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BIM technologies to optimize the catch–up schedule for the implementation of the construction schedule plan, taking into account external stochastic impacts

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In this paper, the subject of research is information models of construction production schedules implemented under conditions of intense stochastic influences. The purpose of the study is to optimize the methods for generating catch-up schedules based on BIM-technologies for monitoring the progress of the project. As a result of the work carried out, a set of parameters was determined that describes the dynamics of the implementation of calendar plans and takes into account the relationship between economic and technological processes. Indices are defined that allow optimizing both operational and strategic management decisions. An algorithm for determining the time intervals during which a resource maneuver is possible is formulated. Dynamic indices are found that adequately describe the use of unique and expensive resources for which the possibilities of a priori reservation are limited. Sources of information are identified that allow the standard business processes to describe both static information based on the schedule and the dynamic part that reflects the results of monitoring. The dimensions, ranks and formats of the matrix elements that define the construction information model, and the hierarchical relationships between them are determined. Both closed expressions of dynamic indices through BIM matrices and recursive procedures reflecting the mechanism of information accumulation in the monitoring process are obtained. The algorithms of information accumulation proposed in the work are implemented in the shell of a relational database management system, and their calculations and graphical interpretation are implemented in a high-level mathematical package. The action of algorithms and their software implementation is demonstrated on a specific example of the implementation of the construction production calendar plan.

Keywords: *building information model, project life cycle, schedule, stochastic impacts, monitoring, optimization, vector model, evaluation criteria, non-stock resources*

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INTRODUCTION

At the turn of the 20th and 21st centuries, the industry of architecture, design and construction and operation (AECO) lagged behind the sectors of the economy leading in terms of growth and innovation [1]. In recent years, this gap has increased significantly. [2]. At the same time, the pace of technological changes in the construction industry is quite high [3] and cannot be the reason for such a significant lag. The main reason for the unsatisfactory performance of the AECO industry is the inadequacy of management methods to the goals of projects and existing conditions [4]. According to this book, in the United States at the turn of the century, 30 % of projects were not completed at all, and in another third of cases, projects are completed behind schedule, with budget overruns reaching up to 100 %, and when initial goals are not met. At the same time, the problem is universal, not related to either the type of project or the country of implementation, and is associated with external stochastic influences. Completing a project on time and within budget is the main goal of any manager. However, most of the projects are delayed, and the estimate exceeds the planned one. An attempt to tighten planning does not lead to anything: life still presents surprises that are not in the plan [4].

One of the methods for reducing the influence of stochastic factors on the results of project implementation, widely used in AECO practice, is the critical path method [5]. This method arose as a result of the synthesis of the principles of Goldratt's theory of constraints [6] and Deming's statistical approach [7]. This method is based on the concept of identifying critical paths (that is, chains of events that do not have a reserve of time) and their a priori (that is, not taking into account the probabilistic nature of the deviation of the schedule from the planned one) damping. The first models of the critical path, built on the assumption of complete certainty of the time and cost of performing work, showed unsatisfactory results in a large number of practical applications [8]. As a result, models were formulated using fuzzy computing methods [9]. In [10], algorithms for constructing fuzzy critical paths were formulated and, on this basis, an extension of fuzzy arithmetic operations was obtained to calculate the last start time of each operation on the critical path [11]. Alternative approaches for taking into account stochastic effects are also formulated, using interactive methods for calculating the critical path [12] and the extension principle [13]. In these works, the key concept of criticality is described as a function of the duration of activity in the network [14, 15]. In [16], an efficient method for calculating the fuzzy latest start and end times is formulated. Zelinsky developed a polynomial algorithm to determine the intervals of the last start time in networks [17]. In [18], Haar ranking is used to order fuzzy numbers, for which fuzzy parameters are converted into Haar tuples [19]. However, even the improved critical path method has a rather narrow range of applicability. In particular, it does not describe complex networks with subcritical paths [20] and variable cardinality of non-storable resources [21].

The limited scope of applicability of the concept based on a priori damping of critical paths has led to the intensification of the development of algorithms based on quantitative methods for taking into account the contribution of stochastic processes. The simplest and, therefore, the most common method of this class are PERT (abbreviation for Project Evaluation and Review Technique). From a practical point of view, the essence of this method is to calculate the performance ranges of non-stock resources, and, consequently, the time of operations using the tools of probability theory. The great possibilities and flexibility of the PERT method have led to its widespread use. So, for example, in the United States, government agencies accept for consideration only those proposals from firms for which a project network based on this method is presented [22]. According to [22], as early as 1995 in the USA, even small enterprises used the PERT method, and all large US corporations have special services involved in the organization of work based on the application of the PERT method. In the PERT method, the duration of an individual process is considered to be a random variable described by a family of two-parameter β distributions of the value x specified on the interval [0.1] of the form [23]:

$$f_{\alpha,\beta}(x) = x^{\alpha-1}(1-x)^{\beta-1} \Big/ \int_0^1 x^{\alpha-1}(1-x)^{\beta-1}. \quad (1)$$

Depending on the value of the parameters α, β, distribution (1) can describe a very wide class of phenomena. As a result, the determination of parameters α, β adequate to a real system is a complex task that does not have an unambiguous solution. Therefore, in practice, a simplified numerical experiment algorithm (Monte Carlo method) is more often used with a uniform distribution of a random variable. In any approach, stochastic modeling is based on an expert assessment of the upper t_{max} and lower t_{min} limits of the duration of individual processes of critical and subcritical chains, which introduces additional uncertainty into the algorithm.

