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Reliability assessment of the construction schedule by the critical chain method

Модель надежности календарного графика строительства

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Ключевые слова: управление проектами; контроль расписания; базовый план; критический путь; метод Голдрата; буфер проекта; строительный проект; критическая цепь; теория ограничений; управление строительством

Abstract. Implementation of the construction projects is associated with significant current material, technical and financial costs. They increase significantly in case of the breaking deadlines the large stages of projects and putting buildings into operation. The main aim of the current research is development the new approach for reliability model of the construction schedule for increasing reliability of the calendar planning regarding the meeting the construction projects on time. The following task were solved: the model of technical, labor and time reserves was developed; the algorithm of effective operational management system for the entire construction production process was offered. The probability of task completion was assessed by the E.M. Goldratt method, the probability function, based on the beta distribution was used. Initiating a shorter work execution period as a more stringent control action leads to an increase in the reliability of the construction program in the established settlement (contract) time from 50% probability to the normative 90% probability. Probabilistic approach allows to assess the achieved effect of applying the methodology of EM. Goldratt for the streamlined construction and to take a measured deadline for the execution of tasks in the development of the construction project.

Аннотация. Условия реализации строительных программ определяют текущие материальные, технические и финансовые издержки, которые существенно возрастают при несвоевременной сдаче крупных этапов работ и при нарушении сроков ввода завершенных строительством объектов в эксплуатацию. Целью исследования является разработка нового подхода к оценке модели надежности календарного плана строительства для повышения вероятности своевременного выполнения проекта. Для оценки надежности выполнения работ, организованных по методу Э.М. Голдратта, была использована функция вероятности на основе бета-распределения. инициирование уменьшенного срока выполнения работ и более жесткое управляющие воздействия приводят к повышению надежности выполнения строительной программы в установленные расчетные (контрактные) сроки с 50 % вероятности до нормативной 90 % вероятности. Разработанный подход позволяет оценить достигаемый эффект при применении методологии Э.М. Голдратта для поточной организации строительства и принять взвешенные сроки выполнения работ при разработке строительной программы.

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1. Introduction

Implementation of the construction projects is associated with significant current material, technical and financial costs. They increase significantly in case of the breaking deadlines the large stages of projects and putting buildings into operation. All current construction costs determined by designers and estimated in documentation are compensated by the investor while making the advance and final payments for the completed construction projects. Late commissioning the buildings into operation, an intensive work at the final stages of the projects lead to the additional costs over the estimated one in the calculation. Exceeded expenses are refunded by the internal resources of the contractor construction organizations. Penalties, fines and forfeits for the untimely completion the project stages become the additional expenses of the construction companies. For this reason, project managers devote the considerable attention to the investigation of methods and approaches for meeting the deadline of construction projects on time [1–4].

The theory of constraints (TOC) and the method of critical chains were formulated and proved by E.M. Goldratt [5–8]. They belong to the category of methods aimed at the formation the logical management procedures to achieve the quality and timeliness performing the various programs [9–12]. TOC and the method of critical chains are designed to take into account possible constraints and disruptions that may arise during the plan implementation, as well as to identify the restraining process for project development [13–16].

At the same time, realization all stages and tasks can be calculated without any delays in conditions of the intensive fulfillment the processes. Taking into account the accompanying factors, the deadlines for the performance of tasks become significantly shortened and their critical chain is determined. For this reason, the measures are provided: the expansion of bottlenecks and the temporary time reserves buffer is formed only before the end of the program at the end of the critical chain [17–20]. Lack of accounting the possible difficulties and delays in determination the individual tasks duration with intensive implementation lead to performing them in a tight schedule. If failures and delays occur, they are compensated by the final program buffer in the form of the provided amount of time and resource reserves [21].

Described organizational approach for the implementation stages and tasks according to the technological program (project) significantly increases the volume of organizational and managerial activities. Therefore, a preliminary effectiveness assessment of this system implementation are required. One of the approaches for assessing the critical chain method can be the usage the probability indicator of the implementation the reduced deadlines for accepted programs and reliability indicator of the project completion at the target deadline.

The main aim of the current research is development the new approach for reliability model of the construction schedule for increasing reliability of the calendar planning regarding the meeting the construction projects on time. The following task were solved:

– construction schedule reliability was assessed by the critical chain method.

2. Methods

To assess the probability of task completion by the E.M. Goldratt method, the probability function, based on the beta distribution was used. Application of critical chain approach of E.M. Goldratt proves its effectiveness not in all calculation cases [22, 23]. The indicators of increasing the of program reliability implementation in fixed dates were obtained experimentally and have positive values. But they were obtained for a small number of tests and have a wide space of data at small values. For a wide application of the critical chain method, it is necessary to obtain a sufficiently convincing apparatus for the effectiveness evaluating of its use. In this connection, it is proposed to apply a stochastic-mathematical model for the reliability assessing of the construction plan (schedule) execution, developed and calculated on the base of critical chains method by E.M. Goldratt.

