UDC 658.5:624.05

Bolotin S.A.
Biche-ool Kh.V.
Dadar A.-K.Kh.

Construction completion forecasting on the basis of statistical modeling and heterogeneous monitoring data

Modern construction represents a complex production process whose effective regulation is based on information about the period of construction works, obtained by way of monitoring. Any delay in the execution of certain works frustrates scheduled project commissioning, which results in increased project management costs, forfeits and lost benefits. Existing monitoring systems need to be improved through the use of probabilistic scheduling geared towards the forecasting of completion dates of certain works and the construction process as a whole. Construction monitoring may be improved by means of taking management quality into account by means of distributing random work durations in the process of statistical modeling of functions. The introduction of six random duration distribution functions, reflecting management quality, is proposed for the improvement of statistical modeling, whereas the use of scheduled durations of works is expedient for identifying optimistic characteristics. The data, extracted from monitoring reports, needs to be used as pessimistic distributions. Monitoring reports contain heterogeneous data, and they may even have no information on particular types of works. Therefore, pessimistic durations based on missing data should be calculated using the time-space analogy method.

Keywords: *construction monitoring and scheduling, project management, heterogeneity of monitoring information, statistical modeling of construction schedules*



Bolotin Sergey Alekseevich,
Doctor of Technical Sciences, Professor, Head of Department of Construction Management; Saint Petersburg State University of Architecture and Civil Engineering (SPbGASU); 4 Vtoraya Krasnoarmeiskaya st., Saint Petersburg, 190005, Russian Federation; ID RISC: 247644, Scopus: 57191531320; sbolotin@mail.ru



Biche-ool Khenzig Vladislavovna,
post-graduate student, Saint Petersburg State University of Architecture and Civil Engineering, Department of Construction Management; Saint Petersburg State University of Architecture and Civil Engineering (SPbGASU); 4 Vtoraya Krasnoarmeiskaya st., Saint Petersburg, 190005, Russian Federation; ID RISC: 1065236, ORCID: 0000-0001-9696-2797; ms.khenzig@mail.ru



Dadar Aldyn-kys Khunaevna,
PhD in Engineering, Assistant Professor of Department of Construction, Housing and Utilities; Tuvan State University (TuvSU); 36 Lenin st., Kyzyl city, Republic of Tuva, 667000, Russian Federation; ID RISC: 717644, Scopus: 57209737498, ORCID: 0000-0002-5304-3747; daryi@mail.ru

INTRODUCTION

Today construction is a complex production process. Its effective management requires a monitoring system that makes the information about the construction process available to construction management stakeholders. Some reference sources view monitoring as a system that is integral to operational construction management [1]. The monitoring system needs ongoing improvements to track the progress in a construction organization [2, 3]. Various types of monitoring systems are used by the construction industry. The principal ones are listed below:

- the monitoring of the technical condition of buildings and structures [4, 5];
- environmental monitoring [6];
- financial-economic monitoring [7];
- the monitoring of the quality of construction and assembly works [8].

The minimization of delays in construction processes, needed to ensure the timely commissioning of a completed project, is thought to be one of the key indicators of construction management quality [9]. If a delay is identified in the course of construction monitoring, there arises a need to forecast the construction completion time [10]. Any failure to fulfill construction term commitments leads to a fine or a penalty [11]. The penalty, if accrued, may be regressively distributed among the subcontractors in accordance with the share of their liability [12]. Delayed commissioning can boost management costs, entailing a forfeit paid for the schedule disruption as well as the lost benefit. These factors, if taken in totality, take a toll on the reputation of a developer and contractors involved in construction. High-quality construction management shall minimize delays. Project managers must timely respond to any deviation of the actual time of the work execution from the schedule, or any inadmissible deterioration of the quality of works. Thus, the launch of an adequate system of construction monitoring substantially raises the economic effectiveness of a construction project.

Various software products have been developed in the Russian Federation to automate the procedures needed for a functional construction monitoring system: "Stroyform: construction control"[1], "Mobile construction solutions"[2], ASIC[3], and others. Software kit "Stroyform: construction control" is geared towards the automation of the work quality monitoring system and its presentation in various executive documents.

The developers of the "Mobile Construction Solutions" software declare the possibility of figuring the estimated time of completion for each item of work (even one day after its commencement!), but they also emphasize the following features of its composition.

The software algorithm is oriented both towards considering the sequence of works and the normative need for and availability of resources. Its developers outline the following simple situation to demonstrate the practical bias of this software: "A wall of 100 bricks needs to be assembled. Today a mason has laid 10 bricks. How long will it take him to complete the whole work? The analysis of the information materials presented by the software developers suggests that the calculated forecast of the work duration is basically in

1 Stroyform. URL: http://www.stroyform.ru/product.aspx?id=2

2 Bimdata. URL: https://promo.bimdata.ru/?utm_source=yandex&utm_medium=cpc&utm_campaign=Софт&utm_ term=мобильные%20решения%20для%20строительства&mango=%7Cc:58273012%7Cg:4424262840%7Cb:10130426251%7Ck:24843164328%7Cst:search%7Ca:no%7Cs:none%7Ct:premium%7Cp:1%7Cr:%7Creg:2%7Cnet:%7Byad%7D&yclid=941299381762025242

3 Automated Investor Control System. Interactive Business Partners. URL: http://www.ibpspb.ru/asic/ASICGlobal.aspx

Table 1. The data from three monitoring reports issued by SetlCity developer[4]

Monitoring	Beginning	End	Time, %	Actual volume, %	Forecast
No. 1	16.01.2017	26.01.2017	63.34	48.40	21.12.2017
No. 2	27.01.2017	09.02.2017	66.19	49.67	31.12.2017
No. 3	10.02.2017	20.02.2017	68.83	51.83	03.01.2018

line with the determined approach. We use the data from the monitoring reports, provided in Table 1, that demonstrate the course of construction of a residential building, to analyze the ASIC (Automated System of Investor Control) system.

