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Research paper

Scheduling with the Probabilistic Coupling Method I (PTCM I) – assuming the continuity of work of working teams

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Abstract: Modeling and numerical analysis of the design of building structures, their technology, organization and management methods of construction processes are the subject of the work of many scientists in Poland. Schedule designers try to best reflect the reality of construction projects with the available methods, although this procedure is not always successful. One of the scheduling methods is the Time Coupling Methods (TCM), which can be refined using the predictive durations of the Multivariate Method of Statistical Models (MMSM) construction processes and standard deviations. A new scheduling method in the probabilistic approach was developed – Probabilistic Time Couplings Method I (PTCM I). At PTCM I, work is organized in such a way as to maintain the continuity of work of employees, as downtime of workers is disadvantageous and costly. The total duration of the new investment was forecasted and compared with the other methods of scheduling and with real time after its completion. The results clearly show that the developed methodology can be successfully used in scheduling construction works.

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

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1. Introduction

The construction sector is one of the most dynamically developing economic sectors in Poland in recent years. This applies primarily to sustainable development, building materials, but also to construction processes. Modeling and numerical analysis of the design of building structures, their technology, organization and management methods of construction processes are the subject of the work of many scientists in Poland. Better and better methods of modeling and scheduling construction works translate into great financial and time savings.

In the process of negotiating construction contracts, there is a need to clearly define the time frame for the duration of the works and the date of their completion. It is very difficult due to the high degree of uncertainty resulting from the parameters that change during the execution of works, and also depends on the nature of construction processes, such as: complexity of the project, high organizational level, multidisciplinary nature, overlapping of various works, the presence of large the number of interdependent components, the scale and the difficulty of implementation [1–5].

Studies of complex construction projects around the world have provided statistical evidence that shows significant deviations in the implementation of these projects compared to planned costs and duration. Sweis and his team say that despite the advanced technology and project management techniques available to practitioners, construction projects face delays [6]. The literature on the construction of hydrotechnical facilities shows an increase in the duration compared to the planned up to 50% [7–9]. San Cristóbal [10] analyzed a sample of 130 projects and indicated that 81.5% completed beyond the scheduled time. On the other hand, Atkinson put forward the statement that construction projects are still described as unsuccessful [11]. Research shows that even every second construction project exceeds the agreed construction deadlines [12, 13], which causes significant losses (contractual penalties) and is often the result of inadequate use of resources [14–18].

Managing a construction project is a very important issue that determines both the costs and time of investment implementation. Planning and organization of construction works are important elements of project management, which many times cause many problems. It is related to the heterogeneity and discontinuity of construction processes, as well as the occurrence of various technological and organizational constraints, which have a decisive impact on the sequence of works, and thus their effectiveness. When drawing up the project plan (schedule), the risks and uncertainties arising from the nature of the work should be taken into account.

Many methods and models have been developed over the years that would be helpful in planning a construction project. The development of technology and computer software significantly facilitated and streamlined the creation of schedules. However, work is still underway to develop scheduling methods that would best reflect the reality and the set constraints.

In order to be able to take full advantage of the developed construction schedules and the final data that they generate were as close to the truth as possible, it is necessary to take a closer look at the issue of the duration of individual processes that make up the entire project. This issue is extremely important, because even the best scheduling method will be ineffective and thus far from the actual conditions of the planned construction works, if the data that we use in the schedule will be far from those obtained in practice. It is extremely difficult to clearly define the duration of a certain construction work, as it is associated with many uncertainties. The experienced worker will get another working time and the learning person will get another working time. People who prepare schedules often ask themselves what time to take in the calculations and whether it is realistic to predict such a complicated process as construction works.

The study attempts to improve the scheduling of construction projects in the pipeline system by developing the Time Couplings Method I – TCM I developed by Professor Afanasjew V.A. [20–23], J. Mrozowicz [24, 25], Z. Hejducki [26–28] and Rogalska [29, 30]. The new probabilistic scheduling method, based on TCM I, is called PTCM I (Probabilistic Time Couplings Methods I). At PTCM I, work is organized in such a way as to maintain the continuity of work of employees, as downtime of workers is disadvantageous and costly. The total duration of the new investment was forecasted and compared with the other methods of scheduling and with real time after its completion.