Initiation of tight deadlines for performing the stages and tasks corresponds to certain functions of the management system and can be considered as a direction for improvement the reliability of meeting the deadlines. In this case, the final temporary buffer plays a secondary supporting role and contributes to the reliability of the project. It is possible to estimate the risk reduction of untimely project completion (construction plan) on the basis the beta distribution function of the probability construction and installation tasks within the established timeframes [24, 25]. This function was widely used in the construction when the methods of network planning and management were frequently used.

The methodology for assessing the construction program reliability in accordance with the approved calendar plan, formed by the critical chain method, can be based on the beta distribution function of the frequency distribution function of a random variable [26]. In general, the probability of executing a work plan can be calculated using the PERT methodology, with the appointment the optimistic and pessimistic estimates terms of tasks performance. In the critical chain method under consideration, the control effect on the work program should be taken into account in order to evaluate the results. It is expedient to use the beta-distribution function taking into account the influence of control solutions. The function has the following form:

$$\varphi(x) = \frac{(\xi+1)(\xi+2)(\xi+3)}{2(b-a)^{\xi+3}}(x-a)^{\xi}(b-x)^{2} \tag{1}$$

where $\varphi(x)$ – density frequency function of a random variable;

x – value of the random variable deadline milestone;

a – minimum possible deadline of the milestone;

b – maximum possible end date of the milestone;

ξ – function parameter that takes into account the system performance effectiveness.

It is possible to determine the mathematical expectation for the beta distribution function of the random variable that takes into account the impact of the control system:

$$T_{me} = \frac{b\xi + b + 3a}{\xi + 4} \tag{2}$$

Dispersion of the deadline for the construction program implementation for this function is calculated by the formula:

$$\sigma^2 = \frac{3(\xi+1)(b-a)^2}{(\xi+4)^2(\xi+5)} \tag{3}$$

Parameter of the considered function ξ counts the different operating level of the control system. When $\xi = 1$ a standard form of the beta distribution function is formed, which arises in the normal operation the control system in terms of the frequency and force impact. The decrease in the value of this parameter characterizes the influence strengthening the management system. It contributes to a more complete, timely and early completion the all planned tasks. The value $\xi = 0$ characterizes the state of the most active management. In this case it is impossible the further reducing the failures risks and increase the reliability the timely tasks while forecasting by means of management activities without additional labor and technical resources. In this case, a well-organized technological process is considered without failures, delays and failures.

Increasing the value parameter ξ to 2 or more indicates a decrease in the level of control and its effectiveness. The parameter ξ value is established on the basis of its correlation with the process monitoring level and the frequency of the influence the control decisions. If the making decisions are made less than one per five days, it is advisable to take this parameter at least 1.5.

When the value of the parameter ξ is decreasing, the area under the curve of the beta distribution function moved towards an optimistic evaluating « a » and accordingly decreases the expectation value (2). In case $\xi = 0$,

$$T_{me} = (b + 3a)/4 \tag{4}$$

The tight terms of tasks performance which are less then established by the standards indicate a high management level and, in accordance with the function (1), the value of the parameter ξ should be taken less than 1 (for example 0; 0.3; 0.5; 0.7). According to the E.M. Goldratt recommendations, the duration of operations is assumed to be 50% shorter than the normative value, and therefore the value of the control parameter can be chosen close to the zero. Reduction of technically based standards used in the plans for construction processes in the general case is possible by approximately 30%. Possible failures and delays can extend task completion time to 50 %.

Reduction of the value the mathematical expectation in comparison with the initial value, determined on the basis of the current standards, forms an additional time reserve (buffer). The created time reserve (buffer) contributes to the plan fulfillment within the approved timeframe and increase of its reliability level.

Consequently, the critical chain method promotes to reduce risks and timely completion of the project in two ways. In the first case, reliability is enhanced by creating the ideal conditions for the construction process and encouraging workers to perform work in a shorter time. In the second case, the reliability increase is provided by the terminal reserve (buffer) at the final stage of project execution.

3. Results and Discussion

Application method for the probability-mathematical model

A set of tasks execution was considered to illustrate the performance ability of this mathematical model.

Determine the project duration by calculating of each separate construction process according to technical standards. Join the processes in a complex and get a plan with a deadline of 160 days.

Assuming that an optimistic project duration is $a=(1-0.3)\cdot 160=112$ days and a pessimistic assessment of the plan fulfillment is $b=(1+0.5)\cdot 160=240$ days.

Assign for executors the term of the plan fulfillment 120 days (25 % reduction in terms). At the same time, the contract has a deadline set by technical standards – 160 days. During this period, the contractor is legally responsible. Considering the contraction of the construction plan for the executors, a pessimistic estimate of the completion time of tasks will be $b=1.25\cdot 160=200$ days. (25 % overall reduction in terms).

