Formation of a system for assessing the renovation of monolithic buildings

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Abstract. Reliability and quality of monolithic construction works are determined by analyzing the system of preparation for implementation of certain technological operations, establishing and ensuring the order, sequence and timetable of works, and supply of all types of resources. Periodic inspections of compliance with construction norms and regulations are held in the course of construction and installation works. As a follow-up on such inspections, prescriptive orders on rectification of detected nonconformities and violations within a specified time limit are issued. There is no provision for the time consumed by corrective action in the calendar plan, and consequently the actual duration of construction as often as not exceeds the scheduled term to a great extent. In this connection, there is a task of assessing the level of impact of violations on the efficiency of functioning and the organizational quality of production processes. Analytic research into this problem allows for a conclusion on the need for development of a mathematical model to be used in the assessment of duration of construction taking into account the random pattern of occurrence of violations.

1. Introduction
Organizational and technological reliability is understood as the ability of technological, organizational, and managerial solutions to ensure attainment of a target result of construction operations under the conditions of random disturbances that are intrinsic to construction as a complex stochastic system. Assessment of the level of organizational and technological reliability of monolithic construction projects requires quantitative characteristics. The main criteria of organizational and technological reliability are duration, cost and quality of construction [1-3]. Collection of information and registration of random events that have an impact on the functioning of a production process in monolithic construction operations include recording the time of occurrence of defects and failures [7-8], their duration, causes and circumstances of loss of productivity, deviations from the schedule of implementation of the planned scope of works, completion of technological stages and stages of works.

2. Materials and methods
The type of distribution of the quantity of violations is determined as follows. There is a list of types of violations numbered by indexes $i=1, 2, \ldots, m$. For the purpose of modelling the time of elimination of violations we assume that the quantity of violations $\xi_i$, of each type $i=1, 2, \ldots, m$ is a random value. In order to derive the type of distribution of random values $\xi_i$ let us fix the time interval $\Delta T$ – (mean)
inspection frequency. Let us divide the $\Delta T$ interval into $s$ equal parts $\Delta T = \Delta T/s$ long and designate by $p_{is}$ the probability of occurrence of at least one $i$ violation during the fixed time phase. Then the probability of an opposite event, namely, not a single $i$ violation occurring in the fixed time phase, is $q_{is} = 1 - p_{is}$, with the $p_{is}$ probability being irrespective of the number of the time phase. It means the presence of binomial distribution at the $\Delta T$ segment, and the probability of occurrence of precisely $k$ violations is equal to

$$B(k) = \binom{s}{k} p^k q^{s-k}.$$ Proceeding from a natural assumption that $sp_{is}$ is limited for all $s$, it appears that $sp_{is} \rightarrow \lambda_i$, with $s \rightarrow +\infty$, where $\lambda_i$ is a constant value that differs for each index $i = 1, 2, \ldots, m$. In this case, with $s \rightarrow +\infty$, $B(0) \rightarrow \pi_i(k)$ [4-6], where

$$\pi_i(k) = \frac{\lambda_i^k}{k!} e^{-\lambda_i}$$  \hspace{1cm} (1)

Thus, the random value $\xi_i$ at the $\Delta T$ segment is distributed by the Poisson law with $\lambda_i$ parameter.

For the purpose of assessment of $\lambda_i$, 1, 2, $\ldots$, $m$ parameters, let us use statistical data on the indicators under review based on analysis of construction control operations. Information has been mainly obtained from results of systemic analysis and statistical processing of actual data on conformities and violations detected by applied research of Scientific Research and Testing Center “MGSU STORY-TEST” in monitoring the quality of construction projects from 2012 to 2016 [2-5, 12]. Prescriptive orders issued by construction supervision authorities specify the names of violations, type of the works performed, deadline for elimination, and the issue date of the prescriptive order. All violations of construction regulations are divided into three groups: violations of requirements of design documentation, violations of requirements of normative documents, and violations of requirements of technological regulations. Nonconformities in production processes have various degrees of impact on the overall construction of the project. There is no provision for the time consumed by corrective action in the calendar plan, and consequently the actual duration of construction as often as not exceeds considerably the scheduled term.

Let us fix index $i = 1, 2, \ldots, m$ and find mathematical expectation $M\xi_i$ of random value $\xi_i$. We obtain directly from the mathematical expectation:

$$M\xi_i = \Sigma_{k=0}^{+\infty} k\pi_i(k) = \Sigma_{k=0}^{+\infty} k \frac{\lambda_i^k}{k!} e^{-\lambda_i} = \lambda_i e^{-\lambda_i} \Sigma_{k=1}^{+\infty} \frac{\lambda_i^{k-1}}{(k-1)!} = \lambda_i e^{-\lambda_i} e^{\lambda_i} = \lambda_i$$  \hspace{1cm} (2)

By virtue of the law of large numbers, mathematical expectation $M\xi_i$ of random value $\xi_i$ is equal to the frequency limit of occurrence of $i$ violation in the sample, i.e. the ratio limit:

$$\lambda_i = \frac{N_i}{N} \text{ with } N \rightarrow +\infty,$$  \hspace{1cm} (3)

where $N_i$ is the quantity of $i$ violations in the sample; $N$ is the overall number of inspections held.

