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Optimized construction work scheduling in the context of integrated urban development

The integrated development of residential areas encompasses a favourable and comfortable living environment as well as the rational use of urban space. A generalized work schedule is one of elements needed for integrated urban development. The proposed methodology of drafting, calculating and optimizing work schedules within the framework of integrated urban development serves this purpose. Its step-wise implementation is reduced to the following procedures.

An organizational and engineering development plan is drafted. It encompasses the calculation (estimation) of work durations, setting up links between the construction work packages along with restrictions imposed for the dates of the events. Further, subject to the input data and the streaming (workflow) method of construction work organization using Microsoft Project software, an acceptable basic solution is identified. It is based on a solution to the system of linear equations that describe the organizational and engineering schedule of construction works. After a basic acceptable solution is obtained, calculations are optimized in Microsoft Project to minimize unit investment costs. The cost-effectiveness of an optimized schedule focused on the integrated development of an urban area is evaluated by the Project Expert software. Further, the feasibility of implementing an optimized schedule is verified using the visual representation of the development process in BIM software similar to Revit. A relatively small number of development prioritization options allows evaluating each of them against the pre-selected cost-effectiveness criteria and choosing the best option.

Keywords: *scheduling of construction, organizational and engineering plan of construction, time constraints in calendar schedules, acceptable scheduling, optimized work schedule, project management software*

INTRODUCTION

The main principle behind the integrated development of residential areas is specified in the Urban Planning Code of the Russian Federation[1]. According to its provisions, integrated urban development encompasses a comfortable enabling living environment and the optimal use of urban space. One of the elements needed for this principle to be implemented is drafting a generalized schedule of works. To draft a construction schedule, organizational and engineering solutions need to be developed to ensure the effective disbursement of capital investments, and the volumes of construction and installation works on buildings, structures as well as between construction periods[2]. The document which determines the efficiency of organizational and engineering solutions is called a construction planning design (CPD) or master plan. According to the project documentation make-up requirements, the CPD is defined as a section setting the overall duration and milestones, as well as the distribution of capital investments along with volumes of construction and installation works[3]. Yet any integrated development includes many projects, and therefore problems related to delays in construction occur in the course of integrated urban development. Quite a few research works mention heterogeneous problems in creating a universal recipe for preventing delays in construction. These problems are associated with the uniqueness of construction projects, the complexity of timing and the allocation of financial and labour resources between different projects which are part of the integrated urban development [1].

Article [2] describes the results of a research exposing the impact of seven groups of factors on construction delays. From the material presented, it appears that 3 groups of factors largely contribute to construction delays. These include factors related to labour and financial resources. Other researchers have also concluded that ineffective time and cost management also leads to project failures [3, 4]. And all authors acknowledge that an accurate forecast of construction time is desirable at the planning stage [5]. Hence, the task of integrated development scheduling should be addressed at the stage of PCD elaboration, and this task is relevant in the initial planning of construction.

The toolkit for planning integrated development schedules includes project management software products, such as Primavera [6] and Microsoft Project [7]. Standing out among the methods of planning an integrated development of urban areas are workflow approaches to construction activities, staking on rational sequencing and prioritization in building various projects [8]. Various methods of directed sorting of options, for example, those set out in works [9, 10], can be used in addressing this kind of tasks. Yet in our opinion, the methods of directed search for the right options do not take into account the possible restrictions associated with the commissioning of projects. For example, a situation may arise, when a project has been built, but cannot be

1 Urban Planning Code of the Russian Federation.

2 SP 48.13330.2019. Construction Organization SNiP 12-01-2004 Rulebook No. 48.13330.2019, dated December 24, 2019.

3 On the make-up of design documentation sections and their content requirements : Russian Government Resolution No. 87 dated February 16, 2008.

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put to use due to the construction of adjacent facilities. It has been shown in [11, 12] that such a situation can be predicted and ruled out by using a construction visualization model generated through the BIM design technology.

Residential and public buildings are the target of integrated urban development. The financial costs of their construction are distributed unevenly, this unevenness being characteristic of all projects reflected in the construction duration standards[4]. Table 1 shows a fragment of the construction duration standards for residential buildings.

