Assessment and analysis of programs for the management of transport infrastructure construction projects

Sergei Bovteev¹, Anastasiia Mishakova²

¹Saint Petersburg State University of Architecture and Civil Engineering, 2-Krasnoarmejskaja, 4, Saint Petersburg, 190005, Russia
²Peter the Great Saint Petersburg Polytechnic University, Politechnicheskaya, 29, Saint Petersburg, 195251, Russia

E-mail: sergeibovteev@gmail.com

Abstract. The use of probabilistic non-alternative network models for planning investment construction projects has been thoroughly studied and has been widely used in construction practice for several decades. One of the common methods based on such models is the Program Evaluation and Review Technique. This method is for planning the project dates in which the durations of all or some of the activities cannot be unambiguously determined due to the high degree of uncertainty in the external environment in which such projects are implemented. However, the problem of controlling the deadlines and milestones of an investment construction project based on the Program Evaluation and Review Technique has not been studied well enough. This article investigates the possibilities of applying the Program Evaluation and Review Technique to track and control the construction project schedule. A method based on monitoring the values of the probability function of the timely completion of the project is presented. The method takes into account possible deviations of the predicted completion date of the project and, if they exceed the established limits, prescribes the initiation of corrective measures. We give recommendations for improving the Program Evaluation and Review Technique that reduce its shortcomings in applying for control the construction period. The greatest effect can be obtained by combining the Program Evaluation and Review Technique with other known methods, in particular, the Critical Chain Project Management.

1. Introduction

Construction planning needs to take into account the influence of uncertainty factors, so probabilistic methods of planning construction projects are widely used in practice. Programme Evaluation and Review Technique (PERT) is a quite simple planning tool which can implement a probabilistic approach to calculate the activity durations and the whole construction lasting. It was developed in 1957-58 and successfully used for project planning of rocket system “Polaris” in the USA. At first, PERT was created for to manage large-scale, elaborate and innovation projects. But also it can be applicable in the planning of construction especially large, unique buildings, structures and their complexes, large-scale industrial objects and energy facilities.

The sequence of activities is set on the network model. But there are some differences from the determinate methods for calculating the terms. The most famous among determinate methods is the Critical Path Method (CPM), developed almost at the same time as the PERT. The PERT involves a probabilistic approach to determining the duration of all or some of the project’s activities in the form of a beta-distribution limited by three estimates of work duration:
- $t_{oa}$ – Optimistic time – The least amount of time it can take to complete an activity.
- $t_{ob}$ – Pessimistic time – The maximum amount of time it should take to complete an activity.
- $t_{om}$ – Most likely time – The estimate corresponding to the mode of probability distribution.

The duration of each individual project activity is considered as a random variable change in the interval $(A, B)$, where $A > 0$ and $B > A$, also $A$ is an optimistic and $B$ is pessimistic estimate of the duration. If $B - M > M - A$, where $M$ is the mode of a beta-distribution, PERT allows to manage project dates with large time reserves. In this case, the assessment of the duration becomes more “pessimistic” and thereby increases the degree of reliability of the resulting schedule.

Due to the using PERT, the following results can be obtained:
- optimistic, pessimistic and expected (with a security of 50%) total project duration (Figure 1);
- function of the normal probability distribution of the total project duration (Figure 2);
- the ability to determine the probability of completion of the project (as well as a separate control event) by the deadline;
- the project duration, which is ensured with an adjusted probability.

![Figure 1. Optimistic, most likely and pessimistic duration of a construction project in the MS Project.](image)

The critical path method (CPM) makes it possible to calculate the total project duration without taking into account the influence of uncertainty factors, though PERT allows to calculate the probability of project completion by the deadline. It helps the project sponsor make a weighted decision about the start of the project (when the project sponsor is ready to accept the risk of untimely completion of the project obtained as a result of the PERT calculation).

The use of the PERT method for planning construction projects has been studied quite deeply. Possibilities of using this tool to track and control project timelines require further analysis and will be described in this article.

We had analyzed some researches of the PERT, which are aimed at its development. One of the main problems of PERT is the lack of consideration of the impact of the actual duration of completed tasks to the estimated duration of the ahead project activities. The article [1] proved four theorems on the inadmissibility of ignoring correlation in PERT calculations.

