Scheduling Construction Processes Using the Probabilistic Time Coupling Method III

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Abstract. The paper presents modelling of construction project schedules using new method: Probabilistic Time Coupling Method III (PTCM III). It is presented in EXCEL application with a description of the calculation scheme. The correctness of the PTCM method was checked by comparison with the results obtained for the same data in the Risky Project Professional (RPP) program. As a result of the analysis, it was found that the PTCM III method is the closest to the RPP, taking into account the beta distribution of the probability of times. Mean absolute percentage error (MAPE) is less than 1%, so it can be assumed that the matching of these two calculation methods is excellent.

1. Introduction
Scheduling construction processes is an integral part of the BIM 7-D methodology. The paper presents modelling of construction project schedules using the TCM III (Time Coupling Method) method in probabilistic approach of PTCM III. The application in the EXCEL program is presented along with a description of the calculation scheme.

The data for the calculations was obtained using the Multivariate Method Statistical Models MMSM. The PTCM III (Probabilistic Time Coupling Method) is a novelty and has not been analyzed so far. The correctness of the method was checked using the Risky Project Professional computer program. Analogical data was introduced for the calculations. Compliance was observed.

2. Building Information Modelling BIM 7-D
Building Information Modelling (BIM) is a digital representation of the physical and functional characteristics of an object. BIM is a common resource of knowledge - information about the object constituting a credible basis for making decisions during its life cycle, i.e. from the earliest concept to demolition (definition of the National BIM Standard - United States). The 7D-BIM methodology uses many computational methods and computer programs. Table 1 [1] presents a summary of individual stages of calculations along with the proposed computer programs and the scope of activities. One of the elements of 5-D BIM is the analysis of schedules by the Time Coupling Method. The article proposes the use of the PTCM III with probabilistic data.
Table 1. The list of computational and research methods 7D-BIM and scope of activities [1]

| Stage | BIM     | Computer program                          | Scope                                                                 |
|-------|---------|-------------------------------------------|----------------------------------------------------------------------|
| 1     | 1D-BIM  | -                                        | -Engineer's journal - project assumptions, information on planning, ground, technical, technological and environmental conditions. |
|       |         | Structural calculation programs           | -Calculation, construction dimensioning - checking the limit states of construction elements. |
|       |         | 3D scanner, thermal imaging camera        | -With regard to existing facilities, the execution of inventory, technical condition assessment as well as in-situ and laboratory tests (humidity, salinity, strength), thermal imaging studies. |
| 2     | 2D-BIM  | Catalogs, technical card, declarations of performance Autocad | -Construction works technology - selection of construction technology, detailed selection of building materials, technical specifications, analysis of the possibilities of construction load deadlines, analysis of technological breaks. |
|       |         | -Two dimensional drawings.                |                                                                     |
| 3     | 3D-BIM  | Revit, Tekla                               | -Three dimensional drawings, average cost estimate.                 |
| 4     | 4D-BIM  | Norma Pro                                 | -Minimum, average and maximum cost estimates - analysis of the possibility of shaping labor costs, number of working hours, costs of materials and equipment, indirect costs and profit. |
|       |         | Excel                                     | -Transition from 4D to 5D - selection of the number of employees, work teams, work cycle. |
| 5     | 5D-BIM  | StatSoft Statistica Microsoft Project     | -Time Coupling Method - sorting of tasks: continuity of work of brigades TCM I, continuity of work in sectors TCM II, minimization of implementation time TCM III. |
| 6     | 6D-BIM  | Risky Project                             | -MMSM method - process time forecasting based on surveys or statistical data: minimum, average, maximum time, computation by multiple regression methods, MARS, GAM, neural networks and ARIMA, forecast error analysis. |
|       |         |                                          | -Moderate schedule - employee work sheets, dependency network, Gantt chart, work progress tracking. |
|       |         |                                          | -Risk analysis - determining risks and assigning them values, preparing risk matrices, drawing up risk and cost risks, cost and time analysis, cash flow, assigning time and costs to probabilistic values, preparing a Gantt chart containing risks and probabilistic values, task simulations for duration, end date and cost with different probabilities. |
| 7     | 7D-BIM  | -Technical inspections of facilities, expertise, analysis of object durability, plans for repairs, documentation of repairs, financial documentation. |