Processing of the data provided shows that preparatory works are carried out at a rate of 5 to 9 % per month, foundation works are carried out at a rate of 15 to 18 % per month, and interior works are carried out at a rate of 6 to 11 % per month. The building's above-ground part is most cost-intensive, with a corresponding execution rate of these works standing at 15 to 31 % per month. The specific costs of the above-ground part will only increase for higher-rise buildings, as a general rule. Consequently, in order to align the investment costs associated with construction, it is necessary to increase the time for above-ground works, which in turn will lead to a reduction in labour requirements.

To further solve the problem related to the reduction of labour requirements, the method of uncertain resource coefficients seems to be most appropriate [13]. But the original version of this method uses a linear (in terms of time) target function, and for the criterion considered above, which determines the intensity of costs, the work duration factor is included in the denominator of the corresponding criterion, which betokens non-linearity. Therefore, in order to adapt this method to the task of drafting an optimized schedule for integrated urban development, it is necessary to change the optimization algorithm.

METHODS

Let us consider one example of integrated urban development. As an initial condition we will assume that its organizational and technological plan should be oriented towards continuous advancement on all work fronts. The accepted constraint corresponds to minimization of interruptions, when related works are performed on each building. The demonstration example shown in Fig. 1

Table 1. Fragment of residential development duration standards (all preparatory works are assumed to take one month)

Type of building	Floor	Area	*T* norm	Foundation	ground	Interior	Integral costs by months, %							
							1	2	3	4	5	6	7	8
Panel	9	3,000	5	1	2	1	8	26	59	89	100			
Cast-in-place	9	3,000	7.5	1	4.5	1	5	29	42	56	75	85	96	100
Brick	9	3,000	8	1	4.5	1.5	9	24	40	55	72	83	94	100