The reports mention the scheduled date of construction completion, that is, 3 July 2017, but they do not mention the work commencement date. We applied a regression approach to figure out the work commencement date: it was 07 March 2016. A huge amount of construction works nearing 170,000 m^2 of the total floor space drew our attention while we were looking through the reports. Three specialists (their number is specified in the reports) are unable to check the whole amount of work performed by the contractors. Therefore, this data is based on the so-called control points. This means that the carryover of sampled measurement results to the general totality requires a respective error to be taken into account. The analysis has also revealed that the estimated date of the work completion can only be viewed as a certain median date. Hence, when the construction completion time is forecasted, the error of this approximation should also be taken into consideration. Certain aspects of selective (sampled) monitoring, aimed at assessing the quality of industrial developments, can be found in the article [13].

The software, that automatically processes the monitoring information with the help of the BIM design technology, is widely used in the construction industry. Software kit Autodesk Nevisworks[5] that comprises *Autodesk Navisworks Simulate* and *Autodesk Navisworks Manage* is among such software products. These software solutions are meant to support the construction phase and ensure proper coordination between the construction stakeholders. Moreover, *MicrosoftProject* and *Primavera* can share data with the project management software. The scheduling system makes it possible to visualize the match between the planned work completion time and the 3D model. In the meantime, as construction works progress, not only the scheduled dates of the work completion, but also the actual dates can be entered, thus demonstrating the gap between the actual dates and the scheduled ones. Yet no probabilistic presentation of the work performance time is available in this software.

This analysis of various automated monitoring systems has revealed a number of elements in need of improvement. We have selected the one that needs probabilistic scheduling to be added to the software that is already in use.

DISCUSSION

Project management software, that is capable of reflecting the random nature of works, has become widespread in construction scheduling. For example, a tool kit included into the *Primavera* software, can analyze the risks that may cause delays. The *PERT* method is used to analyze deviations between the time needed to perform certain tasks/works and the project at large[6]. The *Primavera Risk Analysis* module, built into the *Primavera* software, allows to prognosticate successful project delivery with a high degree of probability [14].

The module capable of analyzing risks of work performance delays is also integrated into the *OpenPlan* software[7]. This analytical tool employs the method of statistical trials or tests, allowing the computation of possible delays in work performance, phases, and the project as a whole. As a result, the *OpenPlan* software estimates the probability of project completion within preset deadlines.

The *MicrosoftProject* software also uses the *PERT* method that serves as the basis of probabilistic scheduling[8]. The software uses three-parameter beta distribution to simulate the probabilistic construction schedule. Three types of work performance terms need to be preset: optimistic *a*, most likely *c*, and pessimistic *b* to activate the construction schedule specified above. Three different work schedules or timetables are compiled on the basis of this data. The optimistic work performance term can be interpreted as a planned option while the pessimistic one is viewed as the least favourable one. It should be noted that neither software product, mentioned above, contains any methodology designated for defining these characteristics. Therefore, it is assumed that all characteristics of random work performance terms shall be determined by the user. In the *MicrosoftProject* software the anticipated performance term for each item of work is calculated using the following formula:

$$t = \frac{w_1 t_1 + w_2 t_2 + w_3 t_3}{6}, \quad w_1 + w_2 + w_3 = 6, \tag{1}$$

where w_1, w_2 and w_3 are weight multipliers and their sum is assumed to be equal to 6 in the software.

By default, weight coefficients have the following values: $w_1 = 1$, $w_2 = 4$ and $w_3 = 1$, in line with the assumed beta distribution. Using variations of weight coefficients, one can calculate the average duration for various distribution types. For instance, assuming that $w_1 = 3$, $w_2 = 0$ and $w_3 = 3$, one can calculate the average duration for the uniform distribution. It should be noted that the identification of weight coefficients is not supported by methodological recommendations. Another shortfall in using beta distribution is the fact that it does not take management quality into account. Therefore, we assume that a logical sequel to the given material would be considering random work durations used in the statistical modeling of distribution functions, depending on the management quality [15].

The formation of post-industrial development patterns gave rise to new types of industrial process organization, namely, territorial and industrial clusters, or simply clusters [6].

A cluster is a geostatistical notion. Depending on the scope of research, which may be performed on regional or urban levels,

4 Setl City is the largest developer in Saint-Petersburg and Leningrad Region in terms of housing volumes under construction. Setl City. URL: www.setlcity.ru

5 Autodesk. URL: https://www.autodesk.ru

6 Oracle. URL: https://www.oracle.com/ru/applications/primavera/solutions/products.html

7 ITSMonline. URL: http://www.pmonline.ru/software/openp/

8 Microsoft Project. URL: https://www.microsoft.com/ru-ru/microsoft-365/project/project-management-software?market=ru

clusters can mean the key industries in a particular region that have competitive advantages, consolidated industry-specific activities in a city, or development enclaves in an urban environment [7].

METHODS

Let's consider the substantiation of the shape of the random work duration distribution curve on the basis of the following empirical fact: the probability of a smaller deviation from the planned duration is higher than the probability of a larger deviation from the planned duration [16]. Hence, the probability density of random work duration is determined by the steadily decreasing (descending) function. A proportionate managerial effort is needed to reduce the speed of the probability increase, which can be described by the following differential equation:

$$\frac{df(t)}{dt} - \alpha \cdot f(t) = 0, \quad (2)$$

where α is the proportionality factor.

