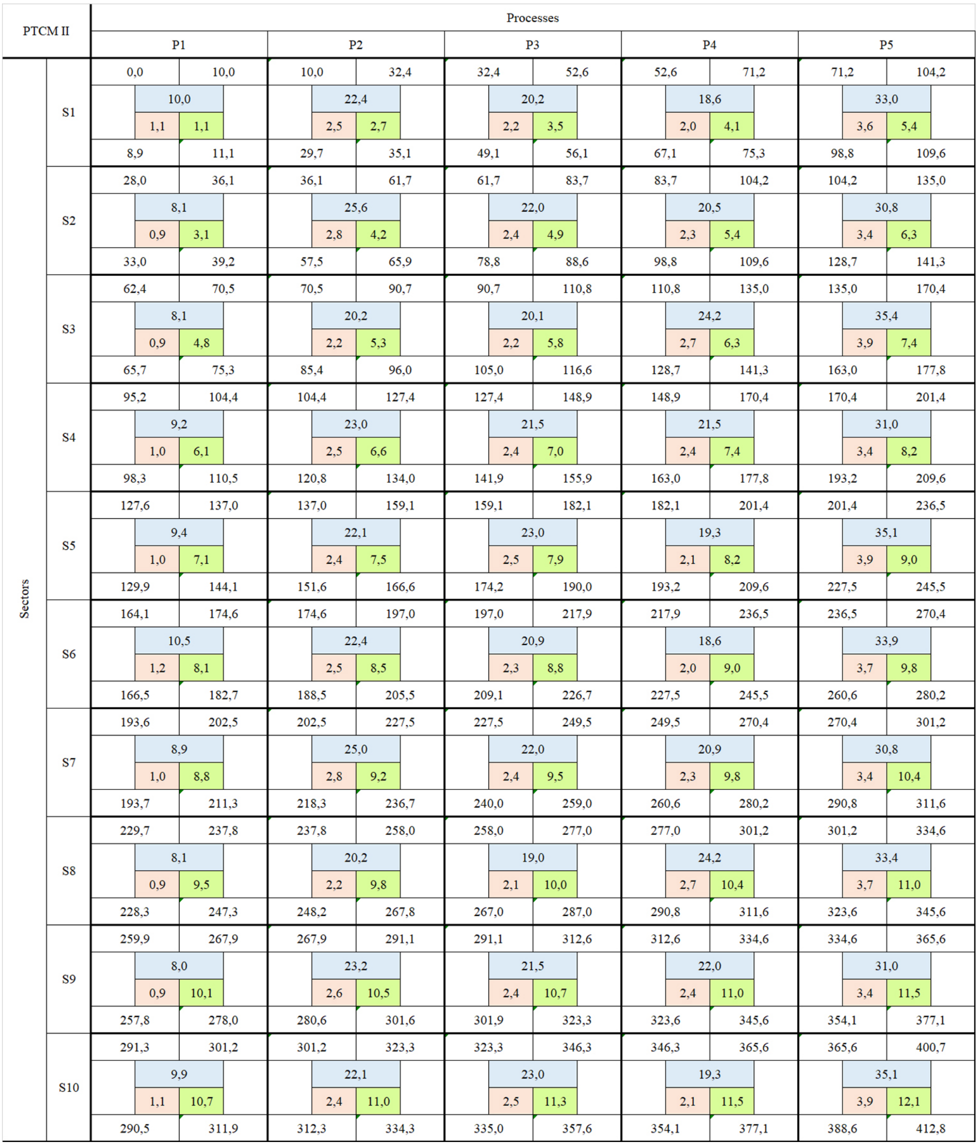
4. PTCM II – results and discussion

The investment considered in the article was divided into 10 sectors, with one sector corresponding to the construction of one house. The processes related to the implementation of the investment have also been divided into smaller, less complicated processes, in accordance with the technological conditions of the investment. The implementation times of 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 forecasted implementation times of individual processes on the plots and the standard deviations of the processes constitute the input data to the PTCM II method, the results of which in the form of a schedule and cyclogram are presented in Figures 3 and 4.

PTCM II results were compared with PTCM I results, duration of the investmwnt planned by the designer and the real time with appropriate assumption of work organisation (Table 3).

