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Research paper

Application of the Randomized Earned Value Method to assess the advancement of the construction of the office building under the unstable implementation conditions

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Abstract: The REVM method is a modernized option of classical EVM method. The new method has been developed for applying in unstable condition of works implementation. When the works can be accidentally disturbed and the impact of random disruption factors on course and results of works must be taken into consideration. Next, Randomized Budgeted Duration to Completion and Randomized Budgeted Cost to Completion that is duration and cost of works remaining to execution after each inspection, as well as the Randomized Budgeted Duration at Completion and Randomized Budgeted Cost at Completion that is duration and cost of all works of the project completion after the site inspection. Moreover, the risk of durations and costs overrun of works are evaluated. It is important that input data required for the REVM method are the similar and are measured in the same way as in typical control of advancement works. But results of the application consist new decision information. Control of the investment under deterministic conditions, without taking into account the risk of disruptions, resulted in a final deviation from the planned budget of over 7%, and from the planned completion of the investment by almost 12%. Without analysing the factor related to disruptions at the investment implementation stage, the material and financial schedule was completely outdated. On the other hand, when controlling the investment under risk conditions and introducing organizational and technological changes adequate to the inspection reports, the final deviation from the planned budget was less than 2%, and slightly more than 2% from the planned completion date. Researches confirm that the results received by using the REVM method well reflect real situation of works implementation.

Keywords: construction investment, duration, cost, risk, randomization, project management

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1. Introduction

The Randomized Earned Value Method (REVM) it is a new version of the classical EVM method. It has been developed for operational control and assessment the advancement of construction works under the unstable implementation conditions.

The article below is an extension, supplement by practical application of the conducted research, the theoretical (mathematical) and descriptive part of which with a pilot study on the investment are presented in the article: "Randomized Earned Value Method for the rolling assessment of construction projects advancement" in 2022 [1].

Investors and contractors regularly face construction delay and cost overrun problems, many of which are likely to have been predictable and avoidable [2, 3]. The Earned Value Method (EVM) has been played an important role in the investment control process, but this really concerns relatively flat implementation conditions. [4–9]. In EVM approach quantity survey and bill of quantities of works as well as incurred costs and cost estimate of works are analysed in deterministic manner [10, 11]. Such analysis and description of the situation, when random factors can forcefully disrupt the works execution, do not guarantee apt assessment of cost and time of the project. Simply, deterministic analysis is overly simplified for unstable conditions because not all crucial disruption factors are taken into consideration. Consequently, there is a risk that revised payments and improved schedule of works can be incorrectly determined, so, lags of payments and schedule delays of the project are very likely. Therefore, in the case of randomly altering of implementation conditions, the quantities BCWP and ACWP should be analysed from the viewpoint of probabilistic consideration [5, 12–14, 16]. Then, after a site inspection and measurement of actual state of works, there would be a greater chance to project acceptable future costs and durations of the project that is, values comparable to those achieved in future during works execution [17–21]. In such situation, for the project cost and time analysis in a stage of implementation, it is proposed to apply the Randomized Earned Value Method (REVM) as EVM method enhancement. However, the REVM can be also used in the deterministic conditions similarly as EVM. But, in probabilistic situations the REVM is better because it is used with new data randomization procedure that allow to take account random disruption of works. The method allows to track the project past performance until the term of site inspection and enables projection future random performance until the random term of project completion. In this way, the identified and randomized data enables systematic analysis and assess past and projected the future real scope, schedule, and cost of works. These allow to improve process of operational planning and reduces or eliminate a lot of issues arising out of schedule and cost overruns. For this purpose, using the REVM method, periodic site inspections are organized, quantity surveys are realized, and allocation of incurred costs are compiled. In this way constant values of individual quantities are determined according to the design documentation and floating temporary values that are measured and estimated on the site construction. To take account of the impact of disturbances on the course and results of the works, these quantities must be randomized. In the randomization process, constant values and floating temporary values are comparatively analysed and random variables of individual quantities are defined. In this way the random values of duration and cost of works are determined. Respectively to these values Actual Duration of Work Performed (ADWP) and fixed Budgeted Duration of Work Scheduled (BDWS) as well as random Actual Cost of Work Performed (ADWP) and fixed Budgeted Cost of Work Scheduled (BDWS) are identified.

Then the differences between ADWP and BDWS as well as ACWP and BCWS are calculated. For the differences values of mass of time cost variation and standard deviations are estimated.

According to these values coefficients of time optimism and coefficients of time pessimism as well as coefficients of cost optimism and coefficients of cost pessimism are estimated. Using these coefficients, random durations and random costs of individual works remained to execution until works completion, are calculated. Applying these random quantities for works remaining to project completion general predicted indicators are being estimated, including: Randomized Budgeted Duration to Completion (RBDtoC) and Randomized Budgeted Cost to Completion (RBCtoC), that is duration and cost of works remaining to project completion after site inspection. For these general indicators, the risk of duration exceeding, and the risk of cost overrun of works remaining to project completion are estimated. Likewise, Randomized Budgeted Duration at Completion (RBDtoC) and Randomized Budgeted Cost at Completion (RBCatC), that is overall duration and total cost of project works after the site inspection, are estimated. Similarly, for these global indicators the risk of exceeding overall duration and the risk of overrun total cost of the project are estimated.

Such consideration and calculation are developed for each site inspection. Of course, number of site inspections belong to a size and conditions of the implemented project.

The described manner of such analysis of duration and cost of works, using a simple special procedure of random calculations, has been called randomization.

2. Description of the revm method on the example of the construction of the building office

2.1. The analytical description

Step 1: Identification of the original project implementation data [1]

1. Modelling of the construction object structure technology, that is the construction technology of the object erected within the project:

$$\mathbf{S} = \langle \mathbf{G}, \mathbf{L} \rangle \tag{2.1}$$

where:
$\mathbf{G} = \langle \mathbf{Y}, \mathbf{U}, \mathbf{P} \rangle$ – coherent and a-cyclic unigraph with a single initial node and a single final node that describes interdependence and permissible sequence of the works execution,
$\mathbf{Y} = \{y_1, \ldots, y_i, \ldots, y_k, \ldots, y_m\}$ – set of the nodes of the graph representing events where works begin or end that is, indicates beginning or completing individual works;
$\mathbf{U} = \{u_1, \ldots, u_j, \ldots, u_l, \ldots, u_n\}$ – set of the arcs (arrows) of the graph representing relatively independent works (activities) that are constrained by initial $y_i \in \mathbf{Y}$ and final $y_k \in \mathbf{Y}$ nodes;

$\mathbf{P} \subset \mathbf{Y} \times \mathbf{U} \times \mathbf{Y}$, $\langle y_i, u_j, y_k \rangle \in \mathbf{P}$ – three-term relation that assigns to each arc $u_j \in \mathbf{U}$ the initial node $y_i \in \mathbf{Y}$ and final node $y_k \in \mathbf{Y}$
$\mathbf{L} : \mathbf{U} \to \mathbf{R}^+$ – function defined on the set $\mathbf{U}$ of arcs of the graph $\mathbf{G}$ which describes bill of quantities of works

$$u_j \in \mathbf{U}, \quad l = \{l_1, \ldots, l_j, \ldots, l_n\}.$$

2. Modelling of the construction object performance technology that is, technology of works that are performed within the project:

$$\mathcal{L} = \{\langle \mathbf{H}, \mathbf{K}, \mathbf{T} \rangle, \mathbf{S}\} \tag{2.2}$$

where:
$\mathbf{H} = \{H^1, \ldots, H^r, \ldots, H^S\}$, $H^r = \{1, \ldots, h, \ldots h^r\}$ – set of rational or optimal task teams H^r for works $u_j \in \mathbf{U}^r$ execution, h – rudimentary resources (staff, laborers, tools, machines and etc.),
$\mathbf{T} : (\mathbf{H} \times \mathbf{U}) \to \mathbf{R}^+$ – function defined on the set $\boldsymbol{H}$ of teams H^r and the set $\mathbf{U}$ of works u_j which determines durations t_j of works $u_j \in \mathbf{U}$, $t = \{t_1, \ldots, t_j, \ldots, t_n\}$;
$\mathbf{K} : (\mathbf{H} \times \mathbf{U}) \to \mathbf{R}^+$ – function defined on the set $\mathbf{H}$ of teams H^r and the set $\mathbf{U}$ of works u_j which determines costs k_j of works $u_j \in \mathbf{U}$, $k = \{k_1, \ldots, k_j, \ldots, k_n\}$;

3. Duration at completion (DAC) i.e. the total performance time of the project which is equal the earliest time v_m of completion of all works $u_j \in \mathbf{U}$ executed within the project:

$$t^1 = \sum_{i=1}^{m} v_i \to \min \tag{2.3}$$

under the constraints: $v_k - v_i \geq t_j$ for $u_j \in U$, $j = 1, 2, \ldots, n$; $[ERR : md : MbegChr = 0x2329, MendChr = 0x232A, nParams = 1] \in \mathbf{P}$; $v_i, v_k \geq 0$

4. Budget at completion (BAC) i.e. the total budget allocated to the project:

$$K = \sum_{j=1}^{n} k_j \tag{2.4}$$

Step 2: Planning and organization the inspection of the project implementation [1]
– organizing an inspection team and defining the rules of control,
– determination the dates of rolling inspections: $\boldsymbol{t}^{\mathbf{I}} = \{\boldsymbol{t}^{\mathbf{FI}}, \boldsymbol{t}^{\mathbf{SI}}, \boldsymbol{t}^{\mathbf{TI}}, \ldots\}$, e.g. *Date of the First Inspection* (FI), *Second Inspection* (SI), *Third Inspection* (TI) etc.