By integrating equation (2), we obtain an exponential function of the probability density distribution where unlimited duration growth is allowed. To limit long delays, one could assume that statistical expectation and standard deviation are defined according to formula (3). When such an allowance is used, the probability of finding the work duration, defined by the range [*a*, *b*], will exceed 98 %, and the formula will look like this:

$$f(t) = \frac{4}{b-a} \exp \frac{-4(t-a)}{b-a}. \quad (3)$$

Formula (3) includes the range of random duration changes, which basically depends on several external factors. At the same time, the organization of quality management hampers the probability growth of a long delay. Thus, we believe that management quality is an internal (in-house) factor dependent on the competence of construction management stakeholders. For the exponential distribution, shown in formula (3), the maximum probability density matches the minimum delay in the performance of work. This distribution can indicate "good" management quality.

Let's consider the example presented in work [17], which confirms the assumptions made above. Table 2 shows statistical data on delayed execution of construction contracts classified as fixed-cost contracts.

Line 1 of Table 2 identifies the ranges of delays; line 2 shows the centres of these ranges while line 3 mentions empirical delay frequencies. The fourth and fifth lines show calculated statistical characteristics of the presented sample. The sixth line provides calculated frequencies with a range spread that is taken into account. The seventh line shows absolute errors in empirical and calculated frequencies. The analysis of their divergence reveals that the maximum absolute error amounts to 6 %, which quite satisfactorily approximates the empirical data. An indirect proof of the earlier made hypothesis can be found in monograph [18] where you may see a chart revealing an increase in the regulatory impact at the end of the process. The author of this monograph [18] claims that an intensified managerial effort is required to make up for the delay if the process is nearing completion.

However, certain statistical data that does not match the exponential distribution is also identified in the construction process. In particular, work [17] provides statistical data on delayed construction performed under PRC (Percentage Rate Contract) and IRC (Item Rate Contract) agreements. This data is shown in Table 3 in the slightly modified form.

It should be mentioned that the lack of detailed drawings and calculations is an important feature of PRC and IRC agreements, which, in our opinion, influences the nature of delay distribution between projects. The analysis of data in Table 2 also shows that the probability density may tend to increase as the delay gets longer.

While analyzing the exponential distribution, one may notice that the average random duration is expressed as $m = 0.25\,(b - a)$. The density reduction pace of this distribution probability is a variable. However, if one assumes that the pace of the probability density reduction is a constant, then the probability density distribution can be expressed as a rectilinear decay (descending) function.

$$f(t) = \frac{2(b-t)}{(b-a)^2}. \quad (4)$$

If compared to the exponential distribution, the average probability density rises to $m = 0.33(b - a)$, thus revealing lower

Table 2. The statistical processing of delayed construction data pursuant to fixed-cost contracts

1. Range of delays	0…20 %	20…50 %	50…100 %	100…200 %	Sums
2. Range centre	10	35	75%	150	
3. Empirical frequencies	52.0	27.0	18.0	3.0	100 %
4. Average delay				32.7	
5. Standard deviation				31.7	
6. Calculated frequencies	46.0	31.4	14.8	2.8	95 %
7. Calculation errors	6.0	– 4.4	3.2	0.2	Max 6 %

Table 3. Statistical data on delays under PRC and IRC agreements

1. Range	0…20 %	21…50 %	51…100 %	101…200 %	Sums
2. Range centre	10	35	75	150	
3. PRC frequency	21.0	20.0	27.0	32.0	100 %
4. IRC frequency	23.0	15.0	29.0	33.0	100 %

management quality. A uniform distribution, expressed by the following formula, follows management quality deterioration:

$$f(t) = \frac{1}{b-a}. \quad (5)$$

And finally, to reflect the potentially destructive nature of management, a linearly increasing (ascending) distribution can be used, which is characterized by the probability density growth in case of the delay increase. For this type of distribution $m = 0.67(b-a)$.

$$f(t) = \frac{2(t-a)}{(b-a)^2}. \quad (6)$$

One can make a generalization on the basis of the analysis of above-listed distributions. The average sample, obtained as a result of the monitoring data processing, may serve as an indicator of management quality. The average value close to 0.25 ($b - a$) indicates "good" quality management, whereas random duration can be described using formula (3). "Satisfactory" management quality corresponds to the average value close to 0.33 ($b - a$) while the random duration can be described using formula (4). Management quality can be considered "poor" if the average value of the monitored sample is 0.5 ($b - a$), whereas the random duration will then be described using formula (5). For the average value close to 0.67 ($b - a$) management quality can be thought to be "destructive", while formula (6) needs to be used for the description of the random duration.

Since the incoming monitoring information can be extremely heterogeneous, we will further demonstrate procedures characterizing the practical aspect of statistical modeling of the future work schedule.

RESULTS

The following situations or scenarios can emerge in the process of using or processing the monitoring data.

The monitoring result may indicate that the average work delay is a rather insignificant value equal to 5 %, for example. This delay may be an indicator of "excellent" management quality which rules out the subsequent representation of the work as a random value.

In a different situation (scenario) the result of the work delay can only be defined as one figure. This may happen if the first or the only monitoring session is conducted in respect of the selected work. Therefore, the given figure can be assumed to be a pessimistic delay which, together with the planned duration, allows to calculate the average delay which is equal to 0.5 ($b - a$). A uniform distribution function can be used to perform the statistical modeling of the duration of such a work, due to its highest entropy [19].