For large-scale projects, different methods of ranking a large number of fuzzy paths give different results. At the same time, the choice of the ranking method is decisive for the choice of the path. The criteria that ranking methods must meet are formulated in the classical works of Yuan Y. [24], Wang et al [25], and Chien et al. [26]. However, their practical application to real projects requires the collection of extensive, usually inaccessible, information. To overcome this difficulty, the Haar wavelet analysis method was proposed, which allows one to expand the objective function in an orthonormal basis [18]. However, the field of practical applicability for the industry of AECO and this optimized fuzzy path ranking algorithm is limited by the complexity of the project and the detail of planning.

The exponential increase in the error in predicting the dynamics of a system experiencing stochastic influences is not specific to the AECO industry. This effect is a particular case of general regularities inherent in complex systems of any nature [27]. Methods to overcome this difficulty is to increase the volume and dispersion of information [28]. This method works effectively for one-parameter systems [29], but is not applicable to the description of multi-parameter socio-economic phenomena [30]. To optimize the management of such systems and, in particular, the progress of construction projects, it is necessary to determine a parameter that takes into account the relationship between economic and technological processes. This problem was successfully solved in [31]. An effective method for reducing the error in predicting the behavior of a complex system experiencing stochastic influences was proposed in [32]. This method is based on dynamic monitoring of the current state of the progress of the schedule, adjusting the forecast for the completion of construction and developing, on this basis, optimal technological and managerial methods to reduce the negative impact of stochastic impacts.

MATERIALS AND METHODS

The special significance of this approach for the AECO industry is determined by its specificity, which does not allow direct transfer of successful practices from other areas of the economy. In [32], it is shown that the dynamic index of the use of personnel and equipment Dipe in combination with the dynamic index of the production of personnel and equipment Dppe make it possible to optimize both the current construction progress and its medium term.

The need for dynamic optimization of the profile of non-stock resources (hereinafter — NR) is determined by the immobility of construction objects and the mobility of personnel and equipment, which greatly complicates the resource maneuver. The life cycle of a construction project takes a long period of time and is characterized by high resource intensity. Since the stored resources are excluded from circulation for a long time, it is necessary to use specific approaches in their distribution in space and time. In addition, the construction industry is more strongly influenced by the external environment than other industries [33]. The types of internal and external risks that affect the effective functioning of construction enterprises, and methods for analyzing and assessing risks are described and classified in [34]. Often these methods involve the use of modern information technologies such as information modeling (BIM) technologies. At the same time, some of these impacts are deterministic in nature (for example, seasonal and daily changes in temperature, humidity, illumination, which determine the characteristics of technological processes) and can be taken into account at the scheduling stage. At this stage, when assessing the integral organizational and technological potential of a construction project, it is necessary to take into account information flows [34], the definition and main characteristics of which are formulated in [35]. Another part of the environmental impacts is stochastic in nature and generates risks of deviations from the work schedule. These impacts include weather and, more recently, epidemiological factors [33, 34].

The use of BIM technologies can significantly expand the scope of practical application of methods for optimizing the catch-up schedule for the implementation of the construction schedule [32, 34]. In [32], closed expressions were obtained for the dynamic index of personnel and equipment use (hereinafter — Dipe from the English *dynamic index of personnel and equipment use*) and the dynamic index of personnel and equipment output (hereinafter — Dppe from dynamic productivity index of personnel and equipment). However, in practice, with an increase in the complexity and duration of the project, recurrent algorithms for optimizing the catch-up schedule using vector algebra methods turn out to be more convenient. The formation of such algorithms and their application to real projects is the goal of this work.