Upon comparing the duration of investment assuming continuous work on sectors (PTCM II) with the actual duration, it can be concluded that the PTCM II scheduling method is accurate and can be utilized for forecasting the implementation time of construction investments [4]. One advantage of the PTCM II method is that it determines the investment implementation time forecast based on a range of estimated dates rather than a specific date.

In contrast, the traditional approach of TCM II planning relies on averages (code times) that require regular updates as construction technology, equipment, and tools evolve [7]. However, practical experience in construction demonstrates that this assumption does not align with reality. Construction processes are highly sensitive to changes in the influencing factors [3, 18]. Therefore, a preferred planning method may involve forecasting, which determines the most probable construction time along with its minimum and maximum projected values. This approach takes into account the inherent uncertainties and variations in construction processes, providing a more realistic and reliable estimation of the project timeline.



PTCM II		Processes									
		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	28,0	36,1	36,1	61,7	61,7	83,7	83,7	104,2	104,2	135,0
		8,1		25,6		22,0		20,5		30,8	
		0,9	3,1	2,8	4,2	2,4	4,9	2,3	5,4	3,4	6,3
		33,0	39,2	57,5	65,9	78,8	88,6	98,8	109,6	128,7	141,3
	S3	62,4	70,5	70,5	90,7	90,7	110,8	110,8	135,0	135,0	170,4
		8,1		20,2		20,1		24,2		35,4	
		0,9	4,8	2,2	5,3	2,2	5,8	2,7	6,3	3,9	7,4
		65,7	75,3	85,4	96,0	105,0	116,6	128,7	141,3	163,0	177,8
	S4	95,2	104,4	104,4	127,4	127,4	148,9	148,9	170,4	170,4	201,4
		9,2		23,0		21,5		21,5		31,0	
		1,0	6,1	2,5	6,6	2,4	7,0	2,4	7,4	3,4	8,2
		98,3	110,5	120,8	134,0	141,9	155,9	163,0	177,8	193,2	209,6
	S5	127,6	137,0	137,0	159,1	159,1	182,1	182,1	201,4	201,4	236,5
		9,4		22,1		23,0		19,3		35,1	
		1,0	7,1	2,4	7,5	2,5	7,9	2,1	8,2	3,9	9,0
		129,9	144,1	151,6	166,6	174,2	190,0	193,2	209,6	227,5	245,5
	S6	164,1	174,6	174,6	197,0	197,0	217,9	217,9	236,5	236,5	270,4
		10,5		22,4		20,9		18,6		33,9	
		1,2	8,1	2,5	8,5	2,3	8,8	2,0	9,0	3,7	9,8
		166,5	182,7	188,5	205,5	209,1	226,7	227,5	245,5	260,6	280,2
	S7	193,6	202,5	202,5	227,5	227,5	249,5	249,5	270,4	270,4	301,2
		8,9		25,0		22,0		20,9		30,8	
		1,0	8,8	2,8	9,2	2,4	9,5	2,3	9,8	3,4	10,4
		193,7	211,3	218,3	236,7	240,0	259,0	260,6	280,2	290,8	311,6
	S8	229,7	237,8	237,8	258,0	258,0	277,0	277,0	301,2	301,2	334,6
		8,1		20,2		19,0		24,2		33,4	
		0,9	9,5	2,2	9,8	2,1	10,0	2,7	10,4	3,7	11,0
		228,3	247,3	248,2	267,8	267,0	287,0	290,8	311,6	323,6	345,6
	S9	259,9	267,9	267,9	291,1	291,1	312,6	312,6	334,6	334,6	365,6
		8,0		23,2		21,5		22,0		31,0	
		0,9	10,1	2,6	10,5	2,4	10,7	2,4	11,0	3,4	11,5
		257,8	278,0	280,6	301,6	301,9	323,3	323,6	345,6	354,1	377,1
	S10	291,3	301,2	301,2	323,3	323,3	346,3	346,3	365,6	365,6	400,7
		9,9		22,1		23,0		19,3		35,1	
		1,1	10,7	2,4	11,0	2,5	11,3	2,1	11,5	3,9	12,1
		290,5	311,9	312,3	334,3	335,0	357,6	354,1	377,1	388,6	412,8