In the third scenario, one should specify the works not included in monitoring measurements because their planned start dates follow the date of monitoring. In this case the execution delay index defined as the b/a ratio can be the ratio of the planned homogenized volume of started and completed works to their actual amount. Under this approach homogenized monitoring data is extrapolated to the execution of future works while the uniform distribution function can also be used in statistical modeling.

The fourth possible scenario deals with the initial state of construction, when statistical data is unavailable. Under this scenario a model for figuring pessimistic durations of work performance, based on the method of space-time analogy [20, 21] can be recommended as a way to identify pessimistic work durations.

In the fifth scenario let's consider the monitoring of data that features pronounced modality. The central limit theorem shows that when a large number of random variables are summed up, the resultant function can be represented as a standard distribution described as the median value equal to the mode plus a standard deviation [22]. In our case this kind of data can be accrued in case of the consolidation of numerous simple works into one compound item of work. Since the normal description of distribution does not restrict the meaning of the random duration of work, a three-parameter beta distribution is used in the project management software such as MicrosoftProject. Yet for practical purposes it is necessary to substantiate each parameter and, in order to do this, a representative set of monitoring data is required. However, it turns out that the amount of monitoring data is insufficient and therefore we propose using a two-parameter beta distribution represented by the formula:

$$f(t) = \frac{6(t-a)(b-t)}{(b-a)^3}. \quad (7)$$

The average duration for the given distribution equals to $m = 0.5(b - a)$. Thus, the set of recommendations takes account of the heterogeneity of the monitoring information.

Almost all modern software products have a built-in generator of random numbers (*Rnd*), generating evenly distributed random numbers ranging from 0 to 1. The formula for calculating a uniformly distributed random duration will then look like this:

$$t = a + (b-a)Rnd. \quad (8)$$

We use the methodology, outlined in [22], to come up with other formulas designated for calculating random durations of works. Let's demonstrate how it can be applied to the generator of random work durations that gives rise to the exponential distribution of the probability density. We find primitive function F by way of integration of distribution $f(t)$ expressed using formula (3):

$$F = \int \frac{4\exp\left[\frac{4(a-t)}{(b-a)}\right]}{(b-a)}dt = \exp\left[\frac{4(a-t)}{(b-a)}\right]. \quad (9)$$

As for this function, we further identify an inverse function where we substitute *Rnd* for *F*. Ultimately, the relation between the exponential generator of random work durations and the uniform generator can be expressed by the following equation:

$$t = a - \frac{b-a}{4}\ln(Rnd). \quad (10)$$

The transition from uniform generator *Rnd* to the generator of random durations, producing a linearly descending triangular distribution, is made using the formula:

$$t = a + (b-a)(1-\sqrt{Rnd}). \quad (11)$$

A similar generator of random durations, producing a linearly ascending triangular distribution, will be found using the formula:

$$t = a + (b-a)\sqrt{Rnd}. \quad (12)$$

A generator of random durations, producing random work durations in accordance with the two-parameter beta distribution, can be expressed by formula (13):

$$t \approx a + (b-a)(2Rnd - 3Rnd^2 + 2Rnd^3). \quad (13)$$

A distinctive feature of formula (13) is that a primitive distribution function cannot be converted into an inverse function. Therefore, it has been simplified to demonstrate the approximate nature of the generator of the two-parameter beta distribution. This distribution approximation data is brought together in Table 4, and a corresponding comparison chart is provided in Fig. 1.

The analysis of the data, provided in Table 4, shows that the maximum absolute error in the adopted approximation reaches 7 %. Other generators reviewed above have notably smaller errors. The comparison of theoretical and experimental data for these generators has identified that the maximum absolute divergence does not

Table 4. Approximation of two-parameter beta distribution

Class number	1	2	3	4	5
Left bound	0	0.125	0.375	0.625	0.875
Right bound	0.125	0.375	0.625	0.875	1
Approximation	7.7 %	23.0 %	41.9 %	21.2 %	6.2 %
Theory	3.5 %	28.1 %	37.5 %	28.1 %	3.5 %

exceed 2 %. This error is explained by the number of trials (tests), but it can be reduced due to a larger sample.

It should be noted that missing monitoring data or even their complete absence makes the biggest contribution to the resulting error; hence, the proposed methodology applies to the tasks of nonparametric statistics [23]. A characteristic feature of such tasks is the development of specific procedures that determine the processing of small data samples.

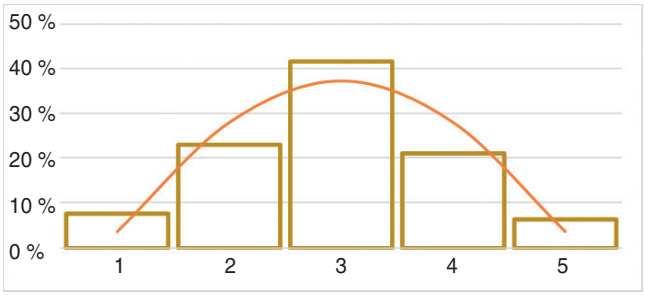


Fig. 1. Graphical approximation of beta distribution

All presented generators of random work durations have two parameters, one of which defines the determined (planned) characteristic of the work duration while the second parameter defines its pessimistic value. Automated statistical modeling, based on non-uniform information monitoring, is realized in *MicrosoftProject*. This software selection is rationalized by the fact that it has a tool kit that enables the development and use of user macros.