Step 3: First step of rolling inspection [1]

1. Quantity survey of works performed:
   – the set $\mathbf{U}^{\mathbf{FI}}$ of works $\boldsymbol{u}_j^{\mathbf{FI}}$ that have been started and partly completed by the date $\boldsymbol{t}^{\mathbf{FI}}$:

$$U^{\mathrm{FI}} = \left\{\ldots, u_f^{\mathrm{FI}}, \ldots, u_j^{\mathrm{FI}}, \ldots\right\} \tag{2.5}$$

   – the set $\mathbf{L}^{\mathbf{AC}}$ of current quantity survey of works $\boldsymbol{u}_j^{\mathbf{FI}} \in \mathbf{U}^{\mathbf{FI}}$ that is the total scope of works $\boldsymbol{u}_j^{\mathbf{FI}}$ performed by the reporting date $\boldsymbol{t}^{\mathbf{FI}}$:

$$L^{\mathrm{AC}} = \left\{\ldots, l_f^{\mathrm{AC}}, \ldots, l_j^{\mathrm{AC}}, \ldots\right\} \tag{2.6}$$

where:
l_j^{AC} – actual quantity survey of part of work u_j^{FI} that has been started and performed by the date t^{FI} (e.g. m^3);

– the set $\mathbf{T}^{\mathbf{AC}}$ of actual duration of works performed (ADWP) that is the total time taken to complete the work $\boldsymbol{u}_j^{\mathbf{FI}}$ as of a reporting date $\boldsymbol{t}^{\mathbf{FI}}$:

$$T^{\mathrm{AC}} = \left\{\ldots, t_f^{\mathrm{AC}}, \ldots, t_j^{\mathrm{AC}}, \ldots\right\} \tag{2.7}$$

$$t_j^{\mathrm{AC}} = l_j^{\mathrm{AC}}\pi_j;\ \text{or}\ t_j^{\mathrm{AC}} = \frac{l_j^{\mathrm{AC}}}{\lambda_j} \tag{2.8}$$

where:
t_j^{AC} – total time spent on part of work u_j^{FI} that has been started and performed by the date t^{FI} (e.g. hours),
π_j – labor consumption (e.g. h/m^3),
λ_j – work productivity (e.g. m^3/h),

– the set $\mathbf{K}^{\mathbf{AC}}$ of actual costs of works performed (ACWP) that is the total cost taken to complete the work $\boldsymbol{u}_j^{\mathbf{FI}}$ as of a reporting date $\boldsymbol{t}^{\mathbf{FI}}$:

$$K^{\mathrm{AC}} = \left\{\ldots, k_f^{\mathrm{AC}}, \ldots, k_j^{\mathrm{AC}}, \ldots\right\} \tag{2.9}$$

$$k_j^{\mathrm{AC}} = \kappa_j l_j^{\mathrm{AC}}\ \text{or}\ k_j^{\mathrm{AC}} = \kappa_j t_j^{\mathrm{AC}} \tag{2.10}$$

where:
k_j^{AC} – total cost spent on part of work u_j^{FI} that has been started and performed by the date t^{FI} (e.g. PLN),
κ_j – piece work or hourly rate paid for performed work u_j^{FI} (e.g. PLN/m^3) or PLN/h,

2. Bill of quantities and cost estimate of works performed:
   – the set $\mathbf{T}^{\mathbf{PV}}$ of budgeted durations of works scheduled (BDWS) that is the total time taken to complete the work $\boldsymbol{u}_j^{\mathbf{FI}}$ as of a reporting date $\boldsymbol{t}^{\mathbf{FI}}$:

$$\mathbf{T}^{\mathrm{PV}} = \left\{\ldots, t_f^{\mathrm{PV}}, \ldots, t_j^{\mathrm{PV}}, \ldots\right\}; \tag{2.11}$$

$$t_j^{\mathrm{PV}} = \pi_j l_j^{\mathrm{PV}};\ \text{or}\ t_j^{\mathrm{PV}} = \frac{l_j^{\mathrm{PV}}}{\lambda_j} \tag{2.12}$$

where:
t_j^{PV} – total time scheduled on part of the work u_j^{FI} that, according to the schedule, should be started and performed by the date t^{FI} (e.g. hours),
l_j^{PV} – bill of quantities of part of the work u_j^{FI} that, according to the schedule, should be performed by the date t^{FI} (e.g. m^3),
π_j – labour consumption (e.g. h/m^3)),
λ_j – work productivity (e.g. m^3)/h)

– the set $\mathbf{K}^{\mathbf{PV}}$ of budgeted costs of works scheduled (BCWS) that is the total cost of the work $\boldsymbol{u}_j^{\mathbf{FI}}$ scheduled as of a reporting date $\boldsymbol{t}^{\mathbf{FI}}$:

$$K^{\mathrm{PV}} = \left\{\ldots, k_f^{\mathrm{PV}}, \ldots, k_j^{\mathrm{PV}}, \ldots\right\}; \tag{2.13}$$

$$k_j^{\mathrm{PV}} = \kappa_j t_j^{\mathrm{PV}} \text{ or } k_j^{\mathrm{PV}} = \kappa_j l_j^{\mathrm{PV}} \tag{2.14}$$

where:
k_j^{PV} – total cost of part of the work u_j^{FI} that, according to the construction works estimate, has been scheduled by the date t^{FI} (e.g. PLN),
κ_j – piece work or hourly rate for performed work u_j^{PV} (e.g. PLN/m^3 or PLN/h,

– the set of budgeted duration of works performed (BDWP) that is the total duration of the work $\boldsymbol{u}_j^{\mathbf{FI}}$ completed/performed as of a reporting date $\boldsymbol{t}^{\mathbf{FI}}$:

$$\mathbf{T}^{\mathrm{EV}} = \left\{\ldots, t_f^{\mathrm{EV}}, \ldots, t_j^{\mathrm{EV}}, \ldots\right\} \tag{2.15}$$

$$t_j^{\mathrm{EV}} = \begin{cases} t_j^{\mathrm{PV}} \text{ when } t_j^{\mathrm{AC}} \geq t_j^{\mathrm{PV}} \\ t_j^{\mathrm{AC}} \text{ when } t_j^{\mathrm{AC}} < t_j^{\mathrm{PV}} \end{cases} \tag{2.16}$$

where:
t_j^{EV} – portion of total time spent on part of work u_j^{FI} that has been started and actually completed by the date t^{FI} (e.g. hours),

– the set of budgeted cost of works performed (BCWP) that is the total cost of the work u_j^{FI} completed/performed as of a reporting date t^{FI} :

$$\mathbf{K}^{\mathrm{EV}} = \left\{\ldots, k_f^{\mathrm{EV}}, \ldots, k_j^{\mathrm{EV}}, \ldots\right\} \tag{2.17}$$

$$k_j^{\mathrm{EV}} = \begin{cases} k_j^{\mathrm{PV}} \text{ when } k_j^{\mathrm{AC}} \geq k_j^{\mathrm{PV}} \\ k_j^{\mathrm{AC}} \text{ when } k_j^{\mathrm{AC}} < k_j^{\mathrm{PV}} \end{cases} \tag{2.18}$$

where:
k_j^{EV} – portion of total cost of part of the work u_j^{FI} that started and actually performed by the date t^{FI} (e.g. PLN),

3. Analysis of works performed before the date t^{FI}:
 (a) data of time:
 – time variance – BDWS–ADWP:

$$\Delta t_j^{\mathrm{SV}} = t_j^{\mathrm{AC}} - t_j^{\mathrm{PV}} \text{ for } u_j^{\mathrm{FI}} \in U^{\mathrm{FI}} \tag{2.19}$$

 – absolute value of the time variances mass:

$$t^{\mathrm{SV}} = \sum_{u_j \in U^{\mathrm{FI}}} \left|\Delta t_j^{\mathrm{SV}}\right| \tag{2.20}$$

 – absolute value of the negative and positive time variances mass:

$$t_n^{\mathrm{SV}} = \sum_{u_j \in U^{\mathrm{FI}}} \left|-\Delta t_j^{\mathrm{SV}}\right|, \quad t_p^{\mathrm{SV}} = \sum_{u_j \in U^{\mathrm{FI}}} \Delta t_j^{\mathrm{SV}} \tag{2.21}$$

– standard deviation of absolute value of the time variances mass:

$$\Delta t^{SV} = \sqrt{\frac{\sum_{u_j \in U^{FI}} \left(\Delta t_j^{SV} - \Delta \bar{t}^{FI}\right)^2}{\text{card}\left|U^{FI}\right|}} \tag{2.22}$$

where:
card $\left|U^{FI}\right|$ – cardinality of the set U^{FI}

– standard deviation of absolute value of the time variances mass %:

$$\Delta t_{\%}^{SV} = \frac{\Delta t^{SV}}{t^{SV}} 100\%, \quad \Delta t_{\% n}^{SV} = \frac{t_n^{SV}}{t^{SV}} 100\%, \quad \Delta t_{\% p}^{SV} = \frac{t_p^{SV}}{t^{SV}} 100\% \tag{2.23}$$

– coefficients of time optimism and time pessimism:

$$\underline{p}^{FI} = \frac{\Delta t^{SV}}{t^{SV}} \frac{t_n^{SV}}{t^{SV}}, \quad \bar{p}^{FI} = \frac{\Delta t^{SV}}{t^{SV}} \frac{t_p^{SV}}{t^{SV}} \tag{2.24}$$

(b) data of cost:

– cost variance – BCWS – ACWP:

$$\Delta k_j^{SV} = k_j^{AC} - k_j^{PV} \text{ for } u_j^{FI} \in U^{FI} \tag{2.25}$$