In article [2], a project risk management model based on PERT is proposed. This model involves dividing risks into two groups: risks that can be accepted, and risks that can be prevented for a certain price. This model is required to help the project manager decide what risks need to be eliminated in the way that the requirements for timely completion of the project are satisfied at a minimum spendings.

In article [3] a model for PERT network failures is considered, in which the probability of occurrence of pessimistic durations of activities is minimized due to the investment of additional funds for performing critical tasks. The results of the application of the proposed model in practice showed a reduction in the construction time, as well as a decrease in the standard deviation, which leads to an increase in the probability of the project completion on time.

In the research [4], a project control technique taking into account the uncertainty in the performance of tasks was proposed. In [5], a dynamic approach to project planning and control is considered, based on the continuous generation and updating of project data, which is an extension of PERT. But, in our opinion, it applies only to project scheduling, as implies recalculation of PERT networks to obtain the optimal planned duration, which is carried out before the start of the project.
Figure 2. Probability distribution of the total project duration obtained as a result of calculating the project using the PERT.

A fixed start method [6] has been proposed as an alternative to CPM and PERT. It is aimed at fixing the deadlines for starting work with a high level of probabilistic confidence for the planned project duration. The duration of the project is proposed to be estimated based on mean, variance and coefficient of variance.

The combination of the PERT and CPM was investigated in [7]. The authors emphasize that high-quality scheduling can only be achieved by combining the positive aspects of one and the other methods, and similar collaboration allows eliminating the negative aspects of these methods. A similar approach is demonstrated in [8], however, in this work, the PERT is combined not only with CPM, but also with the parametric estimation with physical models used in manufacturing field. In addition, the authors point to the need for overestimate total project duration as precautionary behavior. More accurate approaches to determining the duration of individual activity and the entire project can eliminate this problem. A methodology for quantifying risk assessment is proposed in [9]. It can be used to reduce risk-related costs. This tool is based on a general assessment of risk factors using the extension engineering method, it should be taken into account when calculating the network model using PERT.

In [10], PERT is criticized and it is proposed to abandon it in favor of modeling the project based on GERT networks. At the same time, the authors offer some improvements that can be taken into account when upgrading PERT, such as using an inversion formula to obtain the probability distribution of product development completion time, introducing novel measure of schedule risk, and using elasticity analysis to determine the parameters of the network model.

An interesting extension of PERT, combining the earliest and most significant solutions, was proposed in [11]. The so-called M-PERT allows to take into account a number of network modeling functions, such as probabilistic alternative paths, activity self-loops, minima of activity sets and, most importantly, correlation between activities. With all this, M-PERT allows to perform work parameter calculations without using computer technology by using a recursive merging procedure.
A method similar to the PERT approach for evaluating the reliability of total project duration using the reliability theory was proposed in [12]. It eliminates the inaccuracies of the PERT through an innovative solution for accurately assessing the reliability of the project duration.

The proposal to use the generator of random durations as initial data for calculating the terms of tasks by the PERT was given in [13]. At the same time, the planned duration is taken as the minimum (optimistic) duration of the work, and the same planned duration, but multiplied by the "index of late commissioning of the facility", which means the ratio of the completion date of the project at which the customer has zero profitability by the planned date. Articles [14, 15] are presented a model that determines the assessment of the planning horizon and its impact on the assessment of the pessimistic durations of the construction project, while the determination of optimistic estimates of the durations of task is based on the planned determinate values. The authors argue that with the removal of task towards the planning horizon, the visible duration of task decreases, that is, the risk of a prospective decrease in the duration of work increases with an increase in the time between the end of development of the project schedule and the start of construction. This hypothesis can be used to refine estimates of the duration of activity when calculating the network model of a construction project using the PERT.

Critical analysis of PERT and the need for its modification are discussed in [16, 17]. The lack of a reliable planning tool is noted in [18], in which the author offers his universal method for calculating the reliably justified duration of the completion of a construction project based on a network model containing work with indefinite durations.