EXAMPLE

We'll show how the proposed methodology can be applied to the forecasting of the construction completion time using monitoring reports provided by ASIC Co. and shown in Table 1. We'll present the data used in the form of consecutively completed construction phases shown in Fig. 2 and Table 5. The commencement and completion timeframes for all phases represent fixed dates and median values. Monitoring phases are followed by the stage related to the forecasting of the construction completion time, based on the statistical modeling of the duration of this phase. The dates, corresponding to this data, are converted to calendar days counted as of the beginning of

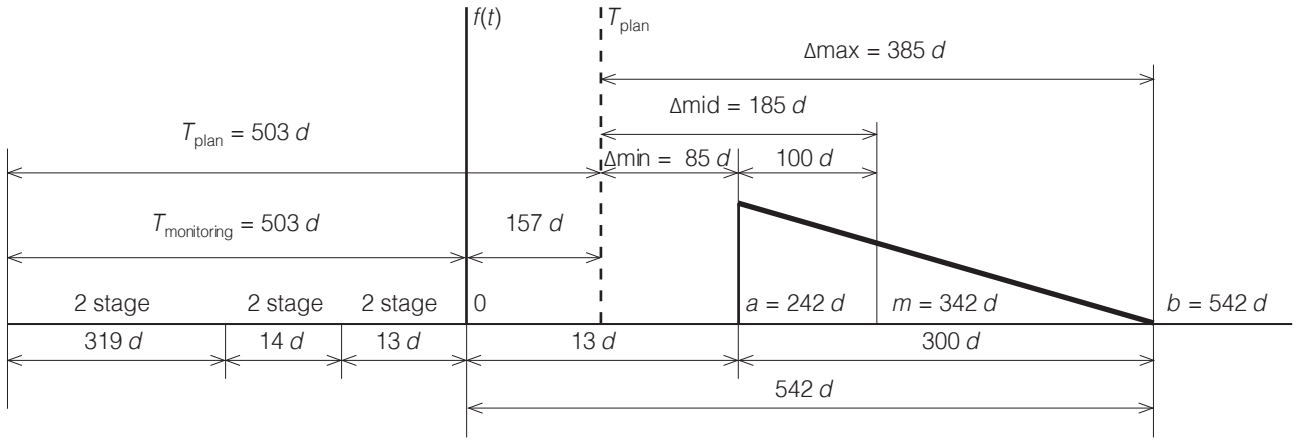


Fig. 2. Graphical Mapping of Forecasting Results

Table 5. The monitoring data that defines the parameters of forecasted time of construction

Report number	Time, days	Actual volume, %	ASIC delay forecast	Phase duration, days	Phase volume, %	Delay index *b/a*
No. 1	319	48.40	151	319	48.40	1.31
No. 2	333	49.67	161	14	1.7	2.24
No. 3	346	51.83	164	13	2.6	1.22
					Max	*b/a* = 2.24
					Average	*b/a* = 1.33

Table 6. The monitoring data that defines the parameters of forecasted time of construction

Extra delay, months	1	2	3	4	5	6	7	8	9	10
Modeling result	17.2 %	17.3 %	15.5 %	14.3 %	10.7 %	9.2 %	6.5 %	4.8 %	3.3 %	1.2 %
Theoretical result	18.2 %	16.4 %	14.5 %	12.7 %	10.9 %	9.1 %	7.3 %	5.5 %	3.6 %	1.8 %

construction activities. This recalculation resulted in obtaining planned construction duration T_{plan} = 503 days.

Submitted monitoring reports contain no reference to the method used to figure the forecasted delays in construction completion. Yet the analysis has revealed that the method of linear extrapolation might generate the most precise results, which are closest to true facts. The calculation of forecasted construction delays, using this method, yields the following results: 156 days, 167 days and 164 days, respectively. These delays differ from the results presented in monitoring reports by less than 6 days, which is within the limit of the relative error of 4 %. As a result, we choose the method of linear extrapolation as the basis for further calculations.

The works of the first phase took 319 days. Yet if we use the method of linear extrapolation to figure the planned duration of works, we get the following result: 503 · 0.484 = 243 days, which means that 76 days were lost. The ratio of the actual duration construed as a pessimistic duration to the planned duration will be b/a = 319/243 = 1.31.

The second phase took 14 days while in fact the volume of work was completed by 1.27 %. Therefore, the planned duration should have been 503 · 0.0127 = 6 days. As a result, 8 calendar days are irrevocably lost, and the respective untimeliness (tardiness) index equals to 2.24.

The work of the third phase took 13 days, with 2.16 % of work actually done. According to the plan, 503 · 0.0216 = 10 days should have been dedicated to the work performance; hence, 3 days were irrevocably lost, and the respective tardiness index is equal to 1.22.

As a result, 85 days were irrevocably lost as of the date of the latest monitoring completion. This means that if the same pace of construction is planned for the prognostication period, the planned duration of work should be extended by 85 days. This figure can be interpreted as the main delay, since no extra production resources are planned as a compensation. Let's assume that the monitoring completion date should be the zero time. As a result, the planned completion of construction work, which will presumably follow an optimistic scenario, will equal to a = 503 – 346 + 85 = 242 days. The pessimistic duration of construction works will then be defined as the maximum index, that is 2.24, and it will be equal to b = 242 · 2.24 = 542 days.

The average weighted tardiness index, calculated with regard for the weights of proportionate volumes of executed work, equals to 1.33. As it was determined earlier, this value defines management quality as "satisfactory". As a result, we use the linearly descending triangular distribution expressed by formula (4) as the probability density distribution function.

The results of statistical modeling are provided in Table 6.