The information required to calculate the dependence of the Dipe index on time is completely determined by matrices with dimensions $N \times M$, where N — the number of types of HP and M — the number of planning intervals (weeks depending on the degree of detail of the schedule of hours, shifts, days, etc.). Further, in all matrices and vectors, the index $i = 1, 2, ..., N$ will number the resources, and the index $j = 1, 2, ..., M$ will number the planning and monitoring intervals. Since the stability of the system to external stochastic influences is determined by the degree of resource reservation, it is necessary to set matrices that describe the characteristics of the contractor ($n_{i,j}^{tot}$ — the total number of available HPs) and the profile of resource use during the implementation of the schedule ($n_{i,j}$ — the planned number of resources used). A matrix $D_{i,j}$ whose components are defined by the equality:

$$D_{i,j} = n_{i,j} / n_{i,j}^{tot}, \qquad (2)$$

dynamically describes the degree of scarcity of the i-th resource. In particular, when the exact upper limit $D_{i,j} = 1$ is reached, the corresponding HP is fully used, as a result of which a resource maneuver in the j-th time interval is impossible. In contrast, small values of the components $D_{i,j}$ from a practical point of view mean irrational use of the resource and are admissible only locally. The integral degree of scarcity of the i-th resource is determined by averaging over the scheduling period;

$$D_i^{tot} = \frac{1}{M} \sum_{j=1}^{M} n_{i,j} / n_{i,j}^{tot}. \qquad (3)$$

Analysis of the parameter value D_i^{tot} allows to determine the possibility of resource maneuver and should be performed already at the scheduling stage. The periods of time when such a maneuver is possible are determined by analyzing the dynamics of the deficit index $D_{i,j}$. Graphically, such an analysis of individual resources, the list of which is given in the table, is shown in Fig. 1. A global analysis of all HP of the project requires displaying the dynamics of the scarcity index in 3D format. An example of such a mapping for a set of specialists given in Table is shown in Fig. 2.

In Fig. 1, the dashed line corresponds to an almost completely used resource c $D_1^{tot} = 0.86$, for which a limited resource maneuver is possible only at the last stages of the implementation of the calendar plan. Such a full load leads to significant risks of untimely completion of construction and is permissible only for resources that are not on critical and subcritical paths. The second resource (dashed line) is used by less than 50 % of its productivity — $D_2^{tot} = 0.44$. The best balanced profile of the use of the third resource (solid line) with integral scarcity $D_3^{tot} = 0.73$ and two periods during which the resource maneuver is possible (on the intervals and (1.5) and (11.21)).

Resources (Table) are ordered by the degree of scarcity at the time of construction. The step of the lines of equal value of the index $D_{i,j}$ (curves on the surface of the scarcity index) is 0.05. The areas of weak use of part of the resources at the beginning of the implementation of the calendar plan and the area of the possibility of resource maneuver for most resources in the period (12, 17) are clearly visible.

The quantities of actually used resources $n_{i,j}^r$ and the resource operation time within the planning interval $T_{i,j}^P$ are determined in the course of monitoring the implementation of the schedule. Stochastic impacts can lead to a decrease in the amount of actually used resources compared to the planned ones. The resource operation time within the planning interval $T_{i,j}^P$ may also decrease compared to the planned T_i^P. This situation can arise both as a result of stochastic impacts on the resource under study, and as a result of a backlog in the scope of work caused by the impact on adjacent HPs.

List of specialists required for the implementation of the project

No.	Personnel	Available limit	
		min	max
1	Painter No. 1	3	7
2	Painter No. 2	3	9
3	Painter No. 3	1	5
4	Concrete worker No. 1	5	9
5	Concrete worker No. 2	3	7
6	Concrete worker No. 3	3	9
7	Tiler No. 1	3	5
8	Tiler No. 2	1	7
9	Tiler No. 3	5	7
10	Installer No. 1	7	7
11	Installer No. 2	5	7
12	Installer No. 3	3	3
13	Concrete worker No. 1	9	9
14	Concrete worker No. 2	0	5
15	Concrete worker No. 3	1	5
16	Coater with synthetic materials No. 1	1	5
17	Coater with synthetic materials No. 2	3	3
18	Coater with synthetic materials No. 3	3	3
19	Waterproofer No. 1	3	3
20	Waterproofer No. 2	3	7
21	Waterproofer No. 3	5	5

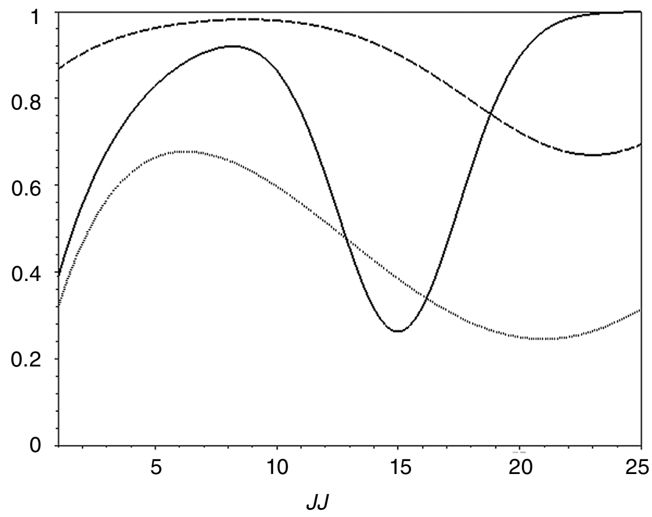

Fig. 1. Relationship between the scarcity index for three non-stock resources and time

