GENERATING A PROBABILISTIC CONSTRUCTION SCHEDULE

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Abstract
Introduction: The design stage and preparations for construction include the development of construction schedules needed to justify the duration of construction works. **Methods:** Based on probabilistic scheduling, a multitude of solutions can be generated for each implementation roadmap (progress chart). These decisions can be defined as optimistic, most probable or likely, and pessimistic. Rational roadmaps are selected in accordance with benchmarking. Simple and discounted payback periods are used as frequently applied criteria included in the system of evaluating the economic effectiveness of investment projects. Based on identifying the given indicators of project evaluation, a method of designing probabilistic construction progress charts has been developed; the latter serve as the basis for devising respective organizational-technological solutions. **Results:** The design of optimistic, pessimistic, and most probable construction roadmaps (schedules or progress charts) enables the use of a developed model for probabilistic prognostication of future production risks affecting the delay of construction completion.

Keywords
Construction scheduling, project management, organizational-technological reliability, probabilistic network construction models, delayed construction.

Introduction

At the stage of design and preparations for construction, carried out as part of the construction organization project, a roadmap or calendar progress chart is developed to justify the duration of project construction and the duration of its various stages (Government of the Russian Federation, 2008). The following recommendation aimed at the selection of organizational-technological solutions is given in Regulations 48.13330.2011 (Ministry of Regional Development of the Russian Federation, 2011): “Construction organization decisions should be based on studying alternatives and using benchmarking and modeling methods as well as modern hardware and software.” Following the given recommendation, one can assume that studying calendar progress chart alternatives must be based on a modern project management system that includes statistical modeling methods and the *PERT* method (PMI, 2008) leaning on optimistic and pessimistic assessments of work durations. A respective benchmark evaluation of alternative construction roadmaps (calendar progress charts) is to be determined by relevant valuation parameters for assessing the economic effectiveness of investment projects (Ministry of Economy of the Russian Federation, Ministry of Finance of the Russian Federation, State Committee for Construction, Architecture and Housing Policy, 2000).

When probabilistic scheduling methods are used, developers of calendar progress charts bear in mind that the construction process is liable to accidental exposures while respective durations of works should be expressed as random variables. The first study (Gusakov et al.,1977) highlighting general matters of probabilistic scheduling gives recommendations on developing and using probabilistic network models in construction. Yet there are no specific recommendations for the numerical definition of all probabilistic characteristics peculiar to calendar progress charts. One of the later works (Barkalov et al., 2010) points out that almost all systems of probabilistic scheduling assume that the density of distribution regarding work duration time estimates is to have three properties: continuity, unimodality, and two nonnegative points of its intersection with the x-axis. The authors further argue that it is a beta distribution that meets these criteria, whereas probabilistic parameters are set by three alternative durations of works: optimistic, pessimistic, and

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the most likely ones. As regards the quantitative determination of these parameters, Barkalov et al. suggest that these are to be provided by managers in charge of construction works, or based on available norms and standards or on actual experience. It should be noted straight off that the analysis of modern databases regarding labor norms shows the lack of probabilistic norms or standards (Bolotin and Kotosvksya, 2013, Porshneva, 2011; Solin, 2011).

The recommendation to use the expert evaluation method is relevant, as proven by Velichkin (2014): "The deadlines can be assumed on the basis of experience and available expertise…." Anferov et al. (2013) say: "The lack of any ways to take into account the probabilistic nature of the construction process that includes construction and power-driven (mechanized) works lowers the reliability of organizational-technological and managerial decisions in the industry." A similar handicap exists in project management software: there is a module meant for the *PERT* method to be used in the *Microsoft Project* software, but the input of probabilistic parameters is methodologically undefined (Kupershtein, 2011).

In some works, you can come across certain criticism of the *PERT* method and even find some recommendations on how it could be improved; however, this criticism and recommendations suggested have nothing to do with the quantitative definition of probabilistic durations of works (Oleynikova, 2008, 2013). There is no easing of this bottleneck in the international PMBOK standard geared towards the use of the project management system (PMI, 2008).

Thus, the main purpose of the given article is addressing the practically relevant task of justifying the values of temporal characteristics of the probabilistic construction roadmap developed within the construction organization project.