The theoretical value of the average extra delay, shown in Fig. 2, equals to 100 days. Having analyzed 3,000 statistical tests or trials, we obtain the average extra delay of 117 days, with the total delay being equal to 85 + 117 = 202 days. Hence, the delay, generated by statistical modeling, is almost 2 months longer than the delay produced by similar forecasts presented in monitoring reports.

Yet the reported data show that the delay increases with the increase of the work performed. This growth can be approximated in

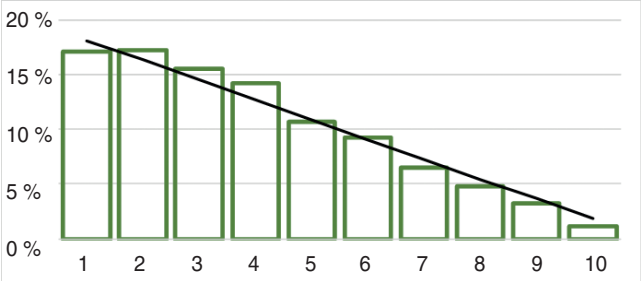


Fig. 3. The histogram of statistical modeling results and the theoretical curve of the presumed distribution

the form of a linear trend outlined in the following regression equation:

$$\Delta T^{forecast} = 3{,}534V - 17{,}9, \quad (14)$$

where $\Delta T^{forecast}$ is the predicted delay of construction completion in days; V is the amount of work completed in percent.

If 100 % of the executed construction volumes were substituted in equation (14), a respective median delay would equal to 335 days, which is way above the average figure obtained on the basis of our statistical experiment. Unfortunately, a more detailed comparison with practical monitoring data is impossible due to the lack of information about the predictive model used by the ASIC system.

CONCLUSION

We've developed a construction completion forecasting methodology, based on statistical modeling and adapted to the non-uniform (heterogeneous) monitoring data. Informational heterogeneity of the monitoring data deals with its quantity and quality as well as the possible extrapolation of data to the work to be performed in the future. Taking quality management into consideration in terms of the description of random work durations allows using adequate functions for distributing random work durations. As a result, further application of statistical modeling ensures more precise calculations of forecasted construction completion delays based on the differential modeling of statistical characteristics of certain works.

REFERENCES

1. Bolotin S.A., Dadar A.H., Magamadov R.A., Malsagov A.R. Features of monitoring organization in the process of construction operational management. Vestnik Grazhdanskikh Inzhenerov/ Bulletin of Civil Engineers. 2017; 4(63):146-152. DOI: 10.23968/1999-5571-2017-14-4-146-152 (rus.).

2. Kosykh A.A., Sursanov D.N. On the need to use modern monitoring methods in construction. Modernization and Scientific Research in Transport Industry. 2012; 4:173-176. URL: https://www.elibrary.ru/item.asp?id=18876127 (rus.).

3. Codd E.F., Codd S.B., Salley C.T. Providing oLAP (on-Line Analytical Processing) to user-analysts: an it mandate. Technical report. 1993. URL: http://www.estgv.ipv.pt/PaginasPessoais/jloureiro/ESI_AID2007_2008/fichas/codd.pdf

4. Mangushev R.A. Monitoring of construction of multi storey buildings on the pile foundations. Vestnik Grazhdanskikh Inzhenerov/ Bulletin of Civil Engineers. 2005; 1(2):25-32. URL: https://www.elibrary.ru/item.asp?id=12877206 (rus.).
5. Osokin A.I., Tatarinov S. V., Denisova O.O., Makarova E.V. The system of geotechnical monitoring as a means of ensuring building safety. Zhilishchnoe Stroitel'stvo/Housing Construction. 2014; 9:10-18. URL: https://www.elibrary.ru/item.asp?id=21971926 (rus.).
6. Nuzhina I.P., Zolotareva M.V., Vasilyeva Y.V. The model of environmental-economic monitoring in construction. Eurasian Union of Scientists. 2017; 12-2(45):19-22. URL: https://www.elibrary.ru/item.asp?id=32248911 (rus.).
7. Nikulina N.O., Alimbekova S.R., Gabbasov R.K., Kulikova V.G. Information system to control the implementation and financing projects in building. Management in economic and social systems. 2008; 1(28):133-142. URL: https://www.elibrary.ru/item.asp?id=11751453 (rus.).
8. Makarov S. Quality management in construction. Intelligent enterprise. 2013; 6(252).
9. Sadi A., Sadiq A. Causes of delay in large construction projects. International Journal of Project Management. 2006; 24(4): 349-357. DOI: 10.1016/j.ijproman.2005.11.010
10. Aldyn-kys Dadar, Sergey Bolotin, Aslan Malsagov, Zita Oolakai. Improving construction duration forecasts and management of construction operations. E3S Web of conferences. 2019; 110:01078. DOI: 10.1051/e3sconf/201911001078
11. Louzolo-Kimbembe P., Mbani E. New approach of delay penalties formulation: Application to the case of construction projects in the Republic of Congo. Journal of Civil Engineering and Construction Technology. 2013; 4(1):6-22. URL: https://academicjournals.org/journal/JCECT/article-stat/B3E08C43887
12. Bolotin S.A., Dadar A-K.H. Bayesian approach in determining the joint and several liability share of the construction participants in case of construction untimely completion. Vestnik Grazhdanskikh Inzhenerov/Bulletin of Civil Engineers. 2019; 2(73):79-84. DOI: 10.23968/1999-5571-2019-16-2-79-84 (rus.).
13. Samofeev N.S., Gareeva Z.A. Some aspects of implementation of selective quality monitoring of construction products for industrial purposes. Naukovedenie. 2017; 5: 1-7. URL: http://naukovedenie.ru/PDF/50EVN517.pdf (rus.).
14. Grakhov V.P., Kislyakova Y.G., Simakova U.F., Mushakov D.A. Development of control system for progress of construction and installation works based on integrated application of Primavera P6 Professional R8.3.2 and ArchiCAD 17.0.0 Software products. Science and Technique. 2017; 6:466-474. DOI: 10.21122/2227-1031-2017-16-6-466-474 (rus.).
15. Bolotin S., Birjukov A. Time Management in Drafting Probability Schedules for Construction Work // World Applied Sciences Journal 23 (Problems of Architecture and Construction). 01-04, 2013.
16. Bolotin S., Dadar A., Ptuhina I. Construction work tasks duration: Pessimistic scenarios based on PERT method. Advanced Materials Research. 2014; 945-949:3026-3031. DOI: 10.4028/www.scientific.net/AMR.945-949.3026
17. Gore P.S. Rationale of contracts awards and contract systems. Proceedings of the ASCE: Journal of the Construction Division. 1980; 106:507-517.
18. Leach L. Critical Chain Project Management. 2nd ed. Artech House Publishers, 2004; 276.
19. Kulikovsky L.F., Motov V.V. Theoretical Fundamentals of Information Processes: Teaching Aid for Students majoring in Automation and Mechanization of Information Processing and Delivery Processes. Moscow, Higher School, 1987; 248. (rus.).
20. Hejducki Z., Rogalska M., Bolotin S., Dadar A. Scheduling of Construction Project with Time-Space Model. Scientific problems in project management. Military Academy of Land Forces in Wroclaw, 2015; 143-152.
21. Bolotin S., Dadar A.-K., Biche-ool Kh., Malsagov A. Generating a Probabilistic Construction Schedule. Architecture and Engineering. 2020; 5(4):44-50. URL: https://aej.spbgasu.ru/index.php/AE/article/view/333/178
22. Korn G.A., Korn T.M. Mathematical handbook for scientists and engineers. McGraw-Hill Book Company, New York, 1968.
23. Corder G.W., Foreman D.I. Nonparametric statistics: A step-by-step approach. Wiley, 2014.