The total efficiency E_i^j of using the i-th resource for the period from the start of the planned use of the resource ($j \geq m_{\min}$) to the time of current monitoring t_j is determined by the following formula:

$$E_i^j = \sum_{m=m_{\min}}^{j} n_{i,m}^r T_{i,m} \Big/ \sum_{m=m_{\min}}^{j} n_{i,m} T_{i,m}^P. \qquad (4)$$

In the software implementation of the estimation algorithm, it is easier to use not closed expressions (4), but recurrent expressions that explicitly take into account the mechanism of information accumulation. In this case, the efficiency calculation algorithm $E_i^j = E_{i,n}^j \Big/ E_{i,d}^j$ is expressed in terms of planned values and monitoring results as follows:

$$\begin{cases} E_{i,n}^j = E_{i,n}^{j-1} + n_{i,m}^r T_{i,m} \\ E_{i,d}^j = E_{i,d}^{j-1} + n_{i,j} T_{i,m}^P \end{cases}; \qquad (5)$$

at initial values $E_{i,n}^0 = 0$; $E_{i,d}^0 = 0$. The target indicator of efficiency E_i^j at all stages of the implementation of the calendar plan is a single value. Stochastic impacts (for example, temporary incapacity for work of personnel, violation of contractual obligations by subcontractors or breakdown of equipment) can lead to a decrease in the index E_i^j compared to the target level. Adjustment of the resource utilization profile can only be carried out within the windows of opportunity envisaged at the planning stage and graphically displayed in Fig. 1 or Fig. 2.

Thus, the coordinated use of the methods of planning, monitoring and adjusting the pace of the implementation of the calendar plan, proposed in this paper, makes it possible to reduce the negative impact of stochastic factors on the progress of construction. However, limited resources pose the challenge of setting priorities, both at the planning stage and at the stages of implementation of the plan. This problem can be solved by ranking HP according to the degree of their scarcity D_i^j. Since the degree of scarcity takes a maximum value equal to one for those resources for which the planned usage profiles do not allow reservation. This situation is typical for unique or expensive equipment and personnel. The impossibility of reserving the corresponding HPs leads to the need to pay maximum attention to their monitoring and dynamic optimization of the usage profile. This problem can be solved by the dynamic index of personnel and equipment use (*dynamic index of personnel and equipment use — Dipe*), defined by the expression:

$$Dipe(t_j) = \left(\sum_{i=1}^{N} E_i^j D_{i,j} \right) \Big/ \sum_{i=1}^{N} D_{i,j}. \qquad (6)$$

The index (6) will make it possible to carry out an integral assessment of the progress of the project implementation for all resources at the moment of time t_j. Multipliers $D_{i,j}$ make it possible to allocate the contribution of scarce resources.

Optimization of high-value projects that use unique equipment requires a more detailed description of the dynamics of HP use. This problem can be solved using the index of the use of unique resources (***URI**$_{j,i}$*), which is expressed in terms of scarcity and efficiency indices as follows:

$$UTI_{j,i} = \sum_{m=m_{\min}}^{j} E_i^m D_{i,m} \Big/ (j + 1 - m_{\min}). \qquad (7)$$

Here, the indices j and i number the times at which the evaluation is performed and the resource, respectively.

The calculation of the ***URI**$_{j,i}$* index by formula (7) requires the use of a complete array of information for the time from the beginning of the use of the resource to the moment of evaluation. When calculating the ***URI**$_{j,i}$* index, as well as when determining the field efficiency index E_i^j, the mechanism of dynamic accumulation of information was used as the monitoring time increased. In this approach, the calculation is carried out on the basis of only information describing one period of time. This mechanism can be described by the following recurrence relation, which allows expressing the ***URI**$_{j,i}$* index for the i-th resource at the j-th time points through its values at the monitoring moment in the form

$$UTI_{j,i} = \frac{(j - m_{\min})\, UTI_{j-1,i} + E_i^j D_{i,j}}{j + 1 - m_{\min}}. \qquad (8)$$