Materials and Methods

Prior to the beginning of design and project-oriented preparations for the construction process, a technical assignment for the design of a capital construction project is set. The standard form of the technical assignment was developed and approved in 2018 by the Russian Ministry of Construction, Housing and Utilities. Among other things, the given form contains information about the presence or absence of a project investor, which can be used to develop and assess the pessimistic and optimistic alternatives of the calendar progress chart (construction roadmap). The hypothesis embraced by the authors of this article was chosen because the alternative related to capital attraction requires additional expenditures disbursed at the discounting rate *E* describing the dependency of the money cost on time (Copeland et al., 1995). In the alternative defined by the lack of attracted capital, there are no extra expenditures. The alternatives presented spawn divergent assessments of the project payback period.

The most graphic illustration of this discrepancy is equations used to find the discounted payback period *DPB* and simple payback period (*PB*). The simple payback period can be calculated using the following equation:

$$\int_0^T c(t)dt = \int_T^{PB} r(t)dt \quad , \tag{1}$$

where *c(t)* is the differential distribution of capital investments in time;
r(t) is the distribution of the recurrent cash flow in time,
T is the construction duration.

The discounted payback period is calculated using the following equation:

$$\int_0^T \frac{c(t)}{(1+E)^t}dt = \int_T^{PB} \frac{r(t)}{(1+E)^t}dt \quad . \tag{2}$$

Both the above-mentioned equations describe the consecutive fulfillment of investing and operating periods defined by cash flows related to project construction and management of a built facility. For the assumed sequence of investing and operating periods in the project's life cycle, the ratio of the discounted to simple payback periods will always be more than 1.

$$ID = \frac{DPB}{PB} > 1 \quad . \tag{3}$$

The given inequation shows that investment funds attracted increase the payback period and this delay depends above all on the adopted discounting rate. The hypothesis of our choice lends itself to the following rationale. Since almost any investment construction project is estimated both in terms of the simple payback period and the one with a discounted cash flow, the ratio of the discounted to simple payback periods may serve as a yardstick of untimely execution of future construction works.

Let us focus on the proposed model of calculating probabilistic durations of works using the example of a simple calendar process chart for the construction of a residential building, comprising the following cycles of consecutive works: preparatory and underground works, aboveground works and interior fit-out works. The choice of the given scope of works coincides with the structure of works used in construction duration standards (Repository for legal documents, standards, regulations and specifications, 2020). For the method described below, the value of the standard presented comes down to information about the distribution of capital investments by months of construction activity. The given standards coupled with consolidated standards of construction costs (Repository for legal documents, standards, regulations and specifications, 2014) allow a complete reproduction of the investment cash flow *c(t),* even without a detailed feasibility study. This being said, minimum information about a future facility is needed in case of residential buildings: wall structure, floor count, and total area.

The recurrent cash flow *r(t)* related to a built facility depends either on the sale schedule and the price per unit of space or on the rental price of built premises. If this information is missing, then it is necessary to set the discounted payback period *DPB* and discounting rate *E* in order to figure such annuity of presumed income that would match the preset payback period. The following equation can be used for the calculations:

$$\sum_{i=1}^{T}\frac{c_i}{(1+E)^i}=A(1+E)^{T/12}\frac{1-(1+E)^{T/12-DPB}}{E}, \quad (4)$$

where C_i is the distribution of investments by months until the construction completion *T*, also expressed in months; *A* stands for the annuity.

The left part of equation (4) represents cumulative investments discounted by the construction start date and calculated with due regard for investments to be provided towards the end of the month (Kovalev, 1998). The right part of equation (4) represents the value of discounted annuity whose duration is determined by the difference between the discounted payback period expressed in years and construction duration expressed in months (Repository for legal documents, standards, regulations and specifications, 2020). Equation (4) can be used to arrive at the equation of calculating the annuity that would ensure the discounted payback period, given the preset discounting rate:

$$A=\frac{E(1+E)^{T/12}}{1-(1+E)^{T/12-DPB}}\sum_{i=1}^{T}\frac{c_i}{(1+E)^i}. \quad (5)$$

With reference to the known annuity, one can find the simple payback period using equation (6):

$$PB=T/12+\frac{\sum_{i=1}^{T}c_i}{\sum_{i=1}^{T}\frac{c_i}{(1+E)^i}}\frac{1-(1+E)^{T/12-DPB}}{E(1+E)^{T/12}}. \quad (6)$$