– absolute value of the cost variances mass:

$$k^{SV} = \sum_{u_j \in U^{FI}} \left|\Delta k_j^{SV}\right| \tag{2.26}$$

– absolute value of the negative and positive cost variances mass:

$$k_n^{SV} = \sum_{u_j \in U^{FI}} \left|-\Delta k_j^{SV}\right|, \quad k_p^{SV} = \sum_{u_j \in U^{FI}} \Delta k_j^{SV} \tag{2.27}$$

– standard deviation of absolute value of the cost variances mass:

$$\Delta k^{SV} = \sqrt{\frac{\sum_{u_j \in U^{FI}} \left(\Delta k_j^{SV} - \Delta \bar{k}^{FI}\right)^2}{\text{card}\left|U^{FI}\right|}}; \tag{2.28}$$

where:
card $\left|U^{FI}\right|$ – cardinality of the set U^{FI}

– standard deviation of absolute value of the cost variances mass %:

$$\Delta k_{\%}^{SV} = \frac{\Delta k^{SV}}{k^{SV}} 100\%, \quad \Delta k_{\% n}^{SV} = \frac{k_n^{SV}}{k^{SV}} 100\%, \quad \Delta k_{\% p}^{SV} = \frac{k_p^{SV}}{k^{SV}} 100\% \tag{2.29}$$

– coefficients of cost optimism $\underline{p}^{\mathrm{FI}}$ and cost pessimism $\overline{p}^{\mathrm{FI}}$:

$$\underline{p}^{\mathrm{FI}} = \frac{\Delta k^{\mathrm{SV}}}{k^{\mathrm{SV}}} \frac{k_n^{\mathrm{SV}}}{k^{\mathrm{SV}}}, \quad \overline{p}^{\mathrm{FI}} = \frac{\Delta k^{\mathrm{SV}}}{k^{\mathrm{SV}}} \frac{k_p^{\mathrm{SV}}}{k^{\mathrm{SV}}} \tag{2.30}$$

(c) data of time and cost of small bridge construction at the date t^{FI}.

4. Data randomization of works to be performed after FI:

(a) the set $\mathbf{U}^{\mathrm{SI}}$ of works to be performed after the date t^{FI}:

$$\mathbf{U}^{\mathrm{SI}} = \mathbf{U} - \mathbf{U}^{\mathrm{FI}} = \left\{u_0^{\mathrm{SI}}, \ldots, u_f, \ldots, u_j, \ldots, u_n\right\} \tag{2.31}$$

(b) normative performance time and cost of works $u_j \in \mathbf{U}^{\mathrm{SI}}$:

$$\mathbf{T}^{\mathrm{SI}} = \left\{t_j : u_j \in \mathbf{U}^{\mathrm{SI}}\right\}, \quad \mathbf{K}^{\mathrm{SI}} = \left\{k_j : u_j \in \mathbf{U}^{\mathrm{SI}}\right\} \tag{2.32}$$

where:
t_j – the most probable normative performance time,
k_j – the most probable normative performance cost,

(c) PERT-beta distribution parameters of duration and cost of works $u_j \in \mathbf{U}^{\mathrm{SI}}$:

– time characteristics:

$$t_j^E = \frac{t_j^o + 4t_j^m + t^p}{6} \text{ for } u_j \in \mathbf{U}^{\mathrm{SI}} \tag{2.33}$$

where:
t_j^E – expected duration of works $u_j \in \mathbf{U}^{\mathrm{SI}}$,
$t_j^o = (1 - \underline{p}^{\mathrm{FI}})t_j$ – optimistic duration of works $u_j \in \mathbf{U}^{\mathrm{SI}}$,
$t^p = (1 + \overline{p}^{\mathrm{FI}})t_j$ – pessimistic duration of works $u_j \in \mathbf{U}^{\mathrm{SI}}$,

– cost characteristics:

$$k_j^E = \frac{k_j^o + 4k_j^m + k^p}{6} \text{ for } u_j \in \mathbf{U}^{\mathrm{SI}} \tag{2.34}$$

where:
k_j^E – expected cost of works $u_j \in \mathbf{U}^{\mathrm{SI}}$,
$k_j^o = (1 - \underline{p}^{\mathrm{FI}})k_j$ – optimistic cost of works $u_j \in \mathbf{U}^{\mathrm{SI}}$,
$k^p = (1 + \overline{p}^{\mathrm{FI}})k_j$ – pessimistic cost of works $u_j \in \mathbf{U}^{\mathrm{SI}}$

5. Projected randomized duration and cost of budgeted works to be completed after the FI:

– modelling the construction object structure technology $\mathbf{S}^{\mathrm{SI}}$ and construction object performance technology $\mathcal{L}^{\mathrm{SI}}$ after the FI:
$\mathbf{S}^{\mathrm{SI}} = \langle \mathbf{G}^{\mathrm{SI}}, \mathbf{L}^{\mathrm{SI}} \rangle$, $\mathcal{L}^{\mathrm{SI}} = \left\{\langle \mathbf{H}^{\mathrm{SI}}, \mathbf{K}^{\mathrm{SI}}, \mathbf{T}^{\mathrm{SI}} \rangle, \mathbf{S}^{\mathrm{SI}}\right\}$,
$\mathbf{G}^{\mathrm{SI}} = \langle \mathbf{Y}^{\mathrm{SI}}, \mathbf{U}^{\mathrm{SI}}, \mathbf{P}^{\mathrm{SI}}, \mathbf{U}^{\mathrm{SI}} = \left\{u_0^{\mathrm{SI}}, \ldots, u_f, \ldots, u_j, \ldots, u_n\right\}$,
$\mathbf{Y}^{\mathrm{SI}} = \left\{y_0^{\mathrm{SI}}, \cdots, y_i^{\mathrm{SI}}, \ldots, y_k^{\mathrm{SI}}, \ldots, y_m\right\}$, $\mathbf{H}^{\mathrm{SI}}\mathbf{K}^{\mathrm{SI}}\mathbf{T}^{\mathrm{SI}}$ – similarly as before, but for the sets adequate to SI,

- randomized budgeted duration to complete (RDTC) i.e. the estimated expected total time v_m^E required to complete the remainder of the project after the FI that is, find the expected earliest date v_m^E of the project completion and the expected earliest starting terms v_i of works $u_j \in \mathbf{U}^{\mathrm{SI}}$ that remain to be performed after the FI: $v = \sum_{i=0}^{i=m} v_i \to \min$, under the constraints: $v_k - v_i \geq t_j^E$ for $u_j \in \mathbf{U}^{\mathrm{SI}}$, $j = 0, \ldots, n$; $\langle y_i, u_j, y_k \rangle \in \mathbf{P}^{\mathrm{SI}}$; $v_i, v_k \geq 0$,
- randomized budgeted duration at completion (RDAC) i.e. the estimated expected time T^E of works $u_j \in \mathbf{U}$ at the end of the project from works start to finish: $T^E = t^{\mathrm{FI}} + v_m^E$,
- randomized budgeted estimate to complete (RETC) k^E i.e. the estimated expected cost required to complete the remainder of the project after the FI: $k^E = \sum_{u_j \in \mathbf{U}^{\mathrm{SI}}} k_j^E$,
- randomized budgeted estimate at completion (REAC) i.e. the estimated expected performance cost K^E of the project at the end of the project from works start to finish: $K^E = k^E + k^{\mathrm{FI}}$, where k^{FI} – cost of works performed to the date t^{FI}.

Step 3 and the next steps are concerned the analysis the rolling assessment of construction projects advancement after the consecutive inspections. The analysis can be done according to the step 3 using data received during the subsequent inspections. Finally, the risk of time and the risk of cost can be calculated by using the formulas [1]:

$$p(t) = P[E(T) \geq t] = 1 - P[E(T) \leq t] = 1 - \Phi\left[\frac{t - E(T)}{\sqrt{D^2(T)}}\right] \tag{2.35}$$

$$p(k) = P[E(K) \geq k] = 1 - P[E(K) \leq k] = 1 - \Phi\left[\frac{K - E(K)}{\sqrt{D^2(K)}}\right] \tag{2.36}$$

2.2. Presentation in practice

Original project implementation has been projected before beginning of works in situ. The Randomized Earned Value Method has been applied within the inspection of advancement of works implemented according to the developed cost estimate and schedule of works. The method has been directly used for comprehensive control of the actual cost expenses and advancement of works in unstable implementation condition. This is used in certain number of consecutive steps. Each individual step consists of some activities that allow to assess past works execution before the site inspections and project future works execution after the site inspection. Below, an application of the REVM has been presented to assess of the advancement of the construction office building. This office building has 4 structure shafts and is five storeys high. The building has a slab and column structure with masonry walls, placed on a foundation slab in the white tub technology, with excavation lining in the form of Larsen walls, due to the expected high groundwater level. Construction of this office building has been presented in some steps, as a referential example.

Step 1. Identification of the original project implementation data

Identification of the project implementation means here development of the model of structure technology of office building (MST) and the model of works technology of office building (MWT). The MST model consists of two parts. The first part of the MST, the graph G (Fig. 1), describes interdependence and permissible sequence of the construction of office building structure, that is execution of appropriate construction works. The second part of the MST, the numerical data, generally describes size and cost of works depicted by the graph to perform by task teams. The MWT model describes performance capacity of rational or optimal task teams organized and allocated to execution of individual works. The size of works and task teams performance capacity have been recomputed and have been tallied up as the duration and cost of works. Based on the identified data the scheduling problem has been formulated and solved. The solution of the problem determines the earliest start and the latest start of works executions as well as the minimal duration at completion (DAC) i.e. the total performance time of the project. According to the schedule of works execution the budget at completion (BAC) have been also calculated (Table 1).