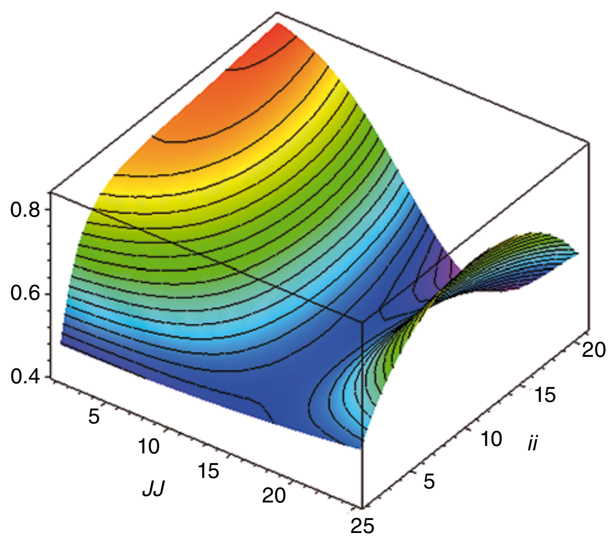

Fig. 2. Relationship between the scarcity index (applicate axis) for 21 HP (abscissa axis) and the planning period number (ordinate axis)

when the initial condition $UTI_{m_{min}-1,i} = 0$ is met. The two-dimensional nature of the index $\boldsymbol{URI_{j,i}}$ leads to the need for a graphical display in the 3d format. An example of such a display is shown in Fig. 3.

Fig. 3 shows the following time intervals:

- a significant delay from the schedule (in the range from 10 % to 25 %) at the beginning of construction;
- interval of efficient use of resources (5–15 planning intervals);
- interval of stochastic impact (17–21 planning intervals), which caused inefficient use of a number of resources;
- interval for eliminating the negative consequences of stochastic impacts (19–25 planning intervals).

RESULTS

Stochastic influences change not only the time of resource use, but also its performance. So, for example, the implementation of a catch-up schedule requires an increase in the intensity of the use of personnel and equipment in comparison with the normative one. Such forced use of HP can lead both to temporary disability of personnel or equipment breakdown, and to a decrease in productivity. Similarly, changes in energy supply modes and quality characteristics of resources supplied by project participants can also affect the implementation of the calendar plan. In addition to stochastic, dynamic influences also influence HP performance. Examples of such impacts are training and additional stimulation of personnel, modification of equipment during the construction process. The method of accounting for changes in productivity during the implementation of the project is proposed in the article [36]. One of the goals of this work is to optimize the BIM project by formulating algorithms for recurrent description of the impact of performance changes on the progress of the implementation of the schedule.

To describe the change in the productivity of HP, caused by both stochastic and non-stochastic influences, allows the index of personnel and equipment productivity — (*index of personnel and equipment productivity — Iep*), defined by the following formula:

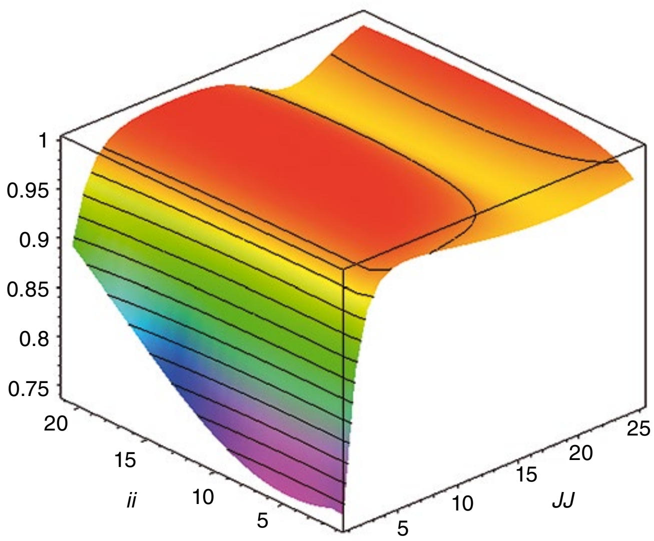

Fig. 3. Index dependency Unique resource utilization index (applicate axis) for 21 resources (abscissa axis) for 25 planning periods (y-axis)

$$P_i^j = \sum_{m=m_{min}}^{j} n_{i,m}^r\, p_i^r(t_m) \Big/ \sum_{m=m_{min}}^{j} n_{i,m}\, p_i(t_m). \quad (9)$$

Here $p_i(t_m)$ and $p_i^r(t_m)$ are the planned and actual productivity of personnel and equipment during the monitoring interval t_m. Recurrent expressions

$$P_i^{j,r} = P_i^{j-1,r} + n_{i,m}^r\, p_i^r(t_m)$$
$$P_i^{j,p} = P_i^{j-1,p} + n_{i,m}\, p_i(t_m) \quad (10)$$

with zero initial values of planned and real total productivity ($P_i^{m_{min}-1,p} = P_i^{j-1,r} = 0$) allow expressing the index *Iep* as a fraction $P_i^j = P_i^{j,r} \Big/ P_i^{j,p}$. Taking into account the degree of scarcity of resources allows us to determine the integral dynamic index of personnel and equipment productivity — (*integral dynamic index of personnel and equipment productivity —* Idipe) in the form

$$Idipe(t_j) = \left(\sum_{i=1}^{N} P_i^j D_{i,j}\right) \Bigg/ \sum_{i=1}^{N} D_{i,j}. \quad (11)$$

The main advantage of the *Iep* and *Idipe* staff and equipment output indices over the staff and equipment utilization indices is the inclusion of the influence of a larger number of factors, which improves the quality of the forecast of the progress of the calendar plan. However, operational management decisions based on adjusting the resource utilization profile do not address the factors that change the HP performance. An exception may be operational measures to stimulate the staff. Therefore, the main area of application of performance indexes, in contrast to usage indexes, is long-term planning. Thus, the classes of indices proposed in this paper complement each other and, together, allow you to optimize the progress of the project throughout a significant part of its life cycle.