3. Methods using for calculations

3.1. Time Coupling Methods

Time Coupling Methods (TCM) allow the performing of schedules which take into account the technological and organizational limitations. These methods include: TCM I – continuity of work on the working plots of land; TCM II – continuity of work of the construction brigades; TCM III – minimizing the duration of the project implementation. TCM is based on algorithmic notation which enables the automation of calculations and the introduction of numerous limitations. Traditional methods of scheduling do not provide the possibility to automatically prioritize tasks. In these methods, tasks are prioritized intuitively based on engineering knowledge. TCM was devised and developed by Professors V. Afanasjew, [2-5], J. Mrozowicz [6-7], and Z. Hejducki [8-10]. Specific methods of flow nature are involved in TCM application. Time coupling methods TCM methods were developed by [12-16] in many scientific works.
3.2. Multivariate Method of Statistical Models

Multivariate Method of Statistical Models MMSM developed by [17] is based on computational analysis of prognostic methods: Multiple Regression, Multivariate Regression Analysis, Generalized Additive Models, Neural Networks, Support Vectors Machine. As a result of calculations by different methods, many prognostic models are obtained, from which the model with the smallest prognostic error is selected for use. It is possible to enter into the calculations a very large number of factors that are assigned numerical or linguistic values. The scope of the method includes defining the prognostic problem, preparation of data for calculations, prognostic calculations with analysis and comparative assessment of obtained models using the average absolute error of MAPE and autocorrelation and partial autocorrelation of the residual series. In the presented work, MMSM was used to determine the duration of construction processes and standard deviations of these times (table 2). The above-described methods of forecasting the time of construction processes’ implementation enable to create schedules that take into account actual and non-averaged conditions.

3.3. Risky Project Professional

Risky Project is advanced project risk management software with integrated risk analysis. Most projects contain many uncertain parameters: task duration, start and finish times, uncertainties in costs and resources, uncertainties in quality, safety, technology, and others. Risky Project analyzes project schedules with risks and uncertainties, calculates the chance that projects will be completed within a given period of time and budget, ranks risks, and presents the results in formats that are easy to read and understand. The Monte-Carlo simulation provides the project manager with realistic forecasts of the duration of the project. The Critical Path method and other deterministic planning techniques give optimistic forecasts for the completion of the project. The main reason for these optimistic completion values is the deviation resulting from the exclusion of other potentially critical paths during analysis and the use of deterministic values. The proposed methods remove this tendency and provide the decision-maker with information on the likely distribution that represents volatility over time, and also the criticality of each activity in the schedule. The result is a procedure that is both economical and impartial presenting information to the decision maker [18-19].

3.4. Excel computational application Beta Pert

The EXCEL Beta Pert application is a special tool enabling determination of alpha and beta coefficients for the Beta probability density distribution. The calculations are performed using the iteration method using Monte Carlo simulation. The application was made by Rogalska in 2016.

3.5. Probabilistic Time Coupling Method

The calculation application in the MS Excel program has been developed as a tool allowing to execute schedules including probabilistic times of building processes. Placing data in the input worksheet requires knowledge of the most likely process execution time and standard deviation of a series of this process. The most likely time is the calculated MMSM method. The input worksheet is presented on table 2.

| Table 2. Input worksheet PCTM |
|-------------------------------|
| SECTOR | 1 | σ₁₁ | ... | ... | tj | σj | ... | ... | tm | σm |
| ....   | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... |
| i      | ti | σi | ... | ... | tj | σj | ... | ... | tm | σm |
| ...    | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... |
| n      | tn | σn | ... | ... | tj | σj | ... | ... | tm | σm |
The calculation sheet is prepared in the following way table 2. In order to be able to take into account standard deviations, it was necessary to apply the formula to the sum of standard deviations of two independent random variables:

$$\sigma_x + \sigma_y = \sqrt{\sigma_x^2 + \sigma_y^2}$$  \hspace{1cm} (1)

A single segment corresponding to the work of one brigade on one plot takes the form shown in table 3.