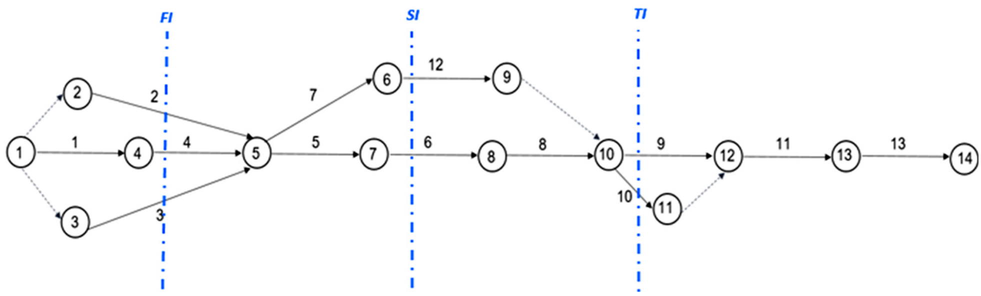

Fig. 1. Basic graph G of the model of structure technology of office building

Table 1. Data of the MST model of structure technology of the office building and data of the MWT model of works technology of the office building (Model 0)

No	Title	y_i	u_j	y_k	H^r	Planned duration (*days*)	Planned cost (PLN)	Earliest start	Latest start	Dummy activities	
						T_j	K_j	$ES(Vi)$	$ES(Vi)$	y_i	y_k
1	2	3	4	5	6	7	8	9	10	11	12
1	Demolition and rebuilding	1	1	4	1	**90**	**150 000**	0	0	1	2
2	Renovation of central heating installations	1	2	2	2	**220**	**750 000**	0	55	1	3

Continued on next page

Table 1 – *Continued from previous page*

	No	Title	y_i	u_j	y_k	H^r	Planned duration (*days*)	Planned cost (PLN)	Earliest start	Latest start	Dummy activities	
							T_j	K_j	$ES(Vi)$	$ES(Vi)$	y_i	y_k
	1	2	3	4	5	6	7	8	9	10	11	12
	3	Repair of the electrical installation	1	3	3	3	**150**	**600 000**	0	125	9	10
FI120	4	Replacement of windows	4	4	5	4	**185**	**900 000**	90	90	11	12
	5	Plasters	5	5	7	5	**120**	**1 200 000**	275	275		
	6	Preparation of the surface for painting	7	6	8	6	**180**	**240 000**	395	395		
SI450	7	Tiling works	5	7	6	7	**120**	**450 000**	275	275		
TI760	8	Painting rooms	8	8	10	8	**150**	**1 500 000**	575	575		
	9	Sanding floors	10	9	12	9	**90**	**840 000**	725	725		
	10	Installation of door joinery	10	10	11	10	**24**	**25 000**	725	725		
	11	Installation of floor strips	12	11	13	11	**16**	**12 000**	815	815		
	12	White assembly	6	12	9	12	**65**	**150 000**	395	660		
	13	Cleaning rooms	13	13	14	13	**8**	**2 000**	831	831		
Budgeted Cost (BCC) and Duration (BDC) at Completion								**6 819 000**	**839**	**839**		

Step 2. Planning and organization the inspection of the project implementation

In this step according to the schedule of the project the timetable of the site inspection has been developed and the team of experts for survey performance and data analysis has been organized. The First Inspection Date (FI) – 01.08.2018 (after 120 calendar days from the commencement of construction), The Second Inspection Date (SI) – 27.06.2019 (after 450 calendar days from the commencement of construction) and The Third Inspection Date (TI) – 02.05.2020 (after 450 calendar days from the commencement of construction) have been fixed.

Experts team organization – (*e.g. construction project manager – chief of team, construction manager, senior construction technician, accounting technician, economic technician, master workman*).

Step 3. First step of rolling inspection (FI):

This step is very important for current and future analysis of the works advancement. Activities taken sequentially in this step provide basic initial data and form the basis of the current analysis and prepare future studies.

1. Quantity survey of works performed:
   Quantity survey of the works that have been executed to the date of inspection – prepared in the same way as bill of quantity;
2. Bill of quantities and construction cost estimate of works performed:
   Abridgement of bill of quantities and construction cost estimate that have been executed to the date of inspection.
3. Analysis of works performed before the date of the first site inspection:
   Comparison of quantity survey of works and bill of quantities.
   Comparison of real expenses and construction cost estimate.
4. Data randomization of works that have been remained to the execution after the first inspection: *Randomization of data based on analysis of variations between quantity survey and bill of quantities as well as real incurred costs and planned costs in estimate.*
5. Projected randomized duration and cost of budgeted works to be completed after the FI
   Projected randomized vales as results of interdependent analysis of the quantity survey of works, bill of quantity, construction cost estimate and finally solution of scheduling problem for works that remained to completion.

   All data (1 – 5) have been tallied in Figure 2, Tables 2 and 3 and referring to the tables.

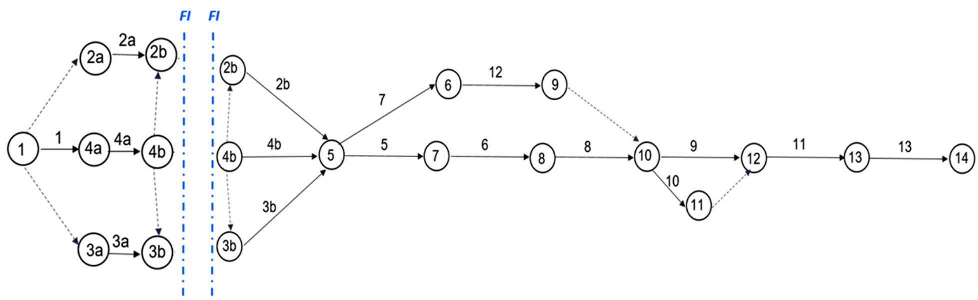

Fig. 2. Graph of the building structure technology – part of works to be performed before and after the date t^{FI}

Step 4. Second step of rolling inspection

The fourth step concerns the analysis of the rolling assessment of construction projects advancement after the first inspection. The analysis can be carried out in accordance with step 3 based on the data obtained during the subsequent inspections. The results of such analysis of the office building construction have been presented at Fig. 3 and in Tables 4 and 5.

This step can be developed analogically as Step 3 but accordingly to the data in Step 4, that is using similar calculations, figures and tables.

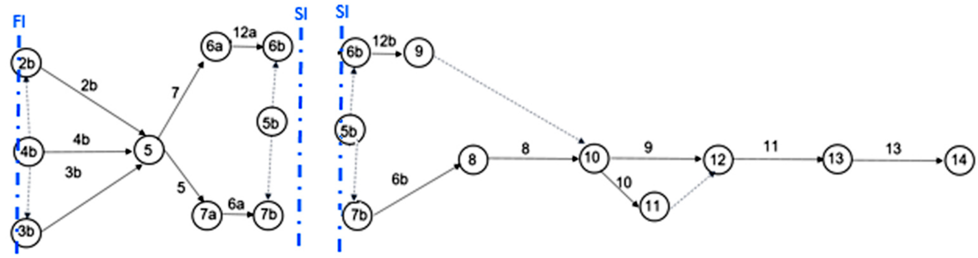

Fig. 3. Graph of the building structure technology – part of works to be performed before and after the date t^{SI}

Step 5. The third step of rolling inspection

The fifth step concerns the rolling progress assessment of the construction office building after the first inspections. The analysis can be carried out in accordance with step 4 using the data obtained from subsequent inspections. The results of such an analysis of the office building are presented in Fig. 4 and in Tables 6 and 7.

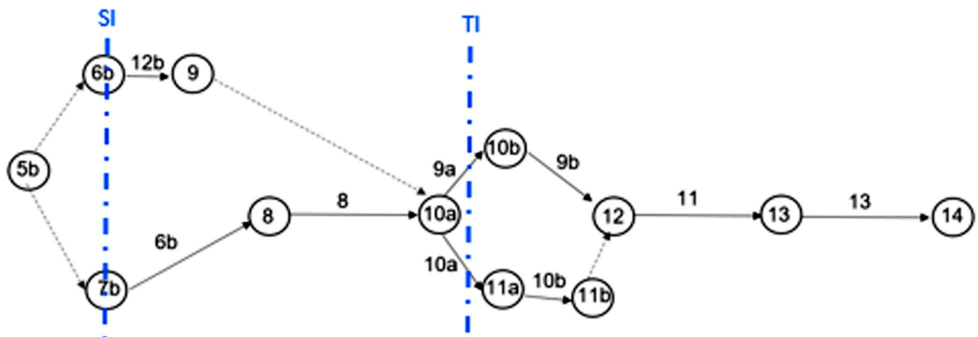

Fig. 4. Graph of the building structure technology – part of works to be performed before and after the date t^{TI}

The fifth step concerns the rolling progress assessment of construction office building after the first inspections. The analysis can be done according to the step 4 using data received during the subsequent inspections. Results of such analysis of the office building have been presented at Fig. 4 and in Tables 6 and 7.

This step should be developed analogically as Steps 3 and 4 but according to the data in Step 5, applying analogous calculation, figures and tables.

Step 6. Charts of the risk of time and the risk of cost

The charts are used to show possible values and probable changes of basic quantities that characterize the process of works execution. The charts (Fig. 5– 10), based on the tabular data (Tables 8 and 9), exemplify the expected duration and the expected cost as well as the risk of overrun the duration and the risk of overrun the cost of works remaining to execution after each inspection.