Determine the reliability (probability) of the plan in contractual period of 160 days with the regular approach and the critical chain method.

The probability of completion the set of tasks for given optimistic and pessimistic estimates for any period can be calculated by the expression:

$$\rho(T)=0.5\alpha^{\xi+1}[\alpha^2(\xi+1)(\xi+2)-2\alpha(\xi+1)(\xi+3)+(\xi+2)(\xi+3)], \qquad (5)$$

where $\rho(T)$ – the probability of execution the tasks in the period T;

$$\alpha=\frac{T-a}{b-a}$$

ξ – a parameter of control system.

– Define the efficiency in the form of the construction plan reliability for the regular standard conditions of work organization for contractual conditions. Accept $\xi=1$.

$$\alpha=\frac{160-112}{240-112}=0.375$$

$$P(160)=0.14(0.14\cdot 3-0.375\cdot 8+6)=0.48$$

– The effectiveness of the plan under standard conditions using the critical chain method for contractual terms will be:

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$$\alpha = \frac{160-112}{200-112} = 0.545$$

$$P(160) = 0.297(0.297 \cdot 3 - 0.545 \cdot 8 + 6) = 0.752$$

Determine the effectiveness (reliability) of implementation the deadline for performers is 120 days by the critical path method:

$$\alpha = \frac{120-112}{200-112} = 0.091$$

$$P(120) = 0.0083(0.0083 \cdot 3 - 0.091 \cdot 8 + 6) = 0.25$$

Define the effectiveness (reliability) of the plan implementation taking into account the using the critical chain method. Calculating of the duration should be made on the basis of labor input standards for 120 days under ideal conditions of work organization and fixed deadlines. Accept $\xi = 0$.

1. $$P(120) = 0.091(0.0083 - 0.091 \cdot 3 + 3) = 0.25$$

Consequently, by setting the shorter terms of tasks execution and forming a temporary buffer, it is possible to get a significant increase in reliability of completion all tasks in the directive dates. It is shown at the graph in Figure 1.

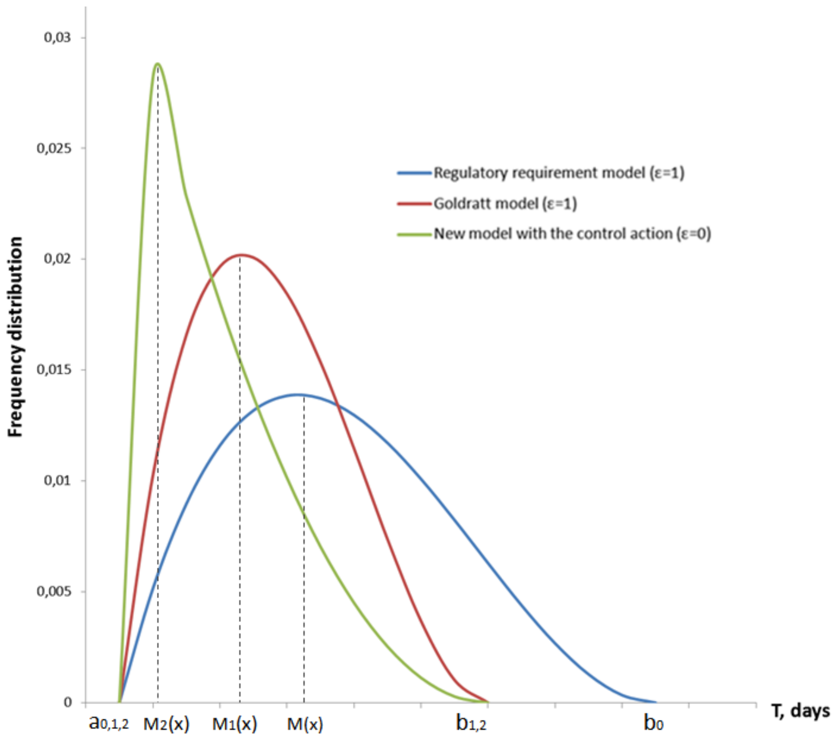

Figure 1. Comparison of normal distribution curves for the mathematical models of the project execution

Existing research examples of the application the critical chain method indicate an increase in reliability by 15–20 %, but the reference frame is not indicated [6, 9, 10]. The conducted studies show the possibility for increasing reliability by 40-45% in comparison with the regulatory base.

4. Conclusions

1. The considered example of the application of the mathematical model shows that initiating a shorter work execution period as a more stringent control action leads to an increase in the reliability of the construction program in the established settlement (contract) time from 50 % probability to the normative 90 % probability.

2. Described probabilistic approach allows to assess the achieved effect of applying the methodology of E.M. Goldratt for the streamlined construction and to take a measured deadline for the execution of tasks in the development of the construction project.

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