Прогнозирование окончания строительства на основе статистического моделирования и информационно неоднородного мониторинга

Современное строительство представляет собой сложный производственный процесс, эффективное регулирование которого основано на получении сведений о сроках выполнения строительных работ посредством мониторинга. Задержка выполнения отдельных работ, как правило, срывает дату ввода строительного объекта в эксплуатацию, что приводит к увеличению затрат на управление проектами, выплатам различных неустоек и к упущенной выгоде. Существующие системы мониторинга требуют совершенствования за счет применения вероятностного календарного планирования, ориентированного на прогноз сроков окончания отдельных работ и строительства в целом. В качестве основы совершенствования строительного мониторинга рассматривается учет качества управления в применяемых при статистическом моделировании функций распределения случайных продолжительностей работ. Для совершенствования статистического моделирования предлагается ввести шесть функций распределения случайных продолжительностей, отражающих качество управления. При этом для определения оптимистичных характеристик целесообразно использовать планируемые длительности работ. В качестве пессимистичных параметров распределений необходимо использовать данные из мониторинговых отчетов. В мониторинговых отчетах содержатся информационно неоднородные сведения вплоть до отсутствия информации по некоторым работам. Поэтому для отсутствующих данных пессимистические длительности следует определять расчетным путем, используя, например, метод пространственно-временной аналогии.

Ключевые слова: *строительный мониторинг, календарное планирование строительства, управление проектами, неоднородность мониторинговой информации, статистическое моделирование графиков строительства*

ЛИТЕРАТУРА

1. Болотин С.А., Дадар А.Х., Магамадов Р.А., Мальсагов А.Р. Особенности организации мониторинга в процессе оперативного управления строительством // Вестник гражданских инженеров. 2017. № 4 (63). С. 146–152. DOI: 10.23968/1999-5571-2017-14-4-146-152
2. Косых А.А., Сурсанов Д.Н. О необходимости применения современных методов мониторинга в строительстве // Модернизация и научные исследования в транспортном комплексе. 2012. № 4. С. 173–176. URL: https://www.elibrary.ru/item.asp?id=18876127
3. Codd E.F., Codd S.B., Salley C.T. Providing oLAP (on-Line Analytical Processing) to user-analysts: an it mandate. Technical report. 1993. URL: http://www.estgv.ipv.pt/PaginasPessoais/jloureiro/ESI_AID2007_2008/fichas/codd.pdf
4. Мангушев Р.А. Мониторинг строительства зданий повышенной этажности на свайных фундаментах // Вестник гражданских инженеров. 2005. № 1 (2). С. 25–32. URL: https://www.elibrary.ru/item.asp?id=12877206
5. Осокин А.И., Татаринов С.В., Денисова О.О., Макарова Е.В. Система геотехнического мониторинга как средство обеспечения безопасности строительства // Жилищное строительство. 2014. № 9. С. 10–18. URL: https://www.elibrary.ru/item.asp?id=21971926
6. Нужина И.П., Золотарева М.В., Васильева Ю.В. Модель эколого-экономического мониторинга в строительстве //

Евразийский союз ученых. 2017. № 12-2 (45). С. 19–22. URL: https://www.elibrary.ru/item.asp?id=32248911

7. Никулина Н.О., Алимбекова С.Р., Габбасов Р.К., Куликова В.Г. Информационная система контроля реализации и финансирования проектов в строительстве // Вестник Уфимского государственного авиационного технического университета. 2008. № 1 (28). С. 133–142. URL: https://www.elibrary.ru/item.asp?id=11751453

8. Макаров С. Управление качеством в строительстве // Intelligent enterprise. 2013. № 6 (252).