A two-dimensional matrix P_i^j carries information describing the performance dynamics of individual resources. In contrast, a one-dimensional vector $Idipe(t_j)$ contains only information averaged over all resources. As a result, the analysis of the dynamics of the index P_i^j based on 3d models requires the involvement of highly qualified specialists and should be used when optimizing expensive projects that use unique equipment and personnel. Analysis of averaged information, which allows optimizing the implementation of the standard project schedule, can be performed by line personnel of contractors in real time.

Methods for monitoring risks during the implementation of the calendar plan based on information technologies attract considerable interest from foreign [37] and domestic [36] researchers. To a large extent, these methods are based on high-dimensional information models [38] of the life cycle of a construction project [39]. At the same time, the high dimensionality of the model hinders its effective local operation [40] and, to an even greater extent, the transfer between project participants [41]. The paper [36] proposes a BIM dimension reduction method that allows one to significantly expand the area of practical application of full life cycle information models. The development of this method based on the indices of use and production of resources and its application to the tasks of monitoring the progress of the implementation of the calendar plan and optimizing the methods of operational and medium-term is one of the goals of this work.

The algorithm for reducing the dimension of the information model formulated in [36] allows expanding the area of practical application of BIM. The implementation of this algorithm is reduced to the formation of basic structures and the formulation of methods for the hierarchical construction of structures of higher ranks. In the information monitoring model being formed (hereinafter referred to as BIMM), all structures (both basic and derived) are matrices, the rank of which is determined by the number of HPs and the number of planning intervals. The formats of the elements are determined by their practical content.

The basic static structures of the information model are two matrices — “Resources” and “Periods”, containing two columns. The first column in both tables “Number” is in integer format; the second column “Name” is in text format. The number of rows of the “Resources” matrix is determined by the number of types of used HPs (parameter N in formula (6)), and the “Periods” matrix is determined by the number of planning and monitoring periods (shifts, days, weeks, decades, months, etc. — parameter M in formula (3)). The data of the “Name” columns of both matrices is not processed in the algorithm and serves only as the basis for the interface of BIMM interaction with users.

Structures of the second level are two-dimensional matrices of M columns and N rows and contain both static, plan components (matrices $n_{i,j}$, $n_{i,j}^{tot}$, $T_{i,j}^{P}$, $p_i(t_m)$), and components dynamically updated as a result of monitoring (matrices $n_{i,m}^{r}$, $T_{i,m}$, $p_i^r(t_m)$). All components of second-level structures have integer and real formats. The values of indexes i, j, m are determined by the fields “Number” of the matrices of the first level. Sources of static information are calendar plans, data on personnel and material support of the contractor, Uniform Rates And Prices (URAPs). Dynamic information is contained in timesheets, accounting documents, data on operational accounting of the progress of the implementation of the calendar plan.

After the formation of matrices $n_{i,j}$, $n_{i,j}^{tot}$, containing static information, prior to construction, according to formulas (2) and (3), the local and integral degrees of scarcity are calculated. Further, analytically or graphically (similarly to Fig. 2 and Fig. 3), an analysis of the possibilities of resource maneuvers is performed and time intervals for adjusting the profile of the use of HP in response to possible negative impacts of stochastic factors are determined.

Further operation of BIMM takes place at the construction stage in the mode of monitoring the progress of the implementation of the calendar plan. Information accumulated as a result of dynamic monitoring is displayed in matrices $n_{i,m}^{r}$, $T_{i,m}$, $p_i^r(t_m)$. According to formulas (4), (5), (9), (10), local indices are calculated, and according to formulas (6) and (11), global indices of the use and output of personnel and equipment. The same operations are performed with the indices of the use of unique resources (formulas (7), (8)). Based on the analysis of utilization indices and time intervals in which a resource maneuver is possible, operational management decisions are determined aimed at reducing the influence of stochastic factors on the progress of the project. On the other hand, the analysis of production indices allows us to formulate strategic decisions that allow us to preventively mitigate the impact of negative impacts.