Thus we can assess $\lambda_i$ parameter using equation (3).

Probability assessment for extending the duration of construction due to any violations requires an assessment of $D\xi_i$ dispersion of random value $\xi_i$ for each index $i = 1, 2, \ldots, m$. For this purpose let us first find the mathematical expectation of random value $\xi_i^2$:

$$M\xi_i^2 = \Sigma_{k=0}^{+\infty} k^2 \pi_i(k) = \Sigma_{k=0}^{+\infty} k^2 \frac{\lambda_i^k}{k!} e^{-\lambda_i} = \lambda_i e^{-\lambda_i} \Sigma_{k=1}^{+\infty} \frac{\lambda_i^{k-1}}{(k-1)!} =$$

$$= \lambda_i e^{-\lambda_i} \left(1 + \Sigma_{k=2}^{+\infty} \frac{1}{(k-1)!} \frac{\lambda_i^{k-1}}{(k-2)!} \right) = \lambda_i^2 e^{-\lambda_i} \Sigma_{k=2}^{+\infty} \frac{\lambda_i^{k-2}}{(k-2)!} + \lambda_i e^{-\lambda_i} \Sigma_{k=1}^{+\infty} \frac{\lambda_i^{k-1}}{(k-1)!} =$$

$$= \lambda_i^2 e^{-\lambda_i} e^{\lambda_i} + \lambda_i e^{-\lambda_i} e^{\lambda_i} = \lambda_i^2 + \lambda_i$$  \hspace{1cm} (3.1)

We obtain from the last equation and equation (2) by virtue of determination of dispersion:

$$D\xi_i = M\xi_i^2 - (M\xi_i)^2 = \lambda_i + \lambda_i^2 - \lambda_i^2 = \lambda_i$$  \hspace{1cm} (4)
Then we should assess the time consumed by elimination of violations at a certain job. Let us use a calendar plan of a construction project that consists of \( n \) jobs numbered by indexes \( j=1, 2, ..., n \). Each \( j \) job is characterized by the time of its commencement \( t_j^0 \), completion \( t_j \), and duration \( T_j \), where

\[
t_j^j > t_j^j \geq 0, T_j = t_j^j - t_j^0
\]  

for all \( j=1, 2, ..., n \), with \( t_j^0 = 0 \)

For each index \( j=1, 2, ..., n \), we draw up a list of \( B_j \) indexes (types) of violations that may occur in the execution of \( j \) job. Each index \( i \in B_j \) is assigned compatibility indicator \( a_i \) equal to 0 in the event that one or more violations with index \( i \) can be eliminated irrespective of another or other violations (in parallel), and equal to 1, if these violations must be eliminated one-at-a-time (in sequence). Let us designate the set of indexes with \( a=0 \) as \( C_j \), and the set of indexes \( i \in B_j \) with \( a=1 \) as \( E_j \).

We know \( \tau_i \), the time of elimination of a single \( i \) violation, for each index \( i=1, 2, ... \) With that in mind and proceeding from the above-mentioned values for \( M \xi_j \) and \( D \xi_j \), we can assess the time consumed by the elimination of violations in the course of execution of each job as follows.

Let us fix \( j \) job and divide it into time intervals \([t_0, t_1], [t_1, t_2], ..., [t_{j-1}, t_j] \) each being \( \Delta T \) long,

\[ J = \{ t_{j0}, t_{j1}, t_{j2}, ..., t_{jn} \} \]

![](image.png)

**Fig. 1.** An extract from a job schedule with \( j \) job broken down by \( \Delta T \) intervals.

The number of \( i \) violations at each of the intervals \([t_r, t_{r+1}] \), \( r=0, 2, ..., t_{j-1} \), where \( i \in B_j \), is a random value \( \xi_i \), which has a Poisson distribution with mathematical expectation and dispersion equal to \( \lambda_i \), (see (2) and (4)). We calculate the time consumed by elimination of these violations by proceeding from the following natural assumptions. With regard to violations capable of being eliminated in parallel, i.e. with \( i \in C_j \), the time of their joint elimination is equal to the maximum duration of elimination of each of them. Regarding violations that can be eliminated in a consecutive manner only, i.e. with \( i \in E_j \), the time of their joint elimination is equal to the total time consumed by elimination of all possible violations.