9. Sadi A., Sadiq A., Causes of delay in large construction projects // International Journal of Project Management. 2006. Vol. 24 (4). Pp. 349–357. DOI: 10.1016/j.ijproman.2005.11.010

10. Aldyn-kys Dadar, Sergey Bolotin, Aslan Malsagov, Zita Oolakai. Improving construction duration forecasts and management of construction operations // E3S Web of conferences. 2019. Vol. 110. P. 01078. DOI: 10.1051/e3sconf/201911001078

11. Louzolo-Kimbembe P., Mbani E. New approach of delay penalties formulation: Application to the case of construction projects in the Republic of Congo // Journal of Civil Engineering and Construction Technology. 2013. Vol. 4 (1). Pp. 6–22. URL: https://academicjournals.org/journal/JCECT/article-stat/B3E08C43887

12. Болотин С.А., Дадар А-К.Х. Байесовский подход в определении доли солидарной ответственности участников строительства при его несвоевременном завершении // Вестник гражданских инженеров. 2019. № 2 (73). С. 79–84. DOI: 10.23968/1999-5571-2019-16-2-79-84

13. Самофеев Н.С., Гареева З.А. Некоторые аспекты реализации выборочного мониторинга качества строительной продукции производственного назначения // Интернет-журнал «Науковедение». 2017. № 5. С. 1–7. URL: http://naukovedenie.ru/PDF/50EVN517.pdf

14. Грахов В.П., Кислякова Ю.Г., Симакова У.Ф., Мушаков Д.А. Развитие системы контроля за ходом строительно-монтажных работ на основе комплексного применения программных продуктов Primavera P6 Professional R8.3.2 и ArchiCAD 17.0.0 // Наука и техника. 2017. № 6. С. 466–474. DOI: 10.21122/2227-1031-2017-16-6-466-474

15. Bolotin S., Birjukov A. Time management in drafting probability schedules for construction work // World Applied Sciences Journal 23 (Problems of Architecture and Construction). 01–04, 2013.

16. Bolotin S., Dadar A., Ptuhina I. Construction work tasks duration: Pessimistic scenarios based on PERT method // Advanced Materials Research. 2014. Vol. 945–949. Pp. 3026–3031. DOI: 10.4028/www.scientific.net/AMR.945-949.3026

17. Gore P.S. Rationale of contracts awards and contract systems // Proceedings of the ASCE: Journal of the Construction Division. 1980. Vol. 106. Pp. 507–517.

18. Лич Л. Вовремя и в рамках бюджета: Управление проектами по методу критической цепи / пер. с англ. М. : Альпина Паблишерз, 2010. 354 с.

19. Куликовский Л.Ф., Мотов В.В. Теоретические основы информационных процессов : учеб. пособие для вузов по спец. «Автоматизация и механизация процессов обработки и выдачи информации». М. : Высш. шк., 1987. 248 с.

20. Hejducki Z., Rogalska M., Bolotin S., Dadar A. Scheduling of construction project with time-space model // Scientific problems in project management — Military Academy of Land Forces in Wroclaw. 2015. Pp. 143–152.

21. Bolotin S., Dadar A.-K., Biche-ool Kh., Malsagov A. Generating a probabilistic construction schedule // Architecture and Engineering. 2020. Vol. 5. Issue 4. Pp. 44–50. URL: https://aej.spbgasu.ru/index.php/AE/article/view/333/178

22. Korn G.A., Korn T.M. Mathematical handbook for scientists and engineers. New York : McGraw-Hill Book Company, 1968.

23. Corder G.W., Foreman D.I. Nonparametric Statistics: A Step-by-Step Approach. Wiley, 2014.

Об авторах: **Болотин Сергей Алексеевич** — доктор технических наук, профессор, заведующий кафедрой организации строительства; **Санкт-Петербургский государственный архитектурно-строительный университет (СПбГАСУ)**; 190005, г. Санкт-Петербург, ул. 2-я Красноармейская, д. 4; РИНЦ ID: 247644, Scopus: 57191531320; sbolotin@mail.ru

Биче-оол Хензиг Владиславовна — аспирант кафедры организации строительства; **Санкт-Петербургский государственный архитектурно-строительный университет (СПбГАСУ)**; 190005, г. Санкт-Петербург, ул. 2-я Красноармейская, д. 4; РИНЦ ID: 1065236, ORCID: 0000-0001-9696-2797; ms.khenzig@mail.ru

Дадар Алдын-кыс Хунаевна — кандидат технических наук, доцент, доцент кафедры строительства и жилищно-коммунального хозяйства; **Тувинский государственный университет (ТувГУ)**; 667000, Республика Тува, г. Кызыл, ул. Ленина, д. 36; РИНЦ ID: 717644, Scopus: 57209737498, ORCID: 0000-0002-5304-3747; daryi@mail.ru.

For citation: Bolotin S.A., Biche-ool Kh.V., Dadar A.-K.Kh. Construction completion forecasting on the basis of statistical modeling and heterogeneous monitoring data. *Real estate: economics, management*. 2021; 2:47-54.

Для цитирования: *Болотин С.А., Биче-оол Х.В., Дадар А.-К.Х.* Construction completion forecasting on the basis of statistical modeling and heterogeneous monitoring data. // Недвижимость: экономика, управление. 2021. № 2. С. 47–54.