2. Methodology

The PTCM I planning method (Probabilistic Time Couplings Method I) is an extension of the scheduling of TCM I construction projects in probabilistic terms. PTCM I uses modern methods of forecasting construction processes and standard deviations of the implementation times of individual processes. Based on the computational calculations carried out in the PTCM I method, a computational application was created that allows for quick application of the method in everyday life.

2.1. Time Couplings Method I – TCM I

Time Coupling Methods represent a special methodology that allows you to plan construction projects taking into account many constraints, including: technological, technical, organizational, time, structural or sequential. These are methods that differ significantly from network scheduling methods developed, inter alia, in North America. The temporal couplings on which TCM methods are based and from which they are named, are simply the distances in time that occur between individual robots. Time couplings are a decisive criterion in creating various methods of organizing TCM works. There are the following types of time couplings [25]:

– 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 P_j process and the S_i 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.

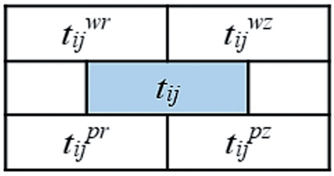

Fig. 1. A single calculation segment of the TCM method

There are several variants of the TCM method, including:
– 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 described in detail in numerous publications [7, 20–26, 28–30], it is also well known in the academic and engineering community in the field of scheduling construction processes, therefore it will not be described in detail. At work, due to the need to maintain permanent employment and lack of downtime for contractors, only the TCM I method was considered.

2.2. Input data – completion time of construction processes

The times of the construction processes used in the schedules can be calculated by any method. The analysis of the existing forecasting methods used for presetting the time of construction works proves that the parametric-regression method Multivariate Method of Statistical Models (MMSM) developed by Rogalska [3, 32, 33] is characterized by a very good mapping of the real time of investment implementation. This method uses multi-factor modeling of the duration of construction works based on real data and the variables affecting them. It is a universal methodology that can be successfully used in both simple and complex processes, as well as for linear and cubature works.

In the described method, it is possible to use any number of factors that may affect the duration of the work, both numerical and descriptive (linguistic). The indicated method uses computational analysis generated on the basis of prognostic methods, including: multiple regression, multivariate adaptive regression using spline functions, generalized additive models, simulated neural networks, support vectors and integrated autoregression. The result of the calculations are prognostic models that determine the duration of construction works through a regression equation. From the developed regression equations, on the basis of a comparative assessment, the ones that most closely reflect the examined construction process, i.e. are characterized by the lowest forecast error (MAPE), are selected. Comparative evaluation of the prediction error is carried out on the basis of the mean absolute percentage error as well as the autocorrelation of series residuals and the autocorrelation of partial series residuals.

2.3. Standard deviations

In order to take into account in the calculations the risk of failure to meet the deadline and uncertainty of construction processes, a standard deviation was used, which can be used, inter alia, for measuring investment risk, determining the coefficient of variation or a typical area of variability. Standard deviation is a type of error – the average deviation of the measurements from the norm (arithmetic mean). It is assumed that the higher the standard deviation, the greater the investment risk. In order to be able to adequately account for the standard deviations in the calculation sheet, it is necessary to apply the formula for the sum of the standard deviations of two independent random variables:

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

where: σ_x – standard deviation of an independent random variable X; σ_y – standard deviation of an independent random variable Y.

Thus, each assigned task duration will additionally contain information about a possible deviation from the planned value. In the last task, there will be information about the total duration of all consecutive work that ends the task and about a possible deviation from the schedule plan.