It should be borne in mind that the distribution of capital investments in time can be expressed both in absolute and relative parameters represented in Construction Rules and Regulations SNiP 1.04.03-85 (Repository for legal documents, standards, regulations and specifications, 2020). As per the earlier determined payback periods, one can then calculate their ratio and assume it to be the ceiling value of the index of delayed works *ID*. Under this estimation of the maximum relative delay of construction works in the calendar process chart, a definite positive factor is that it is in full harmony with the criteria of estimating the effectiveness of investment construction projects.

Discussion

Bolotin et al. (2014) review the method of space-time analogy showing an increase of relative works' execution delay in case of the absolute construction start date incrementing. Based on this method, a model of calculating the pessimistic work execution time is proposed that includes the planning horizon *H* found by means of equation (7):

$$H=\frac{3}{\ln(1+E)}. \quad (7)$$

Bolotin and Dadar (2016) consider a similar calculation model; yet a different equation is suggested for the planning horizon (8):

$$H=\frac{\pi}{2\ln(1+E)}. \quad (8)$$

The numerical value of the planning horizon calculated by means of equation (7) is almost twice as high as the value obtained by means of equation (8), while it does not seem possible to rationalize which of the values is more correct. Therefore, the construction project's payback periods are used as an analog of the planning horizon in the model laid out in the given article.

The calculation of pessimistic durations, proposed by Bolotin et al. (2014), Hejducki et al. (2015) is done using equation (9):

$$t^{pes}=\frac{H\cdot D}{H-L-S+D/2}, \quad (9)$$

where *D* is the work's determined duration; *L* is the duration of works on a project; *S* is the determined (fixed) beginning of works.

Equation (9) shows the increasingly pessimistic duration of the work as it approaches the planning horizon. Equation (9) includes the duration of project works, which is rather uncertain. The circumstances mentioned above decrease the value of the given model. This is why Bolotin and Dadar (2016) propose an alternative equation based on the link between the pessimistic duration of the work and the discounting rate.

$$t^{pes}=\frac{(1+E)^{S+D}-(1+E)^{S}}{\ln(1+E)}. \quad (10)$$

As a result, the calculation of the pessimistic duration of the work lacks uncertain values, but at the same time, the given equation does not take into account an important characteristic of the project, such as the distribution of capital investments in time, even though the latter, as was demonstrated above, affects the project's payback period. Bolotin and Dadar (2016) point out that in the process of deriving equation (9) it was neglected that new pessimistic durations generate a new timetable and new start dates; as a result, the given calculation is correct only for the first iteration.

The model based on using payback periods, proposed in the given article, addresses the above-stated issues in the following way. We

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bring the maximum delay index into conformity with the discounted payback period and assume that the most likely value of the current delay index will be proportionate to time *t* from the construction start date to the construction end date.

$$ID^{mid} = 1 + \frac{ID}{DPB} \cdot t. \quad (11)$$

The pessimistic value of the current delay index should be found using equation (11):

$$ID^{pes} = 1 + \frac{ID}{PB} \cdot t. \quad (12)$$

As was suggested by Bolotin and Birjukov (2013), determined (fixed) values of works' durations can be used for the optimistic roadmap. To devise the likely or pessimistic calendar process charts, it is necessary to calculate respective durations of works (e.g. pessimistic t^{pes}). A respective calculation equation can be obtained through integration of the following expression:

$$t^{pes} = \int_{S}^{S+D} (1 + \alpha t)dt = D\left(1 + \alpha S + \frac{\alpha}{2} D\right), \quad (13)$$

where α for the pessimistic scenario is the function of the *ID/PB* ratio, while the average value is determined by the *ID/DPB* ratio.

It should be noted that the new value of the work duration is determined as the average duration between the start date and the end date. The start date can be assumed to be fixed, the end date will shift depending on the new value and, therefore, equation (13) should be considered approximate. For a more precise calculation of pessimistic durations of construction activities, Bolotin et al. (2016) propose an iteration procedure related to cyclic readjustment of the timetable. However, experimental data show that the relative addition pertaining to subsequent iterations proved to be less by two orders of magnitude and did not exceed 1%. For the correct calculation of the probabilistic durations, the critical path method should be modernized. The modernization applied boils down to the fact that in the calculation of end dates one should figure probabilistic durations using equation (13) instead of their determined (fixed) values.