Thus, we see that a lot of researchers are critical of the possibility of using PERT for planning real construction projects. They point to its limitations, such as the absence of the influence of the durations between different activities, the weak substantiation of optimistic and pessimistic durations of activity or the absence of such justification, the replacement of the beta distribution, which acts as the initial duration of work, with the normal distribution obtained by calculation and many others. Elimination of such disadvantages is proposed due to PERT extensions, as well as scientific justifications for initial estimates of the duration of work.

We also want to note the lack of researches studying the problems of monitoring the construction project schedule using the PERT method.

2. Materials and Methods

First of all, we will analyze the applicability of PERT to the scheduling and control of construction projects and set whether this method can be used to ensure timely completion of the project, and, if so, in which areas and how efficiently.

The accumulated experience of the actual implementation of a large number of construction projects suggests that the project does not complete on time due to one or more reasons. These reasons subdivide into the following categories:

1. Slow (compared with the planned intensity) realization of one or more project’s tasks. First of all, critical activities or non-critical activities, which duration increase went beyond its time reserve;

2. Stopping of the work for a considerable time as a result of the onset of one or more risk events (in this case \( t_{\text{act}} > t_b \), where \( t_{\text{act}} \) is the actual duration of the activity, that means that the actual duration of the activity will exceed the pessimistic estimate of its duration);

3. Failure of task's onset – subsequent activity cannot begin immediately after the end of the previous activity for certain reasons (there are no work crews, workers are not equipped with the required tools or equipment, the construction machine is broken, the delivery of building materials, structures or equipment has low-quality, the working documentation is missing or not approved by technical customers).

The PERT allows to simulate situations caused by the reasons of the first category. However, by definition, it cannot fully cope with the causes of the second and third categories, because it is not aimed to take into account gaps in the performance of activity and stretch of ties between tasks (since possible stretch of ties between two activities caused by the influence of negative factors cannot be modeled with using the beta-distribution).
The PERT has a number of disadvantages, which are indicated by the conducted researches. One of the significant drawbacks is the lack of consideration of the effect of actual work results on the duration of subsequent project work.

This means that estimates of the duration of tasks are independent and do not affect each other. However, this statement is controversial. In cases where the project lags behind the approved deadlines, the project manager begins to exert regulatory impact. He takes measures to increase the intensity of the remaining work, for example, parallel execution of critical work. In cases where the project is ahead of the approved schedule, on the contrary, the intensity of the remaining project work may be slowed down.

In addition, estimates of the duration of work are also considered a drawback. The optimistic, pessimistic, and most probable estimates of the durations are most often given by experts, thus, these estimates are far from always accurate. Poor source data cannot lead to quality results.

There are other drawbacks to the PERT that are beyond the area of this article.

Let’s take a closer look at some features of the application of the PERT to control the timing and overall duration of the project.

Suppose that the project sponsor’s preparedness for risk allows a decision to initiate an investment construction project, which probability of completion by the target date is \( N \) (determined on the basis of the PERT method at the start of the project) and also \( 0 < N < 1 \) (for example, set the value \( N \) equal to 80\%). One of the authors of this article proposed the principle [19, 20], according to which, during the implementation of an investment construction project, the probability of its completion on time should increase evenly and by the time the target date arrives, aim at one. It was proposed to determine the probability of the project reaching the target date at each periods by recalculating the deadlines for completing the work remaining after the date of the report using the PERT.

The assumption of a unified increase in the probability of completion of an investment construction project in a straight line can be considered true only in a first approximation. In some cases, it is possible to pre-establish points for obtaining additional information, the occurrence of which can make it possible to substantially refine and revise estimates of the duration of work, for example, the date of receipt of an updated weather forecast may serve as such a point. Thus, the probability function of the completion of the project in time \( TP(t) \) may be not an increasing straight line, but a broken line or even a curve. This fact does not cancel the reasoning presented in this article, but only supplements them.

With a decrease in the degree of uncertainty that occurs as the construction project is completed, the variance of the estimates of individual task durations should decrease, however, the estimates of the durations themselves can be revised when more accurate information is obtained (for example, when updating the weather forecast).

Thus, there are two objective functions for monitoring a project, which schedule is calculated using the PERT. Namely, the function of the probability of completion of the project in time \( TP(t) \), which tends to one, and the variance function of the estimate of work’s duration \( \sigma_i^2(t) \), calculated for each \( i \)-th work of the construction project, which tends to zero, since in the absence of any or uncertainty in the duration of the project \( t_{ia} = t_{ib} \), and \( \sigma_i^2 = 1 \).