2.4. Probabilistic Time Couplings Method I (PTCM I)

The simplest single calculation segment of the PTCM I method has been extended in relation to the calculation scheme of the TCM I method with new data, such as the standard deviation of a given process, the sum of standard deviations of all processes preceding the current work (taking into account the standard deviation for current work), the minimum time forecast (optimistic) completion of works and maximum (pessimistic) completion of works. The calculation segment of the PTCM I method assigned to the P_j process and the S_i sector is shown in Figure 2 and includes the following information:

- 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,
- Σ_{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).

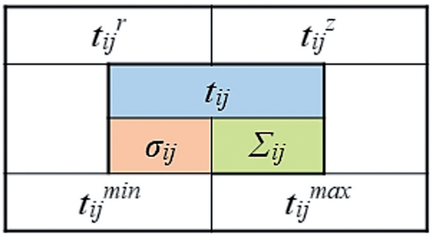

Fig. 2. Single PTCM I calculation segment

Each segment corresponds to the work of one working brigade (P_j) on one working plot (S_i). The size of the investment affects the number of plots/working sectors and the complexity of the work performed on it affects the number of processes. The number of calculation segments of the PTCM I calculation sheet depends on the designated number of sectors and processes on a particular construction site and can be any.

Some of calculation formulas of the PTCM I method are presented below (Eq. (2.2)–Eq. (2.6)), the full description of the PTCM I method is described in [34]:

– Sector S_i i-process P_j:

$$t_{i,j}^{r} = \max \begin{cases} t_{i,(j-1)}^{z} \\ t_{(i-1),j}^{z} \end{cases} \tag{2.2}$$

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

$$\sum_{i,j} = \sqrt{\sum_{i,j}^{2} + \max \begin{cases} t_{i,(j-1)}^{z} \Rightarrow \sum\limits_{i,(j-1)}^{2} \\ t_{(i-1),j}^{z} \Rightarrow \sum\limits_{(i-1),j}^{2} \end{cases}} \tag{2.4}$$

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

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

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

The computing application was developed in Microsoft Excel, primarily due to the universality of the software, intuitive operation and great popularity. The application is prepared in such a way that as many calculations as possible are performed automatically and the user's work is limited only to entering input data.

2.5. Graphical representation of schedules – cyclographs

Schedules, due to the course and a large number of events they describe, should show the sequence of works in a simple and clear way and allow them to be tracked against the background of a larger whole (part of the project or the entire construction site). To make this possible, graphic tools are often used in the investment planning process, which allow to model works in an appropriate way and easily track their progress, even for a person without significant experience. The most frequently used modeling methods are dependency networks, graphs, line charts or cyclic lines. The work uses cyclograms that reflect the basic parameters of the works resulting from the calculations.

3. Case study

The construction of a single-family housing estate is considered, where each individual house is a separate working plot. 10 working plots were separated. Similar construction processes are carried out on individual plots, from which 5 main works have been separated: 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).

Data on the construction of similar objects were collected, taking into account various variables occurring on them. On this basis, calculations of the times of individual construction processes were carried out using the MMSM method, and then PTCM I.

The example of earthworks (P1) shows the methodology, which was applied analogously in all cases, however, due to the large amount of material, the final results will be presented for subsequent cases. In the first process, "earthworks" in m^3/h were defined as the dependent variable (v1). Independent variables affecting the dependent variable include, among others: the duration of the works, employee experience, the area and depth of the excavation, groundwater level or its slope. All the variables used for the analysis are presented in Table 1.

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

No.	Variable	Variable description	Units
1	v1	Earthworks	[m^3/h]
2	v2	Duration of works	[h]
3	v3	Average employee experience	[years]
4	v4	Proximity to neighboring buildings	[m]
5	v5	Groundwater level	[m]
6	v6	The depth of the trench	[m]
7	v7	Trench area	[m^2]
8	v8	The slope of the terrain	[%]
9	v9	Temperature	[°C]
10	v10	Equipment failure rate	[%]

On the basis of the performed calculations, the results of which are presented in Table 2, it was found that the dependent variable and all independent variables influencing the value of the dependent variable "earthworks" are characterized by a normal distribution. It is the most common distribution in nature.