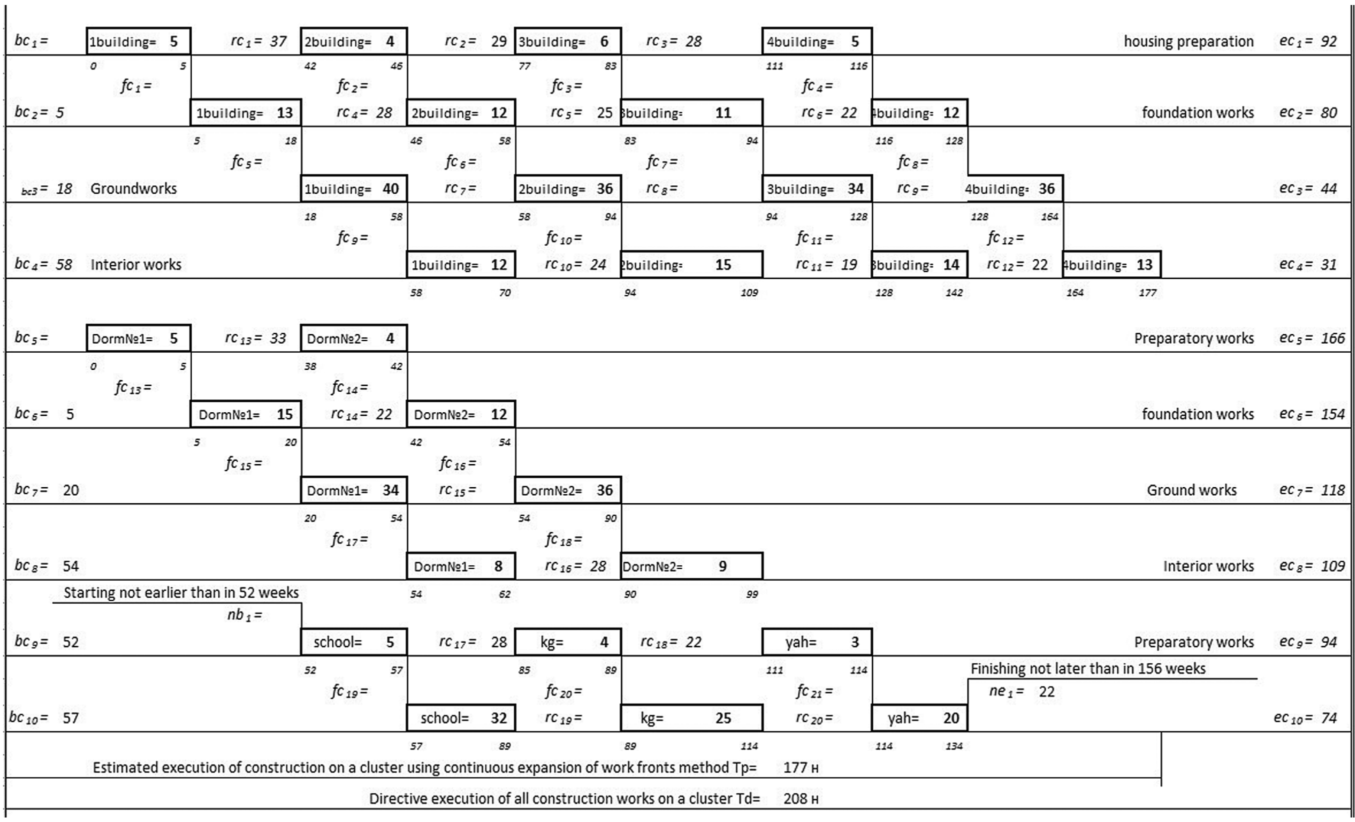


Fig. 1. The diagram of integrated urban development entailing continuous work performance

4 SNiP 1.04.03-85. Construction Duration and Backlog in the Construction of Enterprises, Buildings & Structures Standards. Codex JSC, 2020. URL: http://docs.cntd.ru/document/1200000622

includes the following make-up of projects under construction: four panel buildings for permanent residence, two brick buildings (dormitories) for temporary residence and three buildings oriented towards the integrated educational function, housing a school, a kindergarten (nursery school), and a youth art house. In total, nine buildings are included in the integrated urban development workflow.

When integrated urban development is planned, all panel buildings are consolidated into an integrated construction workflow, having a pre-set order (priority) of construction for each project. Brick dormitory buildings generate another construction stream or workflow, whereas the third workflow comprises educational facilities.

Each rectangle in the workflow chart contains items of work and terms of their performance in weeks. It is not methodologically difficult to estimate the duration of works for this kind of facilities, as there are respective recommended values specified in the Construction Duration Standards[4]. Shown below the corresponding rectangles are the durations of all works (in weeks), calculated by using the method of uncertain resource coefficients. In this calculation, step (stage) 1 of the uncertain resource factor method was used, related to finding an acceptable basic solution. The total number of unknown resource factors (coefficients) depends on the number of construction activities in each of the three identified flows. Each of the resource coefficients is found using formula (1).

$$T=\frac{Q}{R}=\frac{Q}{R}+\frac{Q}{R_{\max}}-\frac{Q}{R_{\max}}=\frac{Q}{R_{\max}}+\frac{Q}{R_{\max}}\left(\frac{R_{\max}}{R}-1\right)= \\ =T_{\min}+aT_{\min}, \tag{1}$$

Where a is an uncertain resource coefficient.

The above formula includes the following parameters: labour intensity — Q, maximum number of resources — $R_{\max}$, minimum duration of work — $T_{\min}$, and estimated number of labour resources — R. Since in this example, the general work schedule formation is based on the use of construction duration standards, we'll assume that these durations correspond to the assumption of labour resources equivalent to 100 %. which is tantamount to the assumption of $R_{\max} = 1$. Then the duration of an individual job will be calculated using the following formula:

$$T = T_{\min}+aT_{\min}, \tag{2}$$

In the search for an acceptable basic solution, all uncertain resource factors should have the status of free or loose variables, which corresponds to their zero value. Therefore, the calculation of an acceptable basic solution is carried out with regard for the minimum durations of individual works.

The results of the calculation show that the last residential building can be commissioned in 177 weeks from the start of construction. Both dormitory buildings should be completed in 99 weeks, whereas all educational facilities are to be completed in 135 weeks. However, there are 2 types of time restrictions imposed on the construction of educational edifices: the works have to start not earlier than in 1 year (52 weeks) and to be completed not later than in 3 years (156 weeks). Taking into account the parallel execution of works on all construction flows, the estimated completion of construction on the entire urban cluster is 177 weeks. As an additional condition, a limit for the directive term of construction completion is assumed, equal to 4 years, which corresponds to a duration of 208 weeks.