Recall that, according to the PERT, the values of the expected duration \( t_{ie} \) and the variance of the works \( \sigma_i^2 \) are calculated in accordance with the following relationships:

\[
\begin{align*}
t_e &= \frac{t_a + 4t_m + t_b}{6}, \\
\sigma^2 &= \left(\frac{t_b - t_a}{6}\right)^2.
\end{align*}
\]

Let’s view the statements above on example of implementation of the investment construction project, which duration is 200 days. Estimates of the duration of the project may change over time of the project, as shown in Table 1. Here we consider the activity, which expected start date is 170th day of project, according to the project schedule.
Table 1. Change in estimates of the work duration in the process of implementing an investment construction project (example).

| Status dates | Optimistic duration $t_{oa}$, days | Most likely duration $t_{im}$, days | Pessimistic duration $t_{ib}$, days | Expected duration $t_{ie}$, days | Dispersion $\sigma_i^2$ |
|--------------|------------------------------------|------------------------------------|------------------------------------|--------------------------------|-----------------------|
| 0            | 4                                  | 8                                  | 15                                 | 8.5                            | 3.361                 |
| 20           | 4                                  | 7.5                                | 14.5                               | 8.083                          | 3.063                 |
| 40           | 4.5                                | 8                                  | 14.5                               | 8.5                            | 2.778                 |
| 60           | 5                                  | 8                                  | 14                                  | 8.5                            | 2.25                  |
| 80           | 5.5                                | 7.5                                | 13.5                               | 8.167                          | 1.778                 |
| 100          | 5.5                                | 8                                  | 13                                  | 8.416                          | 1.563                 |
| 120          | 6                                  | 8.5                                | 12.5                               | 8.5                            | 1.174                 |
| 140          | 6                                  | 8.5                                | 12                                  | 8.667                          | 1                     |
| 160          | 6.5                                | 8                                  | 11                                  | 8.25                           | 0.563                 |

Obviously, in the process of project implementation at its individual stages, the current assessment of the probability of project completion on time $P(t)$ may differ from the objective function $TP(t)$. The project sponsor needs to understand in which cases the project manager and project team will quickly eliminate negative deviations on their own, and in which cases the intervention of a higher level project management subject is necessary: project board or project committee. For this, along with the objective function, two functions of permissible deviations should be introduced: $TP_1(t)$ and $TP_2(t)$. At the start of the project, these functions are equal to the probability of timely completion of the project $N$, accepted at this stage, reduced by a certain amount of permissible deviation, for example, by 2 and 5%, respectively. It is determined by the choice of project sponsor and depends on the degree of his trust in the involved project manager and team.

Function $TP_1(t)$ shows the boundary of the transition from the “green” zone to the “yellow” one, while the transition to the “yellow” zone obliges the project manager to develop a corrective action plan, and the project sponsor to make decisions to increase the budget or reduce the content of the project. The function $TP_2(t)$ shows the border of the transition of their “yellow” zone to “red”, while the transition to the “red” zone signals a significant decrease in the probability of completion of the project at time, which should trigger more active actions by project sponsor (Figure 3).

![Figure 3. Probability functions for a project completion on set time.](image-url)
In fact, the meaning of controlling the project schedule according to the PERT is to ensure a constant and uniform increase in the probability of the project completion in the directive period. And in cases when deviations are recorded, take regulatory measures. Thus, if the initial probability of project completion was assumed to be 80%, and the permissible variation was 2%, then in the middle of the project the probability of project completion on time should be no less than 90% (and the permissible variation should be 1%), and at the time of the approved project completion dates:

\[ TP(t) = TP_1(t) = TP_2(t) = 100\% .\]

We illustrate these arguments with specific examples. Figure 4 shows the nature of the probability function for the project completion within the approved time period \( P(t) \) in the case when the project is successful. Figure 5 shows the nature of the probability function of the project completion in the approved period \( P(t) \) in the case when the project does not complete on time.