The collected data is analyzed in terms of the type of distribution, as some of the computational models used require the determination of the type of distribution of the variable. The most desirable type of variable distribution is the normal distribution. In order to establish the normality of the distribution, the Shapiro–Wilk test [35] is performed. The obtained values of the "W" coefficient are compared with the critical values of the test, which for 32 observed data amounts to $W_{\text{kr}} = 0.93$. All variables acquired the preferred normal distribution.

Linear correlation determines the degree of proportional relationship between the values of two variables. It is important to check that there is no correlation between the variables, as this may lead to erroneous results and distortions in the regression equation. Correlations above 0.8 are considered to be very high and are the basis for the elimination of one of the variables between which it occurs.

The correlation of the dependent and independent variables was calculated and no correlations were found that could cause the rejection of individual independent variables.

A forecast is an attempt to predict future events on the basis of an analysis of past events. In the MMSM method, the prediction is made by a regression equation, which is determined by a number of computational methods, from which the method with the best assessment of the goodness of fit of the model, correctness of prediction and the lowest error is then selected. The prognostic methods used in the modeling were:

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

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 – 4 pos.	Yes – 4 pos.	5.43	Not correct
GAM	No	No	1.65	Correct
MARS	Yes – 2 pos.	Yes – 2 pos.	5.58	Not correct
SVM	Yes – 2 pos.	Yes – 2 pos.	5.84	Not correct
SNN	No	No	1.67	Correct

The results (Figure 3) for the best prognostic model for the determination of the $v1$ variable, which is the GAM method, are presented below.

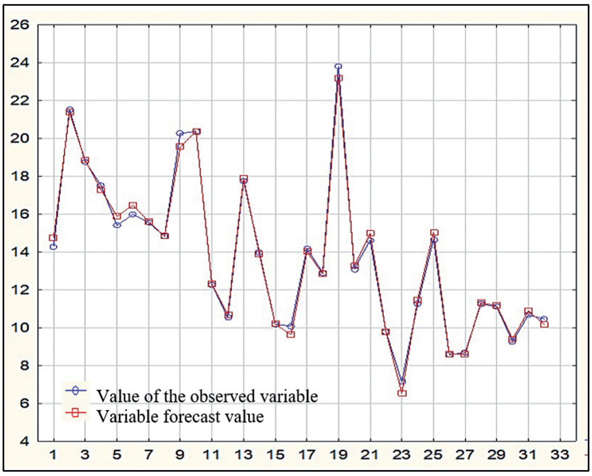

Fig. 3. Graph of observed and forecasted values

Regression equation Eq. (3.1):

$$v1 = 2.381059 - 0.214935 \cdot v2 - 0.092128 \cdot v3 - 0.000470 \cdot v4 - 0.032893 \cdot v5 + 3.383685 \cdot v6 + 0.060130 \cdot v7 - 0.012146 \cdot v8 \tag{3.1}$$

Based on the regression equation for determining the $v1$ variable (process P1), the duration of the processes on the new investment for which the schedule is prepared was generated. The remaining processes were determined by the MMSM method, similarly to the P1 process, for each of the 10 sectors. The summary of the calculation results is presented in Table 3.

Table 3. Summary of the forecast duration of P1–P5 processes in S1–S10 sectors for a new investment – PTCM I

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 I – Results and discussion

The case of building a housing estate described in the paper has been divided into smaller sectors and the works that will be carried out there. The implementation times of individual construction processes were determined using the MMSM method, which are part of the input data for the PTCM I method. The PTCM I schedule and its graphical representation in the form of a cyclogram are presented on Figures 4 and 5.