As per the method of uncertain resource coefficients, the organizational and technological plan of construction can be described as a system of linear equations. In this case, the entire composition of variables included in the system of equations is shown in Fig. 1. This system of equations includes resource links designated as rc_k. There are frontal links between related tasks, determining the technological sequence of works of different types, denoted as fc_j. The duration-defining variables estimated from the general launch of the project to the execution of initial tasks within each type of works are defined as initial links — bc_i. The duration-defining variables from completion of the last works of each type to overall ending of the project are defined as final links — ec_i. The timing of each of the tasks included in the overall activity schedule can be constrained. The "start not earlier than" type of constraints is defined by a date, and the difference between that date and the unknown launch of the work is defined by a variable designated as nb_l. The "finish not later than" type of constraints is also defined by a date, and the difference between that date and the unknown end of the work execution is defined by a variable designated as ne_l.

The final system of equations describing the organizational and technological plan of integrated urban development is divided into 3 groups of equations. The first group includes resource equations describing the execution of works of one type. For instance, the resource equation corresponding to the execution of above-ground works represents the sum of durations of corresponding works in respect of 4 buildings. Added to this sum is the sum of interruptions defined by resource links and the sum of interruptions defined by initial and final links. By summing up all of the above-listed variables, we arrive at the equation determining the equality of the directive construction duration.

$$bc_3 + 146 + 146a_3 + rc_7 + rc_8 + rc_9 + ec_3 = 208. \tag{3}$$

The equation shows the relationship between the two types of works, and it includes the sum of the durations and links of respective parts of the work types. For example, the equation going through the frontal link, fc_6, includes all the durations and links making up the left part of the second work type and the right part of the third work type.

$$bc_2 + 25 + 25a_2 + rc_4 + fc_6 + 106 + 106a_3 + rc_8 + rc_9 + \\ + ec_3 = 208. \tag{4}$$

The third group of equations is made up with regard for constraints on the deadlines for individual tasks. These constraints correspond to dates and unknown variables. The dates define a time limit which, terminologically, can be replaced just by a "limit", and then the corresponding equations could be described as "limited equations". There are only two of these in the example below.

$$52 + nb_1 + 12 + 12a_9 + rc_{17} + rc_{18} + ec_9 = 208, \tag{5}$$

$$bc_{10} + 77 + 77a_{10} + rc_{19} + rc_{20} + ne_2 = 156. \tag{6}$$

As a result, the organizational and engineering plan of integrated urban development, shown in Fig. 1, is described by means of 33 equations including 73 variables. In linear programming, a system of equations of this kind is called a simplex matrix or just a simplex. The optimization solution of the linear programming problem is divided into two stages.

At the first stage an admissible basic solution is formed. For most problems solved using a linear programming method, it is assumed that the order of introducing variables into the admissible basic solution does not matter [14]. Yet for the problem we set, the order of introducing variables determines the workflow method of construction. The monograph [9] assumes that the workflow method of construction organization is determined by the constraints imposed on the links between various activities. Thus, at the first stage a solution is formed in accordance with the workflow method of construction whereas at the second stage, an optimization solution of the problem is used in accordance with the optimization criterion described above.

RESULTS AND DISCUSSION

If in the original simplex all frontal links are moved to the end, then by applying the search of the next baseline variable with a forced return to the beginning, one can possibly obtain the solution for a system of equations with zero values of frontal links. This simplex matrix solution is shown in Table 2.

The second and third columns of Table 2 show the names and values of baseline variables obtained at the stage of finding an admissible basic solution. The number of baseline variables equaling the number of equations is the first sign of the admissible basic solution existence. If the name and value of a respective variable is missing in Table 2, it means that the variable in question is free and its value (by definition) is zero. The problem solution suggested shows that all frontal links turned out to be free variables. This means that an admissible basic solution is equivalent to the method of calculating the workflow organization of construction, corresponding to the continuous advancement on all work fronts. We assume the obtained solution as the basis for further optimization of integrated scheduling.

As was earlier noted, in order to reduce cost peaks, it is necessary to apply a criterion defining specific costs per time unit. Such a criterion can be calculated for each activity, the results being summarized in Table 3.