Results

Let us show the practical result using the example of generating a calendar process chart (roadmap) containing the schedule of integrated territory development with three residential buildings. The parameters of these buildings are taken from the construction duration standards (Repository for legal documents, standards, regulations and specifications, 2020) and are shown in Table 1. The last column of Table 1 shows the results of calculating the coefficient α included in equation (13) and computed under the following values:

Table 1. Characteristics of buildings in the cluster under development

No.	Type of building	Floors	Area, sqm	Works				Integral distribution of capital investments by months												α
				Under	Prep	Above	Int.	1	2	3	4	5	6	7	8	9	10	11	12	
1	Cast-in-situ	5	1500	1	1	3	1	8	20	40	63	86	100							0.174
2	Cast-in-situ	5	6000	1	1	5	1	5	27	38	49	56	74	95	100					0.164
3	Cast-in-situ	9	12,000	1	1	8.5	1.5	4	9	17	24	35	46	55	64	73	82	92	100	0.139

E = 20% per annum and *DPB* = 5 years. Based on these data, an optimistic timetable of works using determined (fixed) durations of works (see Table 1) is presented in the upper part of Table 2. A pessimistic timetable of works generated using the above-stated methodology is shown in the lower part of Table 2. Each element of both timetables contains the start and end dates, whereas the durations of works matching them are shown below.

The performance indicators of construction, widespread in Russia, include the general duration of construction works, which under the optimistic project delivery scenario comes to 20 months and under the pessimistic scenario — to 22.4 months. The pragmatic result of the calculation presented is that the pessimistic delay of 2.4 months can be duly hedged against and also used to calculate the penalty imposed by a developer upon a general contractor for the supposed untimely commissioning of a cluster under development.

Conclusions

The method of generating calendar construction process charts allows probabilistic organizational-technological design at the stage of design with reliance on information known at the given stage and directly related to the standard system of estimating the economic effectiveness of investment construction projects.

Table 2. Optimistic and pessimistic schedules of integrated development

Buildings		Preparations			Foundations			Aboveground			Interior works		
Optimistic	№1	0		1	1		2	2		5	5		6
			1			1			3			1	
	№2	1		2	2		3	5		10	10		11
			1			1			5			1	
	№3	2		3	3		4	10		18.5	18.5		20
			1			1			8.5			1.5	
Pessimistic	№1	0		1.01	1.01		2.01	2.01		5.08	5.08		6.09
			1.01			1.01			3.07			1.01	
	№2	1.01		2.03	2.03		3.06	5.08		10.6	10.6		11.8
			1.02			1.03			5.52			1.15	
	№3	2.03		3.32	3.32		4.36	10.6		20.6	20.6		22.4
			1.29			1.04			9.96			1.87	

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ФОРМИРОВАНИЕ ВЕРОЯТНОСТНОГО КАЛЕНДАРНОГО ПЛАНА СТРОИТЕЛЬСТВА

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Аннотация

Проектная подготовка строительства включает разработку календарных планов, которые необходимы для обоснования продолжительности строительства. **Методы:** На основе вероятностного календарного планирования для каждого календарного плана может быть сформировано множество решений, определяемые как оптимистичные, наиболее вероятные и пессимистичные. Выбор рациональных вариантов календарных планов осуществляется в соответствии с критериальной оценкой. В качестве часто применяемых критериев, входящих в систему оценки экономической эффективности инвестиционных проектов, используются простой и дисконтированный периоды окупаемости. На основе определения данных показателей оценки проекта разработан метод расчета вероятностных календарных планов строительства, в соответствие с которыми на этапе проектирования строительства объектов формируются соответствующие организационно-технологические решения. **Результаты:** Проектирование оптимистического, пессимистического и наиболее вероятного календарных планов строительства позволяет использовать разработанную модель для вероятностного предсказания будущих производственных рисков, влияющих на задержку окончания строительства.

Ключевые слова

Календарное планирование строительства, управление проектами, организационно-технологическая надежность, вероятностные сетевые модели строительства, задержка продолжительности строительства.