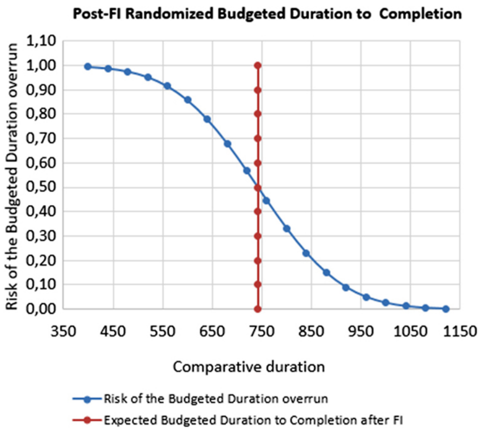

Fig. 5. Chart risk of time after the FI

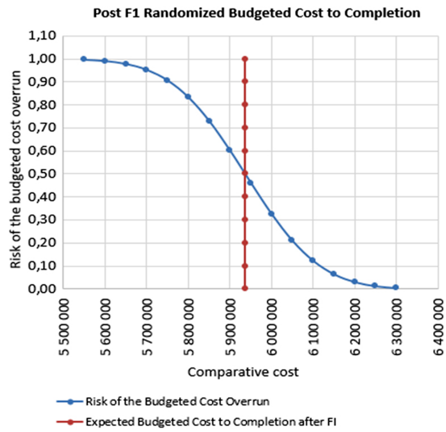

Fig. 6. Chart risk of cost after the FI

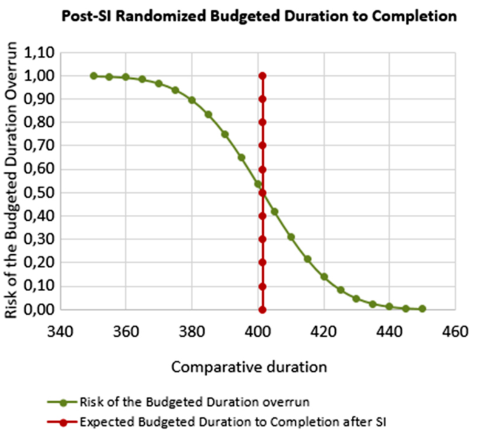

Fig. 7. Chart risk of time after the SI

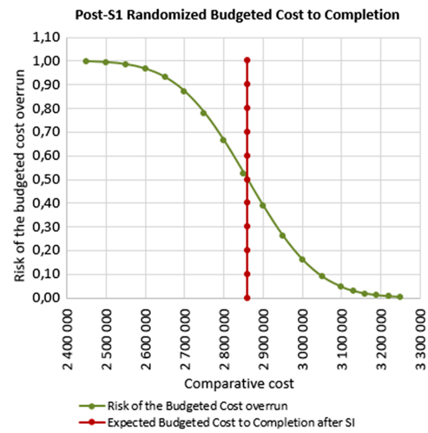

Fig. 8. Chart risk of cost after the SI

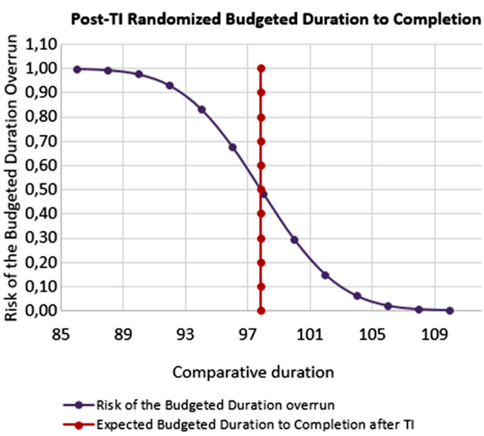

Fig. 9. Chart risk of time after the TI

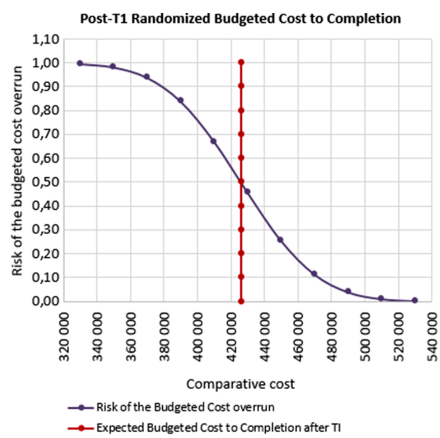

Fig. 10. Chart risk of cost after TI

Table 2. Data of time and cost of office building construction determined at the date t^{FI}

No	Works started but not completed	y_i	u_j	y_k	H^r	Planned duration (days)	Planned cost (PLN)	Earliest start	Latest start	Percent of WW performed	BDWS	BDWP	ADWP	Time variance ADWP–BDWS	BCWS	BCWP	ACWP	Cost variance ACWP–BCWS
						T_j	K_j	$ES(Vi)$	$LS(Vi)$	%								
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
1	Demolition and rebuilding	1	1	4a	1	90	150 000	0	0	100%	90	90	96	6	150 000	150 000	158 000	8 000
2a	Renovation of central heating installations	2a	2a	2b	2	120	409 091	0	0	55%	120	120	128	8	409 091	409 091	448 940	39 849
3a	Repair of the electrical installation	3a	3a	3b	3	120	480 000	0	0	80%	120	120	120	0	480 000	480 000	482 000	2 000
4a	Replacement of windows	4a	4a	4b	4	30	145 946	90	90	16%	30	27	27	–3	145 946	142 850	142 850	–3 096
Budgeted Duration and Cost of Works Performed to FI		**1**		**4b**		**120**	**1 185 037**	Mass of time variances		**17**	**3**	**14**	Mass of cost variances			**52 945**	**3 096**	49 849
									Standard deviation	**5,12**					Standard deviation	**19 314**		
									Standard deviation %	**30%**	**18%**	**82%**			Standard deviation %	**36%**	**6%**	94%
									Coefficient of time optimism	**0,05**					Coefficient of cost optimism	**0,02**		
									Coefficient of time pesymism	**0,25**					Coefficient of cost pesymism	**0,34**		

Table 3. Randomized data of works that remained to be performed after FI

						Planned values	Earliest start	Randomized duration	Randomized cost						
No	Title	y_i	u_j	y_k	H^r	Duration	Cost	$ES(V_i)$	EV	OV	MP	PV	EV OV	MP	PV
1	2	3	4	5	6	7	8	9	10	11	12	13	14 15	16	17
FI	Budgeted duration and cost of works performed to FI	1		4b		120	1 185 037	0	120				1 185 037		
2b	Renovation of central heating installations	2b	2b	5	2	100	340 909	0	103	95	100	125	359 212 333 637	340 909	457 997
3b	Repair of the electrical installation	3b	3b	5	3	30	120 000	0	31	28	30	37	126 443 117 440	120 000	161 215
4b	Replacement of windows	4b	4b	5	4	155	754 054	0	160	147	155	193	794 538 737 969	754 054	1 013 041
5	Plasters	5	5	7	5	120	1 200 000	160	124	114	120	150	1 264 426 1 174 403	1 200 000	1 612 151
6	Preparation of the surface for painting	7	6	8	6	180	240 000	284	186	170	180	225	252 885 234 881	240 000	322 430
7	Tiling works	5	7	6	7	120	450 000	160	124	114	120	150	474 160 440 401	450 000	604 557
8	Painting rooms	8	8	10	8	150	1 500 000	470	155	142	150	187	1 580 532 1 468 004	1 500 000	2 015 188
9	Sanding floors	10	9	12	9	90	840 000	625	93	85	90	112	885 098 822 082	840 000	1 128 506
10	Installation of door joinery	10	10	11	10	24	25 000	625	25	23	24	30	26 342 24 467	25 000	33 586
11	Installation of floor strips	12	11	13	11	16	12 000	718	17	15	16	20	12 644 11 744	12 000	16 122
12	White assembly	6	12	9	12	65	150 000	284	67	62	65	81	158 053 146 800	150 000	201 519
13	Cleaning rooms	13	13	14	13	8	2 000	734	8	8	8	10	2 107 1 957	2 000	2 687
Randomized Budgeted Duration to Completion								742	Randomized Budgeted Cost to Completion				5 936 439		
Randomized Budgeted Duration at Completion								862	Randomized Budgeted Cost at Completion				7 121 476		
Randomized Cost of works partly performed before FI													1 280 192		

Table 4. Randomized data of works started but not finished before SI

No	Title	y_i	u_j	y_k	H^r	Planned duration (days)	Planned cost (PLN)	Earliest start	Latest start	Percent of work performed	BDWS	BDWP	ADWP	Time variance ADWP–BDWS	BCWS	BCWP	ACWP	Cost variance ACWP–BCWS
						T_j	K_j	$ES(Vi)$	$LS(Vi)$	%								
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
5	Plasters	5	5	7a	5	120	1 200 000	160	155	100%	120	120	133	13	450 000	450 000	483400	33 400
6a	Preparation of the surface for painting	7a	6a	7b	6	86	114 749	284	275	48%	86	86	195	109	717 183	717 183	1 513 000	795 817
7	Tiling works	5	7	6a	7	120	450 000	160	155	100%	120	117	117	–3	840 000	832 800	832 800	–7 200
12a	White assembly	6a	12a	6b	12	65	150 000	284	275	54%	65	65	68	3	13 542	13 542	14 100	558
SI	Budgeted works that started before and are being finished after SI	5		5b		120	1 914 749	Mass of time variances		128	3	125	Mass of cost variances			836 975	7 200	829 775
Standard deviation										62.97	Standard deviation					393 842		
Standard deviation %										49%	2%	98%	Standard deviation %			47%	1%	99%
Coefficient of time optimism										0.01	Coefficient of cost optimism					0.00		
Coefficient of time pesymism										0.48	Coefficient of cost pesymism					0.47		