The first row or line in Table 3 shows the investment costs broken down by types of works. One of the sources for estimating the given costs is a document called “Consolidated Standard

Table 2. Simplex matrix for an acceptable basic solution

Eq. No.	Variables	Values	Indices of resource coefficients									
			1	2	3	4	5	6	7	8	9	10
1	ec_1	92	5	1	110							
2	bc_2	5	–5									
3	bc_3	18	–5	–13								
4	bc_4	58	–5	–13	–40							
5	ec_5	166					5	3	34			
6	bc_6	5					–5					
7	bc_7	20					–5	–15				
8	bc_8	54					–5	–15	–34			
9	bc_9	52										
10	bc_{10}	57									–5	
11	ec_2	80	5	13	110							
12	rc_1	37	4	–1	–40							
13	rc_2	31	6	–1	–36							
14	rc_3	28	5	1	–34							
15	ec_3	44	5	13	146							
16	rc_4	28		12	–40							
17	rc_5	25		11	–36							
18	rc_6	22		12	–34							
19	rc_{10}	24			–36	12						
20	rc_{11}	19			–34	15						
21	rc_{12}	22			–36	14						
22	ec_4	31	5	13	146	13						
23	ec_6	154					5	15	34			
24	rc_{13}	33					4	–3	–34			
25	ec_7	118					5	15	70			
26	rc_{14}	22						12	–34			
27	rc_{16}	28							–36	8		
28	ec_8	109					5	15	70			
29	ec_{10}	74									5	77
30	rc_{17}	28									4	–32
31	rc_{18}	22									3	–25
32	ec_9	94									5	57
33	ne_1	22									5	77

Table 3. Optimized calculation of an integrated work schedule

Line No.	Name of the parameter	Work type indices									
		1	2	3	4	5	6	7	8	9	10
1	Investments costs, RUB million	63	97	915	53	36	58	375	45	51	555
2	Initial duration, weeks	20	48	146	54	9	27	70	17	12	77
3	Unit costs, RUB mln/week	3.15	2.02	6.27	0.98	4	2.15	5.36	2.65	4.25	7.21
4	Initial order of optimization	6	9	2	10	5	8	3	7	4	1
5	1st step: duration, weeks	20	48	146	54	9	27	70	17	12	99
6	1st step: unit costs	3.15	2.02	6.27	0.98	4	2.15	5.36	2.65	4.25	5.61
7	Optimization procedure after Step 1	6	9	1	10	5	8	3	7	4	2
8	2nd step: Duration, weeks	20	48	177	54	9	27	70	17	12	99
9	2nd step: unit costs	3.15	2.02	5.17	0.98	4	2.15	5.36	2.65	4.25	5.61
10	Optimization procedure after Step 2	6	9	3	10	5	8	2	7	4	1
11	3rd step: Duration, weeks	20	48	177	54	9	27	188	17	12	99
12	3rd step: unit costs	3.15	2.02	5.17	0.98	4	2.15	1.99	2.65	4.25	5.61
13	Optimization procedure after Step 3	5	8	2	10	4	7	9	6	3	1

Construction Prices” [19][5]. The second row in Table 3 shows the total initial durations of the works, while the third row shows the specific costs determined by the corresponding ratios of investment costs to the initial durations. The fourth row presents the order of optimization, based on the assignment of ranks in accordance with specific costs. Based on the resulting rankings row, it has been found that the optimization should start with the tenth job. The optimization mechanism boils down to performing the following procedures.

The third column of the simplex (see Table 2) shows the values of the baseline variables; their reduction can be used to increase the work durations. However, to make sure that further recalculation of the simplex does not result in negative values of the variables, it is necessary to come out with such an equation whose time reserve is determined by the minimum ratio of the value of a variable to the value of a resource factor. In this case, the search for the minimum is performed only for resource coefficients that have positive values. For works of the 10th type, we obtain:

$$a = \min\left[\left(\frac{74}{77} = 0.961\right); \left(\frac{94}{57} = 1.649\right); \left(\frac{22}{77} = 0.286\right);\right] = \\ = 0.286 \qquad (7)$$

The resulting minimum corresponds to the 33rd row of the simplex. Based on the former, new values of work durations can be found, which will be greater than the initial durations by (77 + 22) / 77 = 1.286 times. As a result, the new total duration of all works of the 10th type will be 99 weeks. The essence of this procedure means reducing the value of the baseline variable to zero and a corresponding increase in the total duration of the work type. Pursuant to the earlier stated formula (1), finding the minimum value of the ratio sought is equivalent to finding the unknown resource coefficient. Next, all the equations are recalculated according to the standard linear programming procedure.