PTCM I		Processes									
		P1		P2		P3		P4		P5	
Sectors	S1	0,0	10,0	10,0	32,4	46,0	66,2	73,0	91,6	91,6	124,6
		10,0		22,4		20,2		18,6		33,0	
		1,1	1,1	2,5	0,0	2,2	3,0	2,0	3,8	3,6	3,8
		8,9	11,1	32,4	32,4	63,2	69,2	87,8	95,4	120,8	128,4
	S2	10,0	18,1	32,4	58,0	66,2	88,2	91,6	112,1	124,6	155,4
		8,1		25,6		22,0		20,5		30,8	
		0,9	1,4	2,8	2,8	2,4	3,9	2,3	4,5	3,4	5,1
		16,7	19,5	55,2	60,8	84,3	92,1	107,6	116,6	150,3	160,5
	S3	18,1	26,2	58,0	78,2	88,2	108,3	112,1	136,3	155,4	190,8
		8,1		20,2		20,1		24,2		35,4	
		0,9	1,7	2,2	3,6	2,2	4,5	2,7	5,2	3,9	6,4
		24,5	27,9	74,6	81,8	103,8	112,8	131,1	141,5	184,4	197,2
	S4	26,2	35,4	78,2	101,2	108,3	129,8	136,3	157,8	190,8	221,8
		9,2		23,0		21,5		21,5		31,0	
		1,0	2,0	2,5	4,4	2,4	5,0	2,4	5,7	3,4	7,3
		33,4	37,4	96,8	105,6	124,8	134,8	152,1	163,5	214,5	229,1
	S5	35,4	44,8	101,2	123,3	129,8	152,8	157,8	177,1	221,8	256,9
		9,4		22,1		23,0		19,3		35,1	
		1,0	2,2	2,4	5,0	2,5	5,6	2,1	6,1	3,9	8,2
		42,6	47,0	118,3	128,3	147,2	158,4	171,0	183,2	248,7	265,1
	S6	44,8	55,3	123,3	145,7	152,8	173,7	177,1	195,7	256,9	290,8
		10,5		22,4		20,9		18,6		33,9	
		1,2	2,5	2,5	5,6	2,3	6,1	2,0	6,4	3,7	9,0
		52,8	57,8	140,1	151,3	167,6	179,8	189,3	202,1	281,8	299,8
	S7	55,3	64,2	145,7	170,7	173,7	195,7	195,7	216,6	290,8	321,6
		8,9		25,0		22,0		20,9		30,8	
		1,0	2,7	2,8	6,2	2,4	6,6	2,3	6,8	3,4	9,7
		61,5	66,9	164,5	176,9	189,1	202,3	209,8	223,4	311,9	331,3
	S8	64,2	72,3	170,7	190,9	195,7	214,7	216,6	240,8	321,6	355,0
		8,1		20,2		19,0		24,2		33,4	
		0,9	2,8	2,2	6,6	2,1	6,9	2,7	7,3	3,7	10,3
		69,5	75,1	184,3	197,5	207,8	221,6	233,5	248,1	344,7	365,3
	S9	72,3	80,3	190,9	214,1	214,7	236,2	240,8	262,8	355,0	386,0
		8,0		23,2		21,5		22,0		31,0	
		0,9	3,0	2,6	7,1	2,4	7,3	2,4	7,7	3,4	10,9
		77,3	83,3	207,0	221,2	228,9	243,5	255,1	270,5	375,1	396,9
	S10	80,3	90,2	214,1	236,2	236,2	259,2	262,8	282,1	386,0	421,1
		9,9		22,1		23,0		19,3		35,1	
		1,1	3,2	2,4	7,5	2,5	7,7	2,1	8,0	3,9	11,5
		87,0	93,4	228,7	243,7	251,5	266,9	274,1	290,1	409,6	432,6