Table 3. A single segment in calculation worksheet of PTCM

| $t_{ij}^{es}$ | $S_i$ | $P_j$ | $\sigma_{ij}^{esu}$ | $t_{ij}^{ef}$ | $\sigma_{ij}^{efu}$ | $t_{ij}^{ls}$ | $\sigma_{ij}^{lbu}$ | $t_{ij}^{lf}$ | $\sigma_{ij}^{lfu}$ |
|--------------|------|------|---------------------|--------------|---------------------|--------------|---------------------|--------------|---------------------|
| $\sigma_{ij}^{efu}$ | $t_{ij}$ | $\sigma_{ij}$ | $\sigma_{ij}^{esu}$ | $\sigma_{ij}^{efu}$ | $\sigma_{ij}^{lbu}$ | $\sigma_{ij}^{lbu}$ | $\sigma_{ij}^{lfu}$ | $\sigma_{ij}^{lfu}$ |
| $t_{ij}^{es}$ | $t_{ij}^{ef}$ | $t_{ij}^{ls}$ | $t_{ij}^{lf}$ |

where:

- $t_{ij}^{es}$ - time of early start of work,
- $t_{ij}^{ef}$ - time of early finish of work,
- $t_{ij}^{ls}$ - time of late start of work,
- $t_{ij}^{lf}$ - time of late finish of work,
- $\sigma_{ij}^{esu}$ - standard deviation from early start of work – up,
- $\sigma_{ij}^{efu}$ - standard deviation from early finish of work – bottom,
- $\sigma_{ij}^{lbu}$ - standard deviation from late finish of work – up,
- $\sigma_{ij}^{lfu}$ - standard deviation from late finish of work – bottom.

Figure 1. Calculation worksheet of PTCM III

Where:

$$t_{ij}^{es} = \max\left\{t_{ij}^{es|j}, t_{ij}^{es|i}\right\}$$  \hspace{1cm} (2)
\[ t_{ij}^f = \begin{cases} t_{i1} + \ldots + t_{i(j-1)} + \ldots + t_{ij} + \sigma_{ij}^{\text{su}} & \text{when } t_{i(j-1)}^f \geq t_{ij}^f \\ t_{i1} + \ldots + t_{i(j-1)} + \ldots + t_{ij} + \sigma_{ij}^{\text{sb}} & \text{when } t_{i(j-1)}^f < t_{ij}^f \end{cases} \]  \tag{3}

\[ \sigma_{ij}^{\text{su}} = \sqrt{\sigma_{i1}^2 + \ldots + \sigma_{i(j-1)}^2 + \ldots + \sigma_{ij}^2 + \sigma_{ij}^2} \]  \tag{4}

\[ \sigma_{ij}^{\text{sb}} = \sqrt{\sigma_{(i+1)j}^2 + \ldots + \sigma_{(j-1)j}^2 + \ldots + \sigma_{ij}^2} \]  \tag{5}

\[ \sigma_{ij}^{\text{esu}} = \sqrt{\sigma_{i1}^2 + \ldots + \sigma_{i(j-1)}^2 + \ldots + \sigma_{ij}^2 + \sigma_{ij}^2} \]  \tag{6}

\[ \sigma_{ij}^{\text{esb}} = \sqrt{\sigma_{(i+1)j}^2 + \ldots + \sigma_{(j-1)j}^2 + \ldots + \sigma_{ij}^2} \]  \tag{7}

\[ t_{ij}^f = \begin{cases} t_{i(j+1)}^f - (t_{i(j+1)} + \ldots + t_{i(j+1)} + \ldots + t_{ij} + \sigma_{ij}^{\text{fu}}) & \text{when } t_{i(j+1)}^f \leq t_{i(j+1)}^f \\ t_{i(j+1)}^f - (t_{i(j+1)} + \ldots + t_{i(j+1)} + \ldots + t_{ij} + \sigma_{ij}^{\text{fb}}) & \text{when } t_{i(j+1)}^f > t_{i(j+1)}^f \end{cases} \]  \tag{8}

\[ t_{ij}^f = \min \left\{ t_{ij}^f, t_{ij}^f \right\} \]  \tag{9}

4. Scheduling of construction processes using Probabilistic Time Coupling Method

Scheduling of construction processes using PTCM III consists in inserting probabilistic data into the spreadsheet, figure 2. The result is presenting information about the probability of project finish time to the decision.

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**Figure 2.** Block diagram of calculations using the PTCM method
5. Case study – PCTM III application (Probabilistic Time Coupling Method)

5.1. Step 1 - measurements of construction process times at the construction site, it can be used numerical and linguistic impact factors. Measurements of execution times of 3 construction processes on site were made.