Taking into account the results obtained at Step 1 of the calculation, the 5th row of Table 3 presents both the previous and the new durations of activities (works), calculated in a similar manner. As per the new durations, the 6th and 7th rows of Table 3 show the results of recalculation of specific costs and the new order of optimization. According to the results obtained in step 1, it is necessary to proceed to the procedure of increasing the duration of third-type works. After performing step 2, job No. 10 reclaimed the first rank. But since this job has completely exhausted the time reserve, the optimization process moves over to job No. 7. Following step 3 of the calculation, all time reserves were exhausted, this fact preconditioning the end of the optimization process.

The calculation procedures presented above are implemented in Microsoft Project management software by creating a macro programme written in the Visual Basic for Applications programming language. Fig. 3 shows the result of automated calculation of the optimized scheduling for integrated urban development.

Fig. 3 shows the obtained solution is totally in line with the calculation of the workflow organization of construction, carried out by way of continuous advancement on all work fronts, this method being described in monograph [9]. The thin lines are used to show the initial schedule of works on the given chart, calculated before applying the above-stated optimization procedures.

Drafting of an optimized construction schedule under the integrated urban development will not be complete unless it is assessed using the standard criteria for economic evaluation of investment projects adopted in the world practice [15] and in the Russian Federation[6]. Automation of the assessment process can be implemented in the Project Expert programme [16]. The optimized schedule in this programme is shown in Fig. 4.

To obtain estimation criteria, information has been entered into Project Expert to supplement the cost-based investment cash flow with positive receipts related to payments for commissioned facilities. In this example, the payment for the facilities is assumed to be 40 % higher than the corresponding investment costs. The calculation takes into account value added and profit taxes of 20 % as well as a discount rate of 12 %. Fig. 5 shows the indicators of various project efficiency assessments calculated in Project Expert.

In general, all estimates have proven their cost effectiveness for the assumed parameters of the future project implementation. However, the optimized schedule of works has been formed for the

5 NCS 81-02-01-2020. Consolidated construction cost standards. Moscow, 2020.

6 Methodological Recommendations on Estimating the Efficiency of Investment Projects: approved by decrees of Russian Economy and Finance ministries. Gosstroy of the Russian Federation, June 21, 1999.