At the initial stages of BIMM functioning, information is accumulated, stored, updated and verified. The functionality of Microsoft Access makes it very efficient to programmatically implement these procedures. Also effectively this DBMS allows you to transfer information between project participants. However, the set of built-in functions and procedures is not efficient enough when performing matrix operations and graphical presentation of the results. Various methods are used to solve this range of problems. So, for example, the implementation of matrix operations can be performed in the built-in application VBA (*Visual Basic for Applications*) [42]. However, the set of technologies for processing graphic objects in this approach is very limited. Therefore, in this paper, we used an approach based on the use of the high-level mathematical package MAPL [43] for performing calculations and graphical processing of the results, and data exchange between the used shells. This approach allows not only to solve all the current problems of this study, but also to avoid program limitations when solving long-term problems of predicting the progress of the project throughout the life cycle.

As an example, here are fragments of the program code for calculating the efficiency index E_i^j in accordance with the recurrence relations (5)

for i **to** N **do**
  $ns_{i,0} := 0;$
  $E_{i,0} := 0;$
  for j **to** M **do**
    $ns_{i,j} := ns_{i,j-1} + nr_{i,j};$
    $E_{i,j} := E_{i,j-1} + \frac{nr_{i,j}\,T_{i,j}}{TP_{i,j}}$
  end do;
  for j **to** M **do**
    if $0 < ns_{i,j}$ **then** $E_{i,j} := \frac{E_{i,j}}{ns_{i,j}}$ $else E_{i,j} := 0$
    end if
  end do
end do

and coefficient ***Dipe***

for i **to** M **do**
  $Dipe_j := 0;$
> **for** i **to** N **do**
    if $.1\ 10^{-5} < nt_{i,j}$ **then** $Dipe_j := Dipe_j + \frac{E_{i,j}\,np_{i,j}}{nt_{i,j}}$
    end if
  end do;
  $DD_i := 0;$
  for j **to** N **do**
    if $.1\ 10^{-5} < nt_{j,i}$ **then** $DD_i := DD_i + \frac{np_{j,i}}{nt_{j,i}}$
    end if
  end do
end do
  $Dipe_i := 0;$
> **for** j **to** N **do**
    if $.1\ 10^{-5} < nt_{j,i}$ **then** $Dipe_i := Dipe_i + \frac{E_{j,i}\,np_{j,i}}{nt_{j,i}}$
    end if
  end do;
  do end do

DISCUSSION

Such a BIMM information structure makes it possible to completely solve the problem of interaction between heterogeneous project participants (designers, builders, operating organizations, supervisory authorities, etc.) at various stages of the life cycle. In the proposed approach, the coordination of the content and format of data is reduced to a standard procedure for the coordination of accounting and management documents. Since a significant part of the factors hindering the implementation of BIM is related to the procedures for the interaction of participants [44], the proposed model for coordinating the content and formats of information at all stages of the life cycle greatly expands the area of practical application of information models. All the information necessary for the creation and operation of BIM is contained in the documents of the project participants and the functioning of the model does not lead to additional costs for collecting and processing data. This approach increases the efficiency of the information model in terms of cost/benefit ratio and increases its performance.

Coordination of formats of heterogeneous documents can be effectively performed in the shells of Database Management Systems (DBMS, in English literature — DBMS is the abbreviation of *Database Management System*). When describing dynamic structures, relational databases are the most effective [45]. Most of the workflow takes place in *Microsoft Office* applications (*Microsoft Word, Microsoft Excel, Microsoft Outlook, Microsoft Power Point,* etc.), which defines Microsoft Access as the optimal choice of DBMS. This choice provides a common application interface that is familiar to most users and compatible data formats. A wide class of users (primarily educational and scientific institutions) use free licensed versions of these software products, and all users have access to a license-free version of *Microsoft Access* with limited functionality. The functionality of this version is sufficient for the operating organizations of BIMM implemented in this shell. All this helps to avoid legal and organizational problems when implementing the interaction of project participants, in particular, in the *Microsoft Groove* collaboration application.

CONCLUSIONS

In the course of the development of the methods proposed in this paper, it is possible to solve the problems of interfacing information models of various stages of the full life cycle of the project. The main factors that make it possible to effectively solve this problem are the determination of the necessary and sufficient volume and content of information that allows you to fully describe the dynamics of the state of the project and predict the course of its implementation under conditions of intense stochastic influences.

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BIM-технологии оптимизации догоняющего графика реализации календарного плана строительства с учетом внешних стохастических воздействий

В данной работе предметом исследования являются информационные модели календарных планов стройпроизводства, реализуемых в условиях интенсивных стохастических воздействий. Цель исследования состоит в оптимизации методов формирования догоняющих графиков на основе BIM-технологий мониторинга хода реализации проекта. В результате проведенной работы определен набор параметров, описывающих динамику реализации календарных планов и учитывающих связи экономических и технологических процессов. Определены индексы, позволяющие оптимизировать как оперативные, так и стратегические управленческие решения. Сформулирован алгоритм определения интервалов времени, в течение которых возможен ресурсный маневр. Найдены динамические индексы, адекватно описывающие применение уникальных и дорогостоящих ресурсов, для которых возможности априорного резервирования ограничены. Определены источники информации, позволяющие в рамках стандартных бизнес-процессов описать как статическую информацию, основанную на календарном плане, так и динамическую часть, отражающую результаты мониторинга. Определены размерности, ранги и форматы элементов матриц, определяющих информационную модель строительства, и иерархические связи между ними. Получены как замкнутые выражения динамических индексов через матрицы BIM, так и рекурсивные процедуры, отражающие механизм накопления информации в процессе мониторинга. Предложенные в работе алгоритмы накопления информации реализованы в оболочке реляционной системы управления базами данных, а расчетов их и графической интерпретации — в математическом пакете высокого уровня. Действие алгоритмов и их программной реализации продемонстрировано на конкретном примере реализации календарного плана стройпроизводства.