5.2. Step 2 - calculation by Multivariate Method of Statistical Models MMSM I

The basis for calculations is a database, consisting of 30 cases of implementation of three construction processes (ranked in technological order) on three subsequent sectors. The analysis of the data began with determining the normality of the distributions. For this purpose, the Shapiro-Wilk test was performed. The critical value for \( \alpha = 0.05 \) was checked, it is equal to \( w_{0.05} = 0.927 \). Table 4 presents the descriptive characteristics and results of the Shapiro-Wilk test. For the first sector as well as for the remaining cases, normal distribution was found. Table 4 lists the minimum and maximum times for construction works in days, for each sector \( S_1, ..., S_3 \) and processes \( P_1, ..., P_3 \), respectively. Table 6 shows the average values of process times for sectors and their standard deviations. These data form the basis for further calculations.

Table 4. Descriptive characteristics of individual processes on the example of sector 1

| Process | Sector 1 | Sector 2 | Sector 3 |
|---------|----------|----------|----------|
| P1      | 30       | 30       | 30       |
| P2      | 30       | 30       | 30       |
| P3      | 30       | 30       | 30       |

Table 5. The minimum and maximum values of process times in sectors

| Process | Sector 1 | Sector 2 | Sector 3 |
|---------|----------|----------|----------|
| P1      | 9.00     | 11.70    | 15.75    |
| P2      | 14.50    | 18.85    | 25.38    |
| P3      | 19.50    | 25.35    | 34.13    |
Table 6. Output - the average time duration of the processes on the sectors and their standard deviations

| Process | Sector 1 | | Sector 2 | | Sector 3 |
|---------|----------|----------|----------|----------|----------|
|         | Time $t_{ij}$ | $\sigma(t_{ij})$ | Time $t_{ij}$ | $\sigma(t_{ij})$ | Time $t_{ij}$ | $\sigma(t_{ij})$ |
| P1      | 12.30    | 1.15     | 15.99    | 1.50     | 21.53    | 2.02     |
| P2      | 17.07    | 1.32     | 22.19    | 1.72     | 29.87    | 2.67     |
| P3      | 21.38    | 0.58     | 27.79    | 0.75     | 37.42    | 1.54     |

5.3. **Step 3 - determination of alpha and beta coefficients for beta distribution**

Alpha and beta coefficients for beta distribution were determined using Excel computational application Beta Pert. Calculations based on minimum, average and maximum value, standard deviation of construction processes.

Table 7. Alpha and beta coefficients for beta distribution

| Process | Sector 1 | | Sector 2 | | Sector 3 |
|---------|----------|----------|----------|----------|----------|
|         | $\alpha$ | $\beta$ | $\alpha$ | $\beta$ | $\alpha$ | $\beta$ |
| P1      | 2.99     | 3.01     | 2.99     | 3.01     | 2.99     | 3.01     |
| P2      | 3.07     | 2.93     | 3.07     | 2.93     | 3.07     | 2.93     |
| P3      | 2.77     | 2.23     | 2.77     | 2.23     | 2.77     | 2.23     |

5.4. **Step 4 - calculation by PTCM Probabilistic Time Coupling Method**

The input sheet in Excel PTCM is shown in table 8. The value of the expected time of processes and their standard deviations from MMSM were used for the calculations.

Table 8. Input worksheet of PTCM

| SECTOR | PROCESS | P1 | | PROCESS | P2 | | PROCESS | P3 |
|--------|---------|----|----------|----|----------|----|----------|----|
| S1     | Time $t_{ij}$ | $\sigma(t_{ij})$ | Time $t_{ij}$ | $\sigma(t_{ij})$ | Time $t_{ij}$ | $\sigma(t_{ij})$ |
| S2     | 12.30    | 1.15     | 15.99    | 1.50     | 21.53    | 2.02     |
| S3     | 17.07    | 1.32     | 22.19    | 1.72     | 29.87    | 2.67     |

Figure 4. Screen shot of calculation worksheet of PTCM III

The minimum value of project is $120.8 - 3.7 = 117.10$ days and maximum value is $120.8 + 3.7 = 124.5$ days, standard deviation of project is equal 3.7 days. The probability of finish time of project was established using Beta Pert application, Figure 4. The results of calculations are presented in table 9.
5.5. Step 5 - checking and comparison of calculation results

In order to compare the obtained results with the PTCM III method, calculations were made in the Risky Project Professional program. Three variants of calculations were adopted. It was assumed that probability density distributions of execution time of individual processes are normal, triangular and beta. The probability of project execution time for these three cases was calculated. Figure 5 shows screen shots from the Risky Project Professional (RPP) program. In table x, the calculated completion times of the project with different probabilities of occurrence of the event are presented.