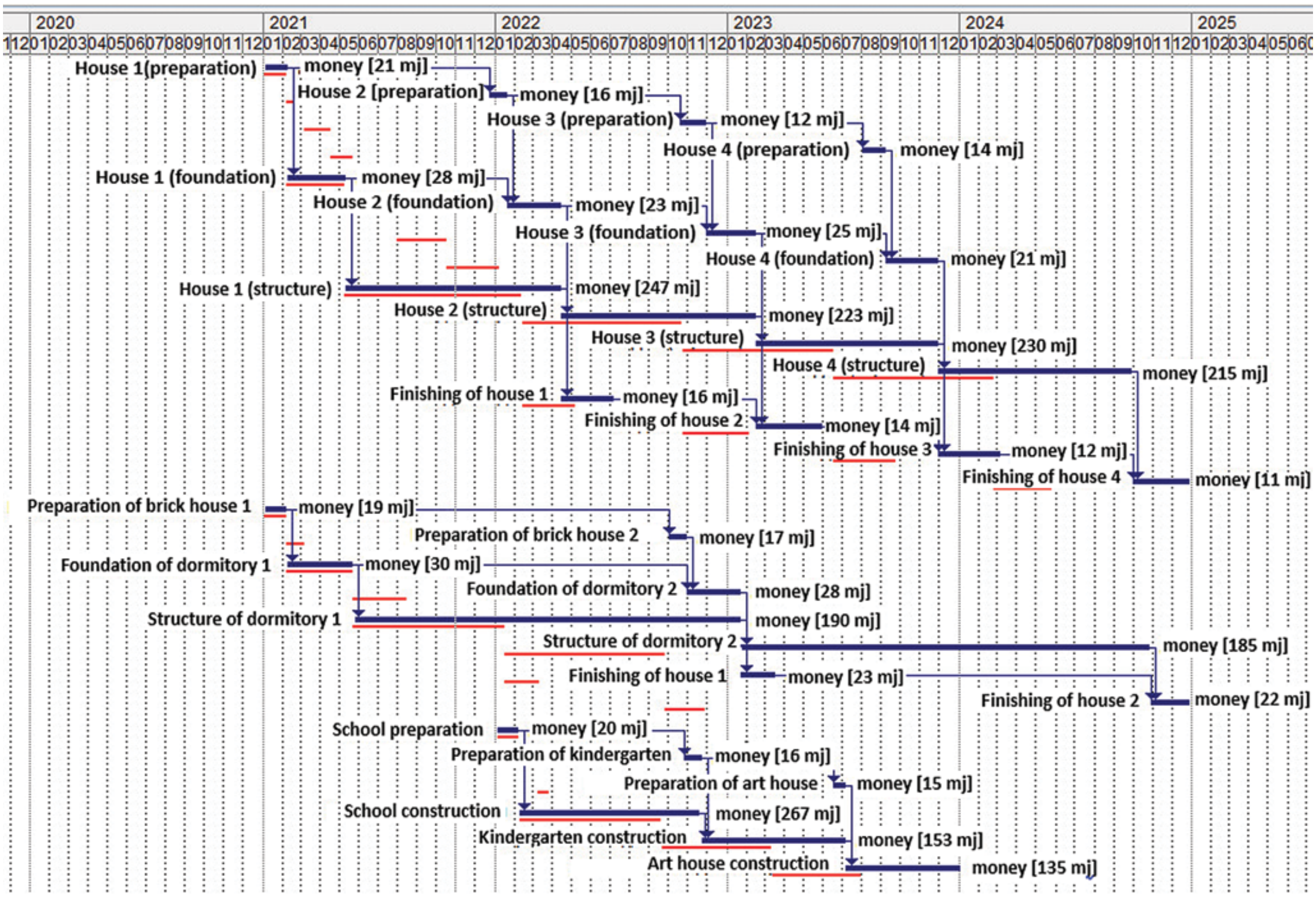
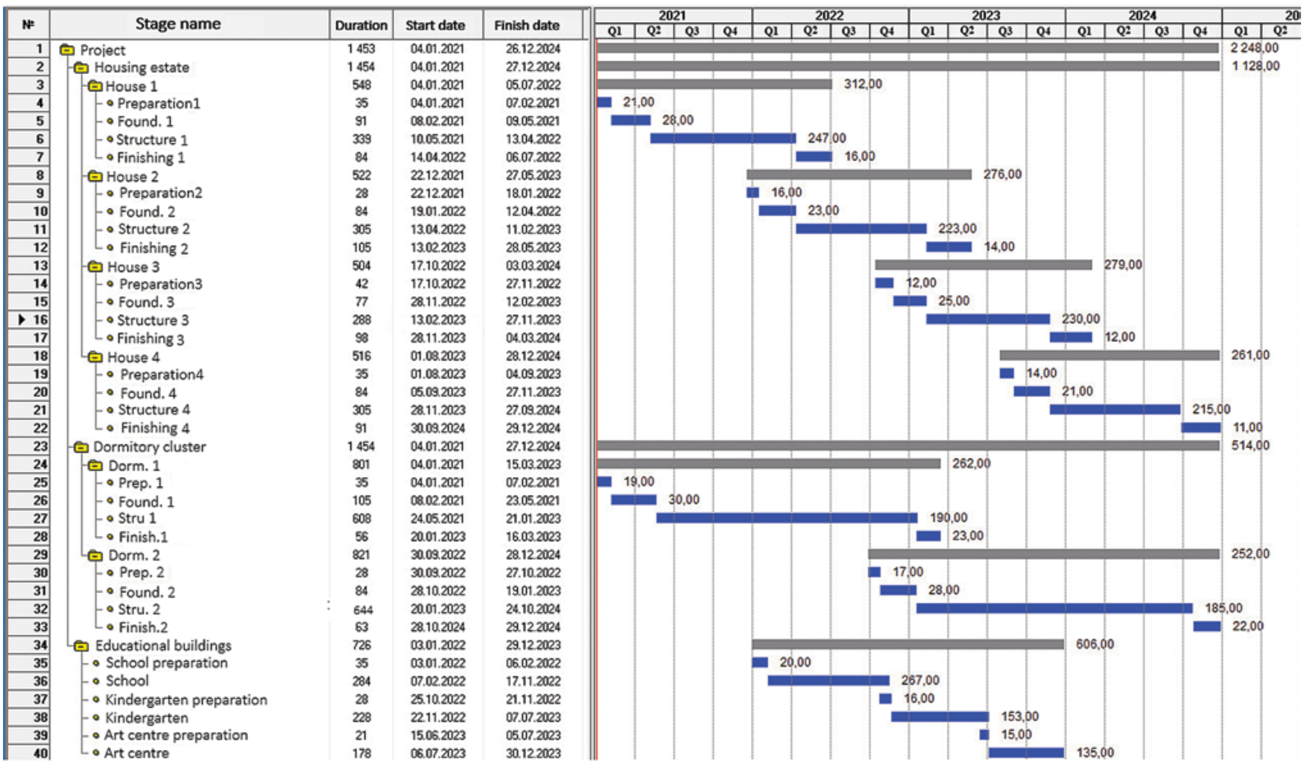
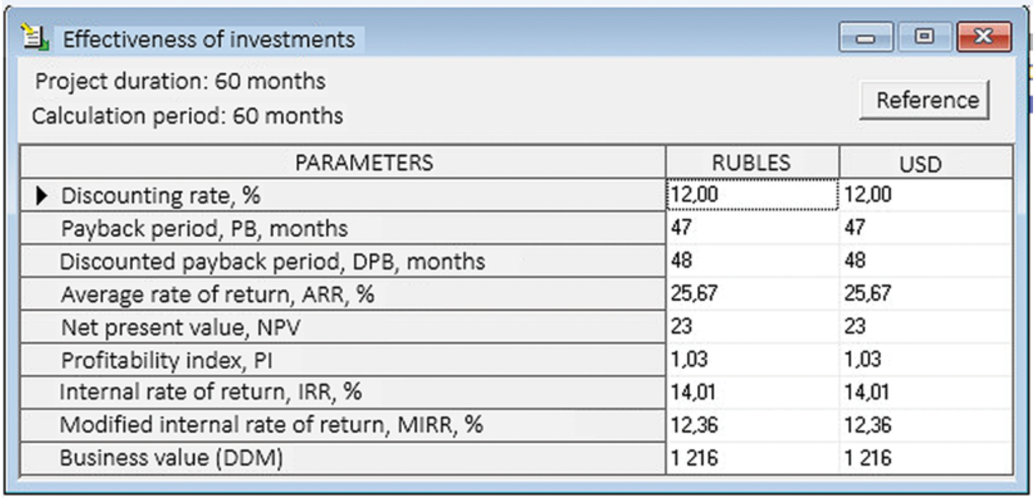