To assess the time spent on parallel elimination of violations in the course of performing a separate work, we fix the index \( j=1, 2, ..., n \) and first, we estimate the total time spent on elimination of all violations with indices \( i \in C_j \) (which allow parallel elimination) on the interval \( \Delta T \) work.

For each index \( i \in C_j \) from equality (1) we have: \( \pi_i(t_k) = \frac{\lambda_i^k}{k!} e^{-\lambda_i} = e^{-\lambda_i} \). Consequently, the probability of occurrence of at least one \( i \) violation on the interval \( \Delta T \) is equal to \( \pi_i(k > 0) = 1 - e^{-\lambda_i} \).

Since these violations can be eliminated sequentially, the time spent on their cumulative elimination is a random variable \( \tau_i \), with the distribution function \( F(t) \), taking the value \( \pi_i(t_k) = e^{-\lambda_i} \) when \( t < \tau_i \), and the value 1 for \( t \geq \tau_i \), that is

\[
F_i(t) = \begin{cases} 
 e^{-\lambda_i} & \text{where } t < \tau_i \\
 1 & \text{where } t \geq \tau_i 
\end{cases}
\]  

With the distribution function (6) for all indices \( i \in C_j \) is easy to obtain the distribution function \( F_0(t) \) of a random variable \( \tau_0 \) - the time spent on the elimination of all such violations in \( j \) work as the product of \( F(t) \) distribution functions for all \( i \in C_j \):

\[
F_{j0}(t) = \prod [F_i(t), i \in C_j]
\]  

Indeed, since \( \tau_0 = \max \{ \tau_i : i \in C_j \} \), then by virtue of the independence of the random variables \( \xi_j \) for all \( i \in B_j \), for arbitrary \( x > 0 \), we have:
\[ F_{j0}(t) = P(\omega: \tau_{j0}(\omega) \leq t) = P(\omega: \max\{\tau_i(\omega), i \in C_j\} \leq t) = P(\cap \{\omega: \tau_i(\omega) \leq t, i \in C_j\}) \]
\[
= \prod_{i \in C_j} \{P(\omega: \tau_i(\omega) \leq t), i \in C_j\} = \prod_{i \in C_j} \{F_i(t), i \in C_j\}. \]

Equalities (6) and (7) allow us to estimate the expectation and variance of a random variable \( \tau_{j0} \) as follows

We enumerate the duration \( \tau_i \) eliminate violations \( i \in C_j \) in ascending order: \( \tau_{i_1} \leq \tau_{i_2} \leq \cdots \leq \tau_{i_k} \), where \( k \) is the number of elements in the set \( i \in C_j \). From formulas (6) and (7) we have:

\[
F_{j0}(t) = \begin{cases} 
  e^{-\lambda_{i_1}} \cdots e^{-\lambda_{i_s}} & \text{where } t < \tau_{i_1}, \\
  e^{-\lambda_{i_1}} \cdots e^{-\lambda_{i_s}} & \text{where } \tau_{i_1} < t < \tau_{i_2}, \\
  \cdots & \\
  e^{-\lambda_{i_q}} \cdots e^{-\lambda_{i_s}} & \text{where } \tau_{i_{q-1}} < t < \tau_{i_q}, \\
  1 & \text{where } t \geq \tau_{i_q}.
\end{cases}
\]

From the last equality, we find the estimates for the average \( M_{\tau_{j0}} \) and the variance \( D_{\tau_{j0}} \) random variable \( \tau_{j0} \):

\[
M_{\tau_{j0}} = \sum_{q=1}^{s} \left( 1 - e^{-\lambda_{i_q}} \right) e^{-\lambda_{i_{q+1}}} \cdots e^{-\lambda_{i_s}} \tau_{i_q}, \tag{8}
\]

\[
M_{\tau_{j0}}^2 = \sum_{q=1}^{s} \left( 1 - e^{-\lambda_{i_q}} \right) e^{-\lambda_{i_{q+1}}} \cdots e^{-\lambda_{i_s}} \tau_{i_q}^2, \tag{9}
\]

\[ D_{\tau_{j0}} = M_{\tau_{j0}}^2 - (M_{\tau_{j0}})^2 \]

3. Conclusion

Analysis of factors affecting the organizational and technological reliability of monolithic construction operations leads to a conclusion that the level of such reliability can be assessed by the indicator of duration of construction and installation works [10, 13-16]. This requires the use of a mathematical model for assessing the duration of construction and installation works taking into account the time losses of elimination of violations. To begin with, the duration of separate works should be determined on the basis of the calendar plan followed by an assessment of the probability of extending the term of construction as required for elimination of violations prescribed by construction supervision authorities. In this connection it is necessary to develop methods of increasing the organizational and technological reliability of monolithic construction projects by means of timely adjustment of the construction calendar plan.

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