Fig. 4. PTCM I schedule

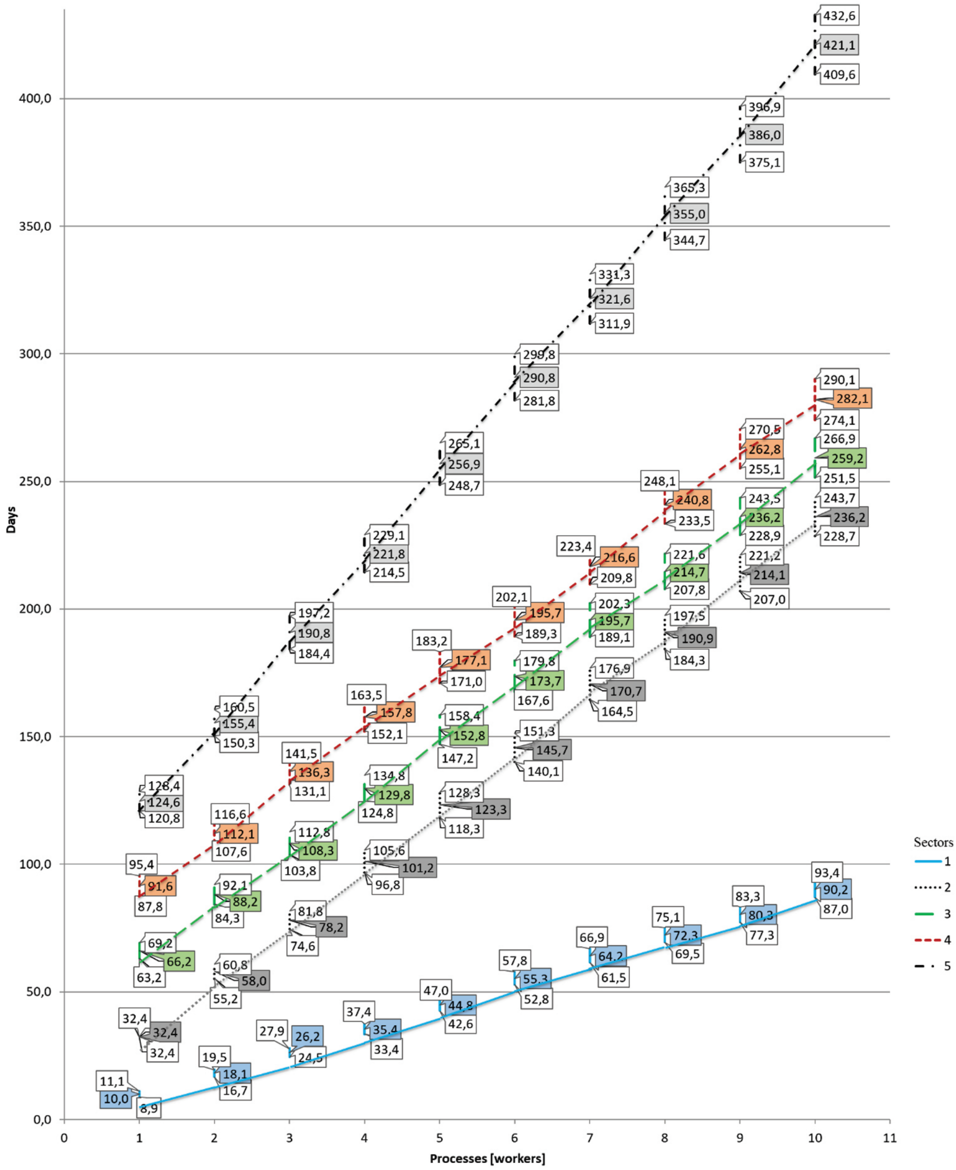

Fig. 5. The PTCM I cyclogram

PTCM I results were compared with forecasts based on traditionally used methods for determining the duration of construction works (Table 4).

Comparing the duration of the investment (Table 4) with the actual time of its duration, it can be concluded that the PTCM I scheduling method is correct and can be used to forecast the time of construction projects. The advantage of the PTCM I method is that

Table 4. Summary of the forecast

The method of determining the schedule	The total duration of the investment [working – days]
PTCM I	Minimal: 409.6 Most likely: 421.1 Maximum: 432.6
TCM I + KNR input data	370.0
The duration of the investment planned by the designer	385.0
Real time	419.0

the forecast of the investment completion time is determined by the range of estimated dates, not as an exact date. The traditional TCM I scheduling approach is based on average values (coding times) that need to be updated as construction technology, equipment and tools evolve. However, construction practice shows that this assumption is far from reality. Construction processes are very sensitive to changes in the factors they depend on. Hence, forecasting, which determines the most probable time of construction works and its prognostic minimum and maximum value, may be the preferred scheduling method.