Table 9. The probability of finish time of project PTCM III

| Distribution | PROBABILITY |
|--------------|-------------|
|              | 0.05 | 0.675 | 0.800 | 0.900 | 0.990 |
| PTCM         | 117.10 | 120.10 | 120.70 | 121.40 | 123.60 |

Table 10. The probability of finish time of project PTCM III and RRP normal, RRP triangular and RRP beta

| Distribution  | Probability |
|---------------|-------------|
|               | 0.05 | 0.675 | 0.800 | 0.900 | 0.990 |
| PTCM          | 117.10 | 120.10 | 120.70 | 121.40 | 123.60 |
| RPP Normal    | 118.85 | 123.00 | 125.23 | 127.05 | 130.79 |
| RPP Beta      | 116.00 | 120.07 | 121.41 | 122.37 | 125.63 |
| RPP Triangle  | 118.85 | 122.04 | 123.83 | 125.09 | 128.89 |
5.6. Step 6 - analysis of calculation results determination of the construction project execution time with a probability of 5% and 95%

On the basis of the data from table 9, the probability diagram of completing the project for 4 cases (PTCM III, normal, triangular and risky Risky Project Professional distributions) was taken.

![Figure 7](image)

**Figure 7.** The probability diagram of completing the project - screenshot of calculations

Calculated probabilities were combined with curves, figure 7. To determine the differences between the curves PTCM III, RRP normal, RRP triangular and RRP beta, Mean Absolute Percentage Error calculations were used, table 10.

**Table 11.** Compilation of calculated MAPE errors between PTCM III, normal RPP, RPP triangular and RPP beta

| MAPE     | PTCM III | Normal | Beta    | Triangle |
|----------|----------|--------|---------|----------|
| PTCM III | 0        | 4.599491 | 1.716518 | 3.5647447 |
| RPP normal | 3.478388 | 0      | 3.103247 | 0.9787682 |
| RPP beta  | 0.804988 | 3.103247 | 0       | 2.1935662 |
| RPP triangle | 2.528779 | 0.978768 | 2.193566 | 0        |

The calculations show that the results obtained using the PTCM III method are very similar to the results of the obtained RPP beta. The MAPE error is 0.804988%, it is less than 1%, which indicates that these curves are perfectly matched. The results of RPP normal and RPP triangle calculations are close to each other MAPE = 0.978768% and differ significantly from RPP beta and PTCM III MAPE from 3.103247% to 4.599491%. However, RPP normal and RPP triangle are close to each other and MAPE = 0.978768%.

6. Conclusion

Scheduling construction processes is an integral part of the Building Information Management BIM 7-D methodology. The paper presents modelling of construction project schedules using the Time Coupling Method (TCM) in a probabilistic approach. It is presented in EXCEL application with a description of the calculation scheme. The data for the calculations was obtained using the multivariate method of the WMMS statistical models. The correctness of the PTCM method was
checked by comparison with the results obtained for the same data in the Risky Project Professional program. In this program the distributions of time probability functions as beta, normal and triangular were assumed. The MAPE error was calculated by comparing the results obtained from the PTCM calculation and assuming the probability distributions of times: normal, triangular and beta. As a result of the analysis, it was found that the PTCM method is the closest to the Risky Project Professional (RPP), taking into account the beta distribution of the probability of times. Mean absolute percentage error (MAPE) less than 1%, it can be assumed that the matching of these two calculation methods is excellent. The PTCM method is very simple and fast to use. The calculation sheet in the EXCEL program is structured in such a way that the user enters only the duration and standard deviation of the processes. In the MPC program, there is a need to assign the probability density distribution to each work task and to calculate the alpha and beta coefficients for the beta distribution. The PTCM III (Probabilistic Time Coupling Method III) is a novelty and has not been analyzed so far.

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