Table 5. Randomized data of works that remain to be performed after SI

						Planned values	Earliest start	Randomized duration	Randomized cost							
No	Title	y_i	u_j	y_k	H^r	Duration	Cost	*ES(Vi)*	EV	OV	MP	PV	EV	OV	MP	PV
FI	Budgeted duration and costs of works performed before FI	1	net	4b		120	1 185 037	0					1 185 037			
	Budgeted duration and cost of works that started before and finished after FI	4b	net	5			1 280 192	120					1 280 192			
	Budgeted works that started before and are being finished after SI	5	net	5b			1 914 749						1 914 749			
	Second inspection SI					450		450								
6b	Preparation of the surface for painting	6b	6b	8	6	100	138 136	0	108	99	100	148	148 876	138 136	138 136	202 577
12b	White assembly	8	8	9	8	2	8 053	0	2	2	2	3	8 679	8 053	8 053	11 810
8	Painting rooms	8	8	10	8	155	1 580 532	108	167	153	155	229	1 703 420	1 580 532	1 580 532	2 317 860
9	Sanding floors	10	9	12	9	93	885 098	275	100	92	93	138	953 915	885 098	885 098	1 298 002
10	Installation of door joinery	10	10	11	10	25	26 342	275	27	24	25	37	28 390	26 342	26 342	38 631
11	Installation of floor strips	12	11	13	11	17	12 644	375	18	16	17	24	13 627	12 644	12 644	18 543
13	Cleaning rooms	13	13	14	13	8	2 107	393	9	8	8	12	2 271	2 107	2 107	3 090
Randomized Budgeted Duration to Completion								401	Randomized Budgeted Cost to Completion				2 859 179			
Randomized Budgeted Duration at Completion								851	Randomized Budgeted Cost at Completion				7 239 158			

Table 6. Randomized data of works started but not finished before TI

No	Title	y_i	u_j	y_k	H^r	Planned duration (days)	Planned cost (PLN)	Earliest start	Latest start	Percent of work performed	BDWS	BDWP	ADWP	Time variance ADWP–BDWS	BCWS	BCWP	ACWP	Cost variance ACWP–BCWS
						T_j	K_j	$ES(Vi)$	$LS(Vi)$	%								
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
8	Painting rooms	8	8	10a	8	155	1 580 532	108	108	100	155	155	165	10	1 580 532	1 580 532	1 670 500	89 968
9a	Sanding floors	10a	9a	10b	9	55	527 929	275	275	60	55	30	30	–25	527 929	302 100	302 100	-225829
10a	Installation of door joinery	10a	10a	11a	10	25	26 342	275	275	100	25	25	28	3	26 342	26 342	29 250	2908
TI	Budgeted works that started before and are being finished after TI	10a		10b		155	2 134 803	Mass of time variances		39	25	13	Mass of cost variances			318 705	225 829	92 876
Standard deviation										18.85			Standard deviation			163 109		
Standard deviation %										49%	3%	97%	Standard deviation %			51%	71%	29%
Coefficient of time optimism										0.32			Coefficient of cost optimism			0.36		
Coefficient of time pesymism										0.17			Coefficient of cost pesymism			0.15		

Table 7. Randomized data of works that remain to be performed after TI

						Planned values	Earliest start	Randomized duration	Randomized cost							
No	Title	y_i	u_j	y_k	H^r	Duration	Cost	*ES(Vi)*	EV	OV	MP	PV	EV	OV	MP	PV
FI	Budgeted duration and costs of works performed before FI	1	net	4b		120	1 185 037	0					1 185 037			
	Budgeted duration and cost of works that started before and finished after FI	2b	net	5			1 280 192	120					1 280 192			
	Budgeted works that started before and are being finished after SI	5	net	5b		450	1 914 749	450					1 914 749			
	Budgeted works that started before and are being finished after TI	10a	net	10b			2 134 803						2 134 803			
	Third inspection TI					760		760								
9b	Sanding floors	10b	9b	12	6	45	425 986	0	44	30	45	52	410 828	271 505	425 986	489 519
10b	Installation of door joinery	11a	10b	11b	8	0	0	0	0	0	0	0	0	0	0	0
11	Installation of floor strips	12	11	13	11	18	13 627	0	17	12	18	21	13 142	8 685	13 627	15 660
13	Cleaning rooms	13	13	14	13	9	2 271	0	9	6	9	10	2 190	1 448	2 271	2 610
Randomized Budgeted Duration to Completion								98	Randomized Budgeted Cost to Completion				426 161			
Randomized Budgeted Duration at Completion								858	Randomized Budgeted Cost at Completion				6 940 942			

Table 8. Tabular summary of the expected duration and the risk of the duration overrun of works remaining to execution after inspections

Time risk analysis

Works remained to be performed after FI	2b	3b	4b	5	6	7	8	9	10	11	12	13									
Model 2 Optimistic duration	95	28	147	114	170	114	142	85	23	15	62	8									
Modal duration	100	30	155	120	180	120	150	90	24	16	65	8									
Pessimistic duration	125	37	193	150	225	150	187	112	30	20	81	10									
Expected duration	103	31	160	124	186	124	155	93	25	17	67	8									
Variance of the duration	1338	120.45	3215.4	1927	4336	1927	3011	1084	77	34	565	8.56									
Variance of the works completion	17646	17646	17646	17646	17646	17646	17646	17646	17646	17646	17646	17646	17646	17646	17646	17646	17646	17646	17646		
Post-FI Budgeted Duration to Completion	742	742	742	742	742	742	742	742	742	742	742	742	742	742	742	742	742	742	742		
Comparative cost	400	440	480	520	560	600	640	680	720	760	800	840	880	920	960	1000	1040	1080	1120		
"Z" value	–2.577	–2.276	–1.975	–1.674	–1.37	–1.072	–0.77	–0.47	–0.17	0.13	0.43	0.73	1.04	1.34	1.64	1.94	2.244	2.544	2.84		
Risk of the Budgeted Duration overrun	1.00	0.99	0.98	0.95	0.92	0.86	0.78	0.68	0.57	0.45	0.33	0.23	0.15	0.09	0.05	0.03	0.01	0.01	0.00		
Works remained to be performed after SI	6b	12b	8	9	10	11	13														
Model 3 Optimistic duration	99	2	153	92	24	16	8														
Modal duration	100	2	155	93	25	17	8														
Pessimistic duration	148	3	229	138	37	24	12														
Expected duration	108	2	167	100	27	18	9														
Variance of the duration	67.00	0.03	161.39	58.10	4.13	1.84	0.46														
Variance of the works completion	291	291	291	291	291	291	291	291	291	291	291	291	291	291	291	291	291	291	291	291	291
Post-SI Budgeted Duration to Completion	401	401	401	401	401	401	401	401	401	401	401	401	401	401	401	401	401	401	401	401	401
Comparative cost	350	355	360	365	370	375	380	385	390	395	400	405	410	415	420	425	430	435	440	445	450
"Z" value	–3.01	–2.73	–2.43	–2.14	–1.85	–1.55	–1.26	–0.97	–0.67	–0.38	–0.09	0.21	0.50	0.79	1.00	1.38	1.67	1.97	2.26	2.5	2.8
Risk of the Budgeted Duration overrun	1.00	1.00	0.99	0.98	0.97	0.94	0.90	0.83	0.75	0.65	0.53	0.42	0.31	0.21	0.14	0.08	0.05	0.02	0.01	0.01	0.00

Table 8 – *Continued from previous page*

Works remained to be performed after TI	9b	10b	11	13									
Model 4 Optimistic duration	30	0	12	6									
Modal duration	45	0	18	9									
Pessimistic duration	52	0	21	10									
Expected duration	44	0	17	9									
Variance of the duration	13.16	0.00	2.08	0.52									
Variance of the works completion	15.76	15.76	15.76	15.76	15.76	15.76	15.76	15.76	15.76	15.76	15.76	15.76	15.76
Post-TI Budgeted Duration to Completion	98	98	98	98	98	98	98	98	98	98	98	98	98
Comparative cost	86	88	90	92	94	96	98	100	102	104	106	108	110
“Z” value	–2.98	–2.47	–1.97	–1.47	–0.96	–0.46	0.04	0.55	1.05	1.56	2.06	2.56	3.067
Risk of the Budgeted Duration overrun	1.00	0.99	0.98	0.93	0.83	0.68	0.48	0.29	0.15	0.06	0.02	0.01	0.00

General analysis of the works implementation

Budgeted Duration at Completion	839	839	839	839	839	839	839	839	839	839	839
Probability of the Budgeted Duration at Completion	0.00	0.10	0.20	0.30	0.40	0.50	0.60	0.70	0.80	0.90	1.00
Expected Budgeted Duration to Completion after FI	742	742	742	742	742	742	742	742	742	742	742
	0.00	0.10	0.20	0.30	0.40	0.50	0.60	0.70	0.80	0.90	1.00
Expected Budgeted Duration to Completion after SI	401	401	401	401	401	401	401	401	401	401	401
	0.00	0.10	0.20	0.30	0.40	0.50	0.60	0.70	0.80	0.90	1.00
Expected Budgeted Duration to Completion after TI	98	98	98	98	98	98	98	98	98	98	98
	0.00	0.10	0.20	0.30	0.40	0.50	0.60	0.70	0.80	0.90	1.00

Table 9. Tabular summary of the expected cost and the risk of the cost overrun of works remaining to execution after inspections