The PTCM I method determines the range of possible project implementation times with the most probable, minimum and maximum time. Knowing these values, it is also possible to take into account the preferences of the decision maker. The decision maker can be a contractor who has full information about the available equipment, the processing capacity of his employees, etc., therefore, based on possible profits and losses, he can choose a specific value from the given range. Moreover, choosing a value close to the minimum time must take into account possible penalties for delays, and choosing a value close to the maximum time – lack of competitiveness against other companies and the possibility of not receiving the order.

The real time of the investment is within the time range generated in the PTCM I method. The time based on data from KNR catalogs is the shortest and the most different from the real value. The company carrying out the investment has also defined its own duration. Based on many years of experience, the designer estimated the time of individual processes and, consequently, the duration of the entire project. This time is closer to real time than TCM I+KNR, but requires great skill and knowledge of the person who prepares the schedule.

5. Conclusions

It is impossible to predict the occurrence of random phenomena during the construction implementation. They may or may not occur. However, mathematical sciences show that it is possible to successfully forecast random phenomena and their effects. In the case of implementation of construction investments and preparation of a schedule or cost estimate of works, it is necessary to take into account the occurrence of various random events affecting the documents being prepared. The traditional computational approach to the duration of the construction process or its costs, unfortunately, does not take into account random factors, which is often far from the actual results.

Improvements have been made to the traditional scheduling methodology building on the TCM I and MMSM methodology. In addition, standard deviations of individual construction processes (constituting a statistical inference about the probability of the results) were used. Thanks to this, not one specific duration of the investment was determined (which is not a good practice in construction), but three values of the time of performing a given activity (minimum, most probable and maximum). This allowed for a more precise definition of the duration of individual tasks and the project completion date.

The results of the total investment times, calculated using various methods, are summarized in Table 4. It shows that the best forecasting results compared to real time were achieved with the PTCM I method. The developed calculation application of the PTCM I method in the popular and well-known Microsoft Excel program gives the possibility of popularizing the developed methodology.

Further research will focus on the analogous development of the implementation times of the TCM II and TCM III methods and on the search for more effective methods of determining the input data or the risk of investment failure. Another direction of further research may be the search for methods of designing schedules that will maximize the use of resources and optimize the implementation time investment.

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Harmonogramowanie probabilistyczną Metodą Sprzężeń Czasowych I (PTCM I) – założenie ciągłości pracy brygad roboczych

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

Streszczenie:

Modelowanie i analiza numeryczna projektowania konstrukcji budowlanych, ich technologii, organizacji i metod zarządzania procesami budowlanymi są przedmiotem pracy wielu naukowców w Polsce. Projektanci harmonogramów starają się jak najlepiej odzwierciedlić realia projektów budowlanych dostępnymi metodami, choć procedura ta nie zawsze jest skuteczna. Jedną z metod planowania jest metoda Time Coupling Methods (TCM), którą można udoskonalić za pomocą predykcyjnych czasów trwania procesów konstrukcji wielowymiarowej metody modeli statystycznych (MMSM) i odchyleń standardowych. Opracowano nową metodę szeregowania w podejściu probabilistycznym – Probabilistic Time Couplings Method I (PTCM I). W PTCM I praca jest zorganizowana w taki sposób, aby zachować ciągłość pracy pracowników, gdyż przestoje pracowników są niekorzystne i kosztowne. Prognozowano łączny czas trwania nowej inwestycji i porównano ją z innymi metodami harmonogramowania oraz z czasem rzeczywistym po jej zakończeniu. Wyniki jednoznacznie pokazują, że opracowaną metodykę można z powodzeniem zastosować w harmonogramowaniu robót budowlanych.

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