Fig. 3. PTCM II schedule

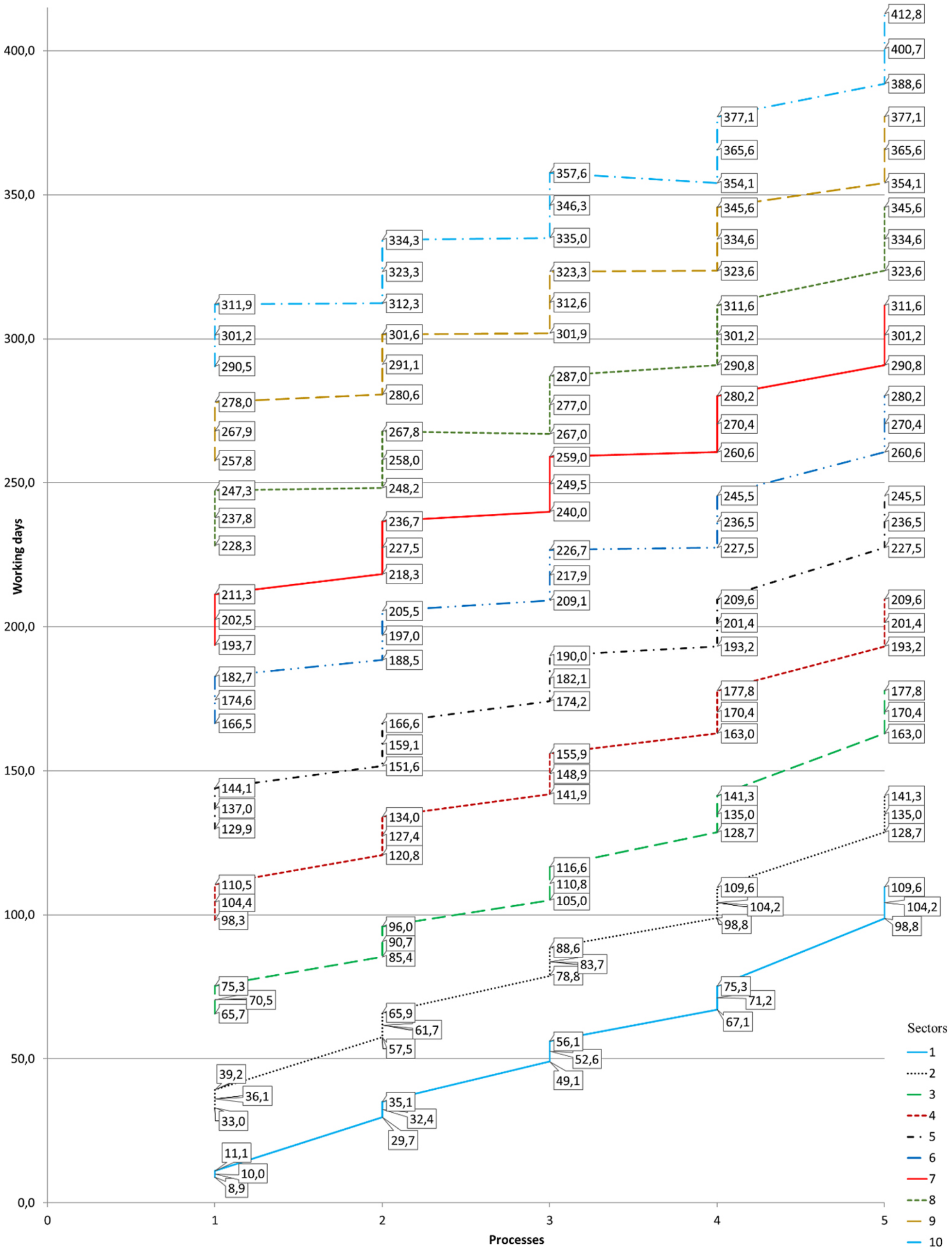


Fig. 4. The PTCM II cyclogram

Table 3. Summary of the forecast

The method of determining the schedule	**The total duration of the investment [working-days]**
PTCM II	Minimal: 388.6 Most likely: 400.7 Maximum: 412.8
Duration of the investment planned by the designer, assuming continuity of work in the working sectors	360.0
Real time assuming continuity of work in the working sectors	398.6
PTCM I	Minimal: 409.6 Most likely: 421.1 Maximum: 432.6
The duration of the investment planned by the designer, assuming the continuity of workers' work	385.0
Real time assuming the continuity of workers' work	419.0

The PTCM II method provides a range of possible project implementation times, including the most probable, minimum, and maximum durations. These values allow for the consideration of the decision maker's preferences. For instance, a contractor who possesses comprehensive information about available equipment, employee processing capacity, and other factors can make an informed decision based on potential profits and losses. Contractor can select a specific value from the provided time range. When choosing a value close to the minimum time, the decision maker must consider possible penalties for delays. On the other hand, selecting a value close to the maximum time may result in reduced competitiveness against other companies and the risk of not securing the project order.