3. Results and Discussion

This article proposes a technique to control the dates of the construction project, which schedule is calculated by the PERT. It is possible to determine at certain stages the probability of project completion at time, which should increase with the course of the project. It based on the periodic monitoring of the actual project’s parameters and correction of the parameters of remaining activities. Based on the obtained value, it should be determined in which zone the probability of an investment construction project is located, this result affects to further decisions.

This method involves the following sequence of actions:

1. Take the acceptable for project sponsor (at the start of the project) probability of a project completion on time.
2. Set the functional relation of probability of project completion on time, which varies by the accepted risk at start of the construction project from \( TP(t_s) < 1 \) to \( TP(t_f) = 1 \) at the finish of the project. Here \( t_s \) is the project start date, \( t_f \) is the project finish date. Also set the nature of the function – a straight line, a broken line or a curve.
3. Set the frequency for tracking the project schedule and planned dates for recalculating the schedule of the remaining activities using the PERT (dates of clarification of project information or dates of reduction of uncertainties).
4. To determine the permissible deviations from the probability of completion of the project on time \( TP_1(t) \) and \( TP_2(t) \), and the nature of their changes in the process of project implementation.

![Figure 4. An example of the probability function of project completion on time if the project is successful.](image-url)
Figure 5. An example of the probability function of project completion on time if the project is failed.

5. Accept that if at a certain time point the probability of project completion becomes lower than $TP_1(t)$ (the project is in the “yellow zone”), it is necessary to formulate and approve a request for changing the parameters of the construction project or a plan of corrective measures.

6. Accept that if at a certain time point the probability of project completion becomes lower than $TP_2(t)$ (the project is in the “red zone”), it is necessary to recognize the project as unsuccessful.

The proposed algorithm can be applied not only to the entire investment construction project, but also to predict the timely onset of its individual control points – in this case, the sequence indicated above must be applied to the corresponding individual blocks of the project schedule.

In addition, we offer several principles that make it possible to apply the PERT to control investment construction projects more efficiently than with the traditional approach. Firstly, the independence of the duration estimates for each activity is recognized as a drawback of the method. However, with a periodic reassessment of the duration of the activity, one can take into account the lag factor or, conversely, the factor ahead of schedule. Thus, the actual duration of the performed task begins to directly affect the estimates of the duration of the upcoming tasks. We also propose an approach according to which estimates of the duration of immediately forthcoming tasks are multiplied by a decreasing coefficient, for example 0.9, and estimates of the duration of tasks located closer to the completion of the project are multiplied by a raising coefficient of 1.1. This will lead to the fact that the project at the beginning of its implementation will begin to be a little late, which will force the project manager to take compensatory accelerating effects. And a reserve of time will be created in the final phases of the project completion, that will contribute to the timeliness of the completion of the project.

Secondly, as we established above, PERT cannot cope with situations of unforeseen delays in the start of activities, that is, in the PERT-modeling there are no such calculated capabilities. In this case, it is necessary to compensate possible delays by forming the project buffer, known in the Critical Chain Project Management (CCPM). Thus, the combination of PERT and CCPM principles, which will be investigated in our subsequent works, can be considered more effective for monitoring investment construction projects.

Note that a significant number of researchers indicate that during the work on the "pessimistic scenario" additional costs are needed to increase the probability of timely completion of the project. In other words, it is necessary to find the optimal point on the ratio of the duration and cost of construction. And this can be the main optimization task in controlling the schedule using the PERT method.
4. Conclusions
This article presented the development of the PERT in relation to the monitoring of the implementation of investment construction projects. It is proposed to carry out time control on the basis of the formation of the objective function of the probability of timely project completion, which increases from the accepted probability of completion at the project’s beginning to one at the end of the project. We propose to accept in advance the values of possible deviations of probability from this function, in which the project moves from the green zone to the yellow one, and from the yellow zone to the red one, while the transition from one zone to another can initiate the adoption of appropriate corrective measures.

We propose the refinement of estimates of the remaining task’s duration with a certain degree of periodicity, with the obligatory taking into account the actual duration of the performed work and the relationship of the actual duration with the previously given estimates - pessimistic, most likely and optimistic. The degree of uncertainty is reduced and the variance of the work should consistently decrease when refining the estimates of the duration.

The authors hope that the proposed approach, as well as its subsequent development, can increase the effectiveness of PERT for investment construction project scheduling and controlling.

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