Cost risk analysis

Budgeted Works to Completion after FI	2b	3b	4b	5	6	7	8	9	10	11	12	13							
Optimistic cost	333 637	117 440	737 969	1 174 403	234 881	440 401	1 468 004	822 082	24 467	11 744	146 800	1 957							
Modal cost	340 909	120 000	754 054	1 200 000	240 000	450 000	1500000	840000	25000	12000	150000	2000							
Pessimistic cost	457 997	161 215	1 013 041	1 612 151	322 430	604 557	2 015 188	1 128 506	33 586	16 122	201 519	2 687							
Expected cost	359 212	126 443	794 538	1 264 426	252 885	474 160	1 580 532	885 098	26 342	12 644	158 053	2 107							
Variance of the cost	429 596 227	53 228 691	2 101 784 823	5 322 869 090	212 914 764	748 528 466	8 316 982 953	2 608 205 854	2 310 273	532 287	83 169 830	14 786							
Variance of the works completion	19 880 138 042	19 880 138 042	19 880 138 042	19 880 138 042	19 880 138 042	19 880 138 042	19 880 138 042	19 880 138 042	19 880 138 042	19 880 138 042	19 880 138 042	19 880 138 042	19 880 138 042	19 880 138 042	19 880 138 042	19 880 138 042			
Post-F1 Budgeted Cost to Completion	5 936 439	5 936 439	5 936 439	5 936 439	5 936 439	5 936 439	5 936 439	5 936 439	5 936 439	5 936 439	5 936 439	5 936 439	5 936 439	5 936 439	5 936 439	5 936 439			
Comparative cost	5 550 000	5 600 000	5 650 000	5 700 000	5 750 000	5 800 000	5 850 000	5 900 000	5 950 000	6 000 000	6 050 000	6 100 000	6 150 000	6 200 000	6 250 000	6 300 000			
"Z" value	–2.7407	–2.38614	–2.03152	–1.6769	–1.32229	–0.96767	–0.6130	–0.2584	0.09617	0.45079	0.80541	1.16002	1.514647	1.869264	2.22388	2.57850			
Risk of the Budgeted Cost Overrun	1.00	0.99	0.98	0.95	0.91	0.83	0.73	0.60	0.46	0.33	0.21	0.12	0.06	0.03	0.01	0.00			
Budgeted Works to Completion after SI	6b	12b	8	9	10	11	13												
Optimistic cost	138 136	8 053	1 580 532	885 098	26 342	12 644	2 107												
Modal cost	138 136	8 053	1 580 532	885 098	26 342	12 644	2 107												
Pessimistic cost	202 577	11 810	2 317 860	1 298 002	38 631	18 543	3 090												
Expected cost	148 876	8 679	1 703 420	953 915	28 390	13 627	2 271												
Variance of the cost	115 351 896	392 057	15 101 455 628	4 735 816 485	4 194 849	966 493	26 847												
Variance of the works completion	19 958 204 255	19 958 204 255	19 958 204 255	19 958 204 255	19 958 204 255	19 958 204 255	19 958 204 255	19 958 204 255	19 958 204 255	19 958 204 255	19 958 204 255	19 958 204 255	19 958 204 255	19 958 204 255	19 958 204 255	19 958 204 255	19 958 204 255	19 958 204 255	19 958 204 255
Post-S1 Budgeted Cost to Completion	2 859 179	2 859 179	2 859 179	2 859 179	2 859 179	2 859 179	2 859 179	2 859 179	2 859 179	2 859 179	2 859 179	2 859 179	2 859 179	2 859 179	2 859 179	2 859 179	2 859 179	2 859 179	2 859 179
Comparative cost	2 450 000	2 500 000	2 550 000	2 600 000	2 650 000	2 700 000	2 750 000	2 800 000	2 850 000	2 900 000	2 950 000	3 000 000	3 050 000	3 100 000	3 130 000	3 160 000	3 190 000	3 220 000	3 250 000
"Z" value	–2.8963	–2.5424	–2.188	–1.83453	–1.480	–1.1267	–0.7728	–0.418	–0.06497	0.2889470	0.6428704	0.9967938	1.3507172	1.7046406	1.9169946	2.1293487	2.3417027	2.5540568	2.7664108
Risk of the Budgeted Cost overrun	1.00	0.99	0.99	0.97	0.93	0.87	0.78	0.66	0.53	0.39	0.26	0.16	0.09	0.04	0.03	0.02	0.01	0.01	0.00

Table 9 – *Continued from previous page*

Budgeted Works to Completion after TI	9b	10b	11	13							
Optimistic cost	271 505	0	8 685	1 448							
Modal cost	425 986	0	13 627	2 271							
Pessimistic cost	489 519	0	15 660	2 610							
Expected cost	410 828	0	13 142	2 190							
Variance of the cost	1 320 286 512	0	1 351 142	37 532							
Variance of the works completion	1 321 675 186	1 321 675 186	1 321 675 186	1 321 675 186	1 321 675 186	1 321 675 186	1 321 675 186	1 321 675 186	1 321 675 186	1 321 675 186	1 321 675 186
Post-T1 Budgeted Cost to Completion	426 161	426 161	426 161	426 161	426 161	426 161	426 161	426 161	426 161	426 161	426 161
Comparative cost	330 000	350 000	370 000	390 000	410 000	430 000	450 000	470 000	490 000	510 000	530 000
"Z" value	–2.6450	–2.0949	–1.54479	–0.9946	–0.4445	0.1056034	0.6557363	1.2058693	1.7560022	2.3061351	2.8562680
Risk of the Budgeted Cost overrun	1.00	0.98	0.94	0.84	0.67	0.46	0.26	0.11	0.04	0.01	0.00
General analysis of the works implementation											
Budgeted Cost at Completion	6 819 000	6 819 000	6 819 000	6 819 000	6 819 000	6 819 000	6 819 000	6 819 000	6 819 000	6 819 000	6 819 000
Probability of the Budgeted Cost at Completion	0.00	0.10	0.20	0.30	0.40	0.50	0.60	0.70	0.80	0.90	1.00
Expected Budgeted Cost to Completion after FI	5 936 439	5 936 439	5 936 439	5 936 439	5 936 439	5 936 439	5 936 439	5 936 439	5 936 439	5 936 439	5 936 439
	0.00	0.10	0.20	0.30	0.40	0.50	0.60	0.70	0.80	0.90	1.00
Expected Budgeted Cost to Completion after SI	2 859 179	2 859 179	2 859 179	2 859 179	2 859 179	2 859 179	2 859 179	2 859 179	2 859 179	2 859 179	2 859 179
	0.00	0.10	0.20	0.30	0.40	0.50	0.60	0.70	0.80	0.90	1.00
Expected Budgeted Cost to Completion after TI	426 161	426 161	426 161	426 161	426 161	426 161	426 161	426 161	426 161	426 161	426 161
	0.00	0.10	0.20	0.30	0.40	0.50	0.60	0.70	0.80	0.90	1.00

3. Results

The data received as result of the REVM method application describe duration and cost of works executed and works to be executed along with the risk of them implementation. The data concerning works that have been executed until the site inspection are measured during the quantity survey and analysis of incurred cost allocation. The data concerning the works to be executed after the site inspection are developed based on description of earlier identified data concerning works already executed. Such developed data are randomized and as random are used to projection future works execution.

The most important results concern:

1. Method of analyzing the data measured during the site inspections, including scope, durations and costs of individual works that have been executed and will have to be executed in order the construction project to be completed.
2. Method of estimation random durations and random costs as well as the expected durations and expected costs of individual works.
3. Estimation of duration and cost of works to completion.
4. Estimation of duration and cost of works at completion.
5. Estimation the risk of the duration overrun, and cost overrun.

The all above enumerated data are estimated after each site inspection. The results of the construction of the office building advancement assessment after the first, second and third inspections received by using the new REVM method and the classic EVM method have been tallied in Table 10.

Table 10. Comparison of final results received by using REVM method and EVM method

REVM Final results		EVM Final results	
Duration at Completion	**839**	**839**	**Duration at Completion**
Estimate at Completion	**6 819 000**	**6 819 000**	**Estimate at Completion**
Randomized Budgeted Duration to Completion projected after FI	742	805	Budgeted Duration to Completion projected after FI
Randomized Budgeted Cost to Completion projected after FI	5 936 439	5 633 963	Budgeted Cost to Completion projected after FI
Randomized Budgeted Cost at Completion projected after FI	7 121 476	6 865 753	Budgeted Cost at Completion projected after FI
Randomized Budgeted Duration at Completion projected after FI	862	925	Budgeted Duration at Completion projected after FI
Overrun the Budgeted Cost at Completion projected after FI	**302 476**	**46 753**	**Overrun the Budgeted Cost at Completion projected after FI**