The actual project duration falls within the time range generated by the PTCM II method. The company responsible for the investment also establised its own defined duration. Drawing from years of experience, the designer estimated the time required for individual processes and, consequently, the overall project duration. This methodology, based on the designer's experience, necessitates significant skill and knowledge on the part of the individual preparing the schedule. The time estimated by the designer is shorter than the real time and the time projected by the PTCM II method.

The results obtained using the PTCM I and PTCM II methods were also compared, where in the second organizational method (PTCM II) the implementation times are shorter. This is a correct and predictable result [4, 7]. To ensure the continuity of work in work sectors, it is necessary to increase the employment of workers and then work is performed faster [19].

Results presented in this paper indicates the practical advantages of the PTCM II method and the possibility of its use in scheduling. The PTCM II method, due to the analysis of numerous data from the past and taking into account standard deviations in the implementation times of various processes, is able to generate a schedule that is more faithful to the actual course of work.

5. Conclusions

The occurrence of random phenomena during construction implementation is unpredictable. These phenomena may or may not happen. However, mathematical sciences have demonstrated that it is possible to successfully forecast random events and their impacts. When it comes to construction investments and the preparation of schedules or cost estimates, it is crucial to consider the occurrence of various random events that can affect the documents being prepared. Unfortunately, the traditional computational approach to estimating the duration or costs of construction processes often fails to account for these random factors, leading to results that deviate significantly from reality.

To address this issue, improvements have been made to the traditional scheduling methodology, building upon the TCM II and MMSM methodology. These improvements include the incorporation of standard deviations for individual construction processes, which provide statistical inferences about the probability of outcomes. Rather than determining a single duration for the investment (which is not ideal in construction), this approach establishes three values for the time required to complete a given activity: minimum, most probable, and maximum. This allows for a more precise definition of task durations and the overall project completion date.

Table 3 summarizes the results of total investment times calculated using various methods. It demonstrates that the PTCM II method yields more accurate forecasting results compared to the time estimated by the designer, based od his experience. The development of a calculation application for the PTCM II method using the widely-used Microsoft Excel program facilitates the dissemination and popularization of this methodology.

Future research endeavors will focus on the analogous development of implementation times for TCM III methods and the exploration of more effective approaches to determining input data or assessing the risk of investment failure. Another area of research may be the development of better methods for presenting graphically prepared schedules.

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Harmonogramowanie Probabilistyczną Metodą Sprzężeń Czasowych II (PTCM II) – założenie ciągłości pracy na sektorach roboczych

Słowa kluczowe: zarządzanie przedsięwzięciem budowlanym, harmonogram, Probabilistyczna Metoda Sprzężeń Czasowych II (PTCM II), Multivariate Method of Statistical Models (MMSM)

Streszczenie:

Skuteczne planowanie ma kluczowe znaczenie w sektorze budowlanym, aby zapewnić realizację projektów na czas i zgodnie z budżetem. Jednak branża budowlana stoi przed różnymi wyzwaniami, które mogą skomplikować proces planowania. Jedną z metod planowania są metody sprzężeń czasowych (TCM), które można ulepszyć za pomocą metody predykcyjnego wielowymiarowego modelu statystycznego (MMSM) czasów procesu konstruowania i odchyleń standardowych. Opracowano nową metodę szeregowania w podejściu probabilistycznym – Probabilistic Time Couplings Method II (PTCM II). W PTCM II priorytetem jest utrzymanie ciągłości pracy na pracujących sektorach, gdyż przestoje sektora są niekorzystne i wydłużają czas realizacji inwestycji. W pracy przedstawiono studium przypadku i porównano je z innymi metodami planowania oraz z rzeczywistym czasem realizacji rozważanej inwestycji. Wyniki wyraźnie pokazują, że opracowana metodologia może być z powodzeniem stosowana w planowaniu robót budowlanych.

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