Ключевые слова: *информационная модель строительства, жизненный цикл проекта, календарный план, стохастические воздействия, мониторинг, оптимизация, векторная модель, критерии оценки, нескладируемые ресурсы.*

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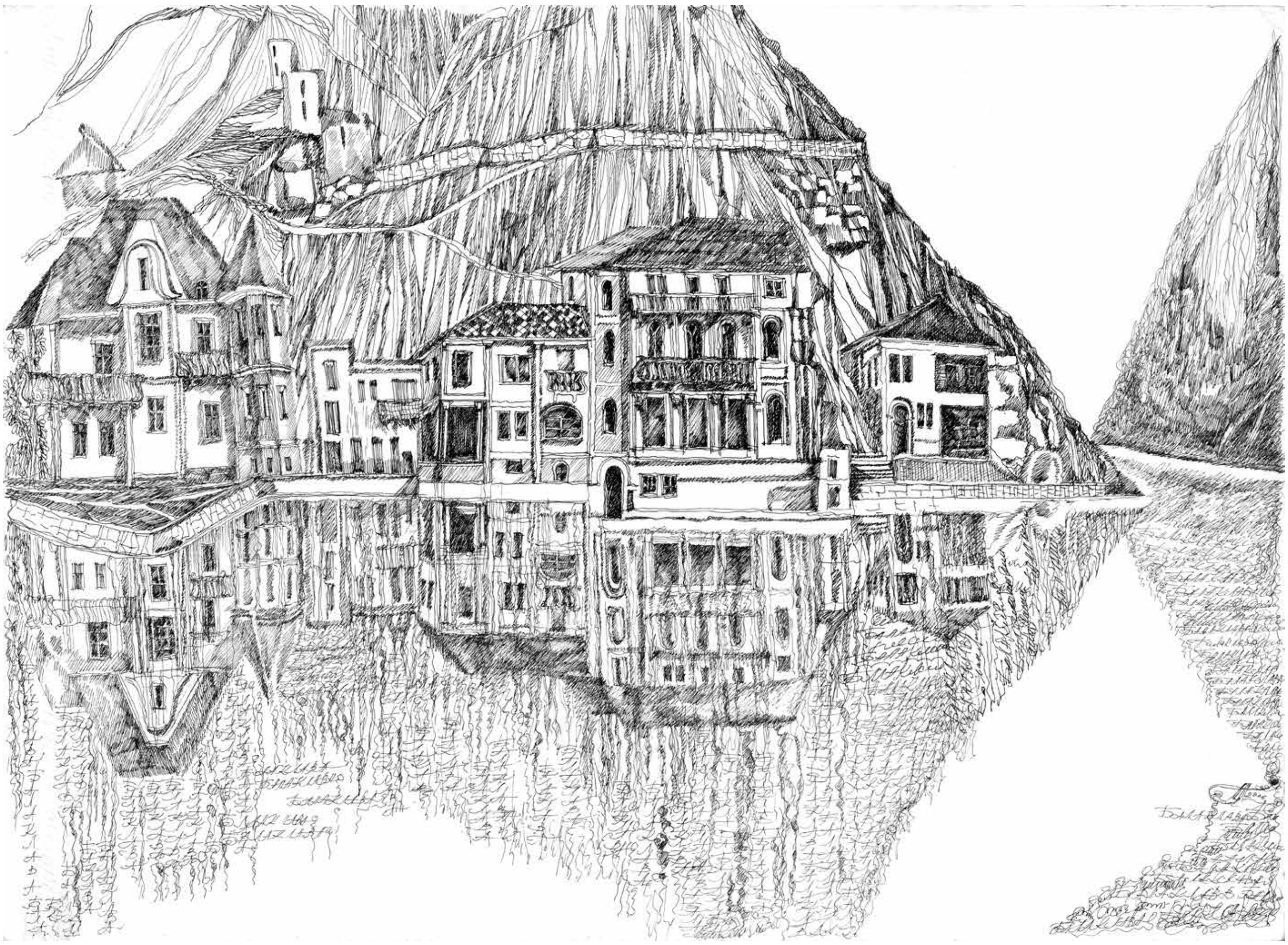

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