Continued on next page

Table 10 – *Continued from previous page*

REVM Final results		EVM Final results	
Percentage of budgeted cost overrun at completion projected after FI	**4%**	**1%**	**Percentage of budgeted cost overrun at completion projected after FI**
Overrun the Budgeted Duration at Completion projected after FI	**23**	**86**	**Overrun the Budgeted Duration at Completion projected after FI**
Percentage of budgeted duration overrun at completion projected after FI	**3%**	**10%**	**Percentage of budgeted duration overrun at completion projected after FI**
Randomized Budgeted Duration to Completion projected after SI	401	488	Budgeted Duration to Completion projected after SI
Randomized Budgeted Cost to Completion projected after SI	2 859 179	2 492 333	Budgeted Cost to Completion projected after SI
Randomized Budgeted Cost at Completion projected after SI	7 239 158	7 782 386	Budgeted Cost at Completion projected after SI
Randomized Budgeted Duration at Completion projected after SI	851	938	Budgeted Duration at Completion projected after SI
Overrun the Budgeted Cost at Completion projected after SI	**420 158**	**963 386**	**Overrun the Budgeted Cost at Completion projected after SI**
Percentage of budgeted cost overrun at completion projected after SI	**6,16%**	**14,13%**	**Percentage of budgeted cost overrun at completion projected after SI**
Overrun the Budgeted Duration at Completion projected after SI	**12**	**99**	**Overrun the Budgeted Duration at Completion projected after SI**
Percentage of budgeted duration overrun at completion projected after SI	**1.49%**	**11.74%**	**Percentage of budgeted duration overrun at completion projected after SI**
Randomized Budgeted Duration to Completion projected after TI	98	176	Budgeted Duration to Completion projected after TI
Randomized Budgeted Cost to Completion projected after TI	426 161	14 000	Budgeted Cost to Completion projected after TI
Randomized Budgeted Cost at Completion projected after TI	6 940 942	7 305 903	Budgeted Cost at Completion projected after TI
Randomized Budgeted Duration at Completion projected after TI	858	936	Budgeted Duration at Completion projected after TI
Overrun the Budgeted Cost at Completion projected after TI	**121 942**	**486 903**	**Overrun the Budgeted Cost at Completion projected after TI**

Continued on next page

Table 10 – *Continued from previous page*

REVM Final results		EVM Final results	
Percentage of budgeted cost overrun at completion projected after TI	**1,79%**	**7,14%**	**Percentage of budgeted cost overrun at completion projected after TI**
Overrun the Budgeted Duration at Completion projected after TI	**19**	**97**	**Overrun the Budgeted Duration at Completion projected after TI**
Percentage of budgeted duration overrun at completion projected after TI	**2.24%**	**11.61%**	**Percentage of budgeted duration overrun at completion projected after TI**

Based on the data tallied in Table 10 one can discern variations between two shown options. The variations concern duration and cost of individual works and the whole set of project works.

Overrun the Budgeted Cost at Completion projected after FI amount for the proprietary REVM method: 302 476 PLN and for the classic EVM method: 46 753 PLN, however after the second inspection (SI) Overrun the Budgeted Cost at Completion projected amount for the proprietary REVM method: 420 158 PLN and for the classic EVM method: 963 386 PLN, which is accordingly 6,16% and 14,13% deviations from the planned budget (Estimate at Completion). This proves the implementation of changes and repair programs during the implementation of the investment and conscious investment management in the case of control using the REVM method or the lack of any corrective adjustments and slow loss of control over the investment in the case of the EVM method. Further lack of awareness of the changes taking place in the investment carried out under risk conditions is shown by inspection no. 3 (TI), where for classic EVM method Overrun the Budgeted Cost at Completion projected is 486 903 PLN (deviation: 7,14%). The situation is completely different when construction project is implemented using the risk-based REVM approach, here Overrun the Budgeted Cost at Completion projected amount 121 942 PLN (deviation: 1,79%).

Whereas Overrun the Budgeted Duration at Completion projected after FI amount for the proprietary REVM method: 23 days and for the classic EVM method: 86 days, which is accordingly 3% and 10% deviations from the planned schedule (Duration at Completion).

After the second inspection (SI) the situation for investment management using the REVM method improves, the deviation from the planned schedule is only 1.49% (Overrun the Budgeted Duration at Completion projected after SI is 12 days), while for investment management using the EVM method, the deviation from the planned schedule deepens and already amounts to 11.74% (Overrun the Budgeted Duration at Completion projected after SI is 99 days). Ultimately, Overrun the Budgeted Duration at Completion projected after TI amount for the proprietary REVM method: 19 days and for the classic EVM method: 97 days, which is accordingly 2.24% and 11.61% deviations from the planned schedule (Duration at Completion). The result confirms the conclusions drawn during the analysis of cost changes.

Control of the investment under deterministic conditions, without taking into account the risk of disruptions, resulted in a final deviation from the planned budget of over 7%, and from the planned completion of the investment by almost 12%. Without analysing the factor related to disruptions at the investment implementation stage, the material and financial schedule was completely outdated.

On the other hand, when controlling the investment under risk conditions and introducing organizational and technological changes adequate to the inspection reports, the final deviation from the planned budget was less than 2%, and slightly more than 2% from the planned completion date.

The risk assessment of construction works consists in the analysis of a random execution situation and random characteristics of works, defining threats and opportunities for implementation, calculating the expected time and expected costs of works, and estimating the probability of exceeding or not exceeding various contractual values of time and costs of works in the anticipated conditions of implementation. The risk assessment of construction works is the last stage of the analysis before making the final decision on the correction of the works and possible assumptions regarding the permissible values of shortening and extending the time as well as reducing or increasing the costs of works, what has been used in this investment. The risk assessment is the basis for a realistic estimate of the likely benefits or losses of the investor and the contractor in connection with the performance of the construction works contract [22–30].

Finally, based on comparable analysis of the above presented methods, one can confirm that the REVM method enable better assessment of actual progress and projected further works execution. The results of the REVM method are more realistic and more accurate in comparison to the assessment by the EVM method and better reflect real situation of works implementation. The REVM method can be good support for management decision making.

4. Final remarks and comments

The Randomized Earned Value Method is a new approach to control and assessment the advancement of works implemented on the construction site under the unstable conditions. The method provides new probabilistic management information that are developed based on data commonly used also at present. But in the Author's method at the beginning, these data are randomized. Then, using such remodified data, probable durations and probable costs of works remaining to project completion after each site inspection, as well as the probable overall duration and probable total cost of works completion also after each site inspection are estimated. Moreover, using the method, the risk of exceeding duration and the risk of overrun cost of works remaining to the project completion as well as the risk of exceeding overall duration and overrun total cost of all works are estimated. The main results of the REVM method application have been tallied in the Table 10.

In general, the REVM method can be used in conditions of weak and strong impacts disrupting the process of works execution. In the first case, when the impacts of random disturbances can be eliminated by implementation special direct operational actions, the early part of the method can be applied. It is a deterministic analysis, analogous to the classical EVM method. In the second case, when accidental interferences can significantly disturb works execution, full REVM method must be used. It can be done similarly as presented here referential example of the rolling assessment the advancement of the construction of the office building. Based on the foregoing and other results of the REVM method application one can conclude that the method has been already well theoretically tested and can be used for the rolling assessment the advancement of various construction objects erection. Moreover, on the grounds of research that has been conducted, the Authors and professionals that have who have become acquainted with the method appraise that under the risk conditions, the proposed REVM method allows more thoroughly and reliably assess the advancement of construction works than by using the classic EVM method. Finally, it should be mentioned that currently, from a practical point of view, an operational applying the REVM method would be very difficult or even impossible. This is because practical application of the method is strongly limited by lack of convenient software which would allow to apply the method without knowing the process of assessment the advancement of the works. Heaving such software, the REVM method can be used by construction works managers based on results of the quantity survey and allocation of cost of works already executed. Using these results, the managers should be prepared according to the simple rules only strictly determined input data. Then the process of assessment the advancement of works would be developed by software program. Of course, in this case, managers should scrutinize the received output results, maybe in connection with extrinsic factors that can also impact works implementation. Based on results of the analyse they would be able to make decisions that determined corrections future implementation of the project or, in a particular case, a comprehensive verification the further organization or even abandonment an implementation of the works.

Finally, it should be noted that the method still required a profound further studying and especially analysis of practical applying and development of convenient full project management software. All these problems are studied by Authors.

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Zastosowanie randomizowanej metody wartości wypracowanej do oceny zaawansowania budowy biurowca w niestabilnych warunkach realizacji

Słowa kluczowe: inwestycja budowlana, czas trwania, koszt, ryzyko, randomizacja, zarządzanie projektem

Streszczenie:

Metoda REVM jest unowocześnioną wersją klasycznej metody EVM. Nowa metoda została opracowana do stosowania w niestabilnych warunkach realizacji robót. Kiedy roboty mogą zostać przypadkowo zakłócone i należy wziąć pod uwagę wpływ przypadkowych czynników zakłócających na przebieg i wyniki robót. Następnie Randomizowany Budżetowy Czas Trwania do Ukończenia i Randomizowany Budżetowy Koszt do Ukończenia, czyli czas trwania i koszt robót pozostałych do wykonania po każdej kontroli, a także Randomizowany Budżetowy Czas Trwania po Ukończeniu i Randomizowany Budżetowy Koszt po Ukończeniu, czyli czas trwania i koszt wszystkich prac związanych z realizacją projektu po dokonanej kontroli. Ponadto oceniane jest ryzyko przekroczenia czasu trwania i kosztów robót. Ważne jest, aby dane wejściowe wymagane do metody REVM były podobne i mierzone w taki sam sposób, jak w typowej kontroli zaawansowania robót. Jednakże wyniki zastosowanej metody zawierają nowe informacje decyzyjne. Sterowanie inwestycją w warunkach deterministycznych, bez uwzględnienia ryzyka zakłóceń, spowodowało ostateczne odchylenie od planowanego budżetu o ponad 7%, a od planowanego czasu zakończenia inwestycji o prawie 12%. Bez analizy czynnika związanego z zakłóceniami na etapie realizacji inwestycji harmonogram rzeczowo-finansowy byłcałkowicie nieaktualny. Z kolei przy kontroli inwestycji w warunkach ryzyka i wprowadzaniu zmian organizacyjnych
i technologicznych adekwatnych do protokołów z kontroli ostateczne odchylenie od planowanego budżetu wyniosło mniej niż 2%, a od planowanego terminu zakończenia nieco ponad 2%. Badania potwierdzają, że wyniki uzyskane metodą REVM dobrze odzwierciedlają rzeczywisty stan realizacji robót.

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