Fig. 3. Optimized analysis of an integrated urban development schedule in the case of continuous advancement of all types of work



№	Stage name	Duration	Start date	Finish date
1	Project	1 453	04.01.2021	26.12.2024
2	Housing estate	1 454	04.01.2021	27.12.2024
3	House 1	548	04.01.2021	05.07.2022
4	Preparation1	35	04.01.2021	07.02.2021
5	Found. 1	91	08.02.2021	09.05.2021
6	Structure 1	339	10.05.2021	13.04.2022
7	Finishing 1	84	14.04.2022	06.07.2022
8	House 2	522	22.12.2021	27.05.2023
9	Preparation2	28	22.12.2021	18.01.2022
10	Found. 2	84	19.01.2022	12.04.2022
11	Structure 2	305	13.04.2022	11.02.2023
12	Finishing 2	105	13.02.2023	28.05.2023
13	House 3	504	17.10.2022	03.03.2024
14	Preparation3	42	17.10.2022	27.11.2022
15	Found. 3	77	28.11.2022	12.02.2023
16	Structure 3	288	13.02.2023	27.11.2023
17	Finishing 3	98	28.11.2023	04.03.2024
18	House 4	516	01.08.2023	28.12.2024
19	Preparation4	35	01.08.2023	04.09.2023
20	Found. 4	84	05.09.2023	27.11.2023
21	Structure 4	305	28.11.2023	27.09.2024
22	Finishing 4	91	30.09.2024	29.12.2024
23	Dormitory cluster	1 454	04.01.2021	27.12.2024
24	Dorm. 1	801	04.01.2021	15.03.2023
25	Prep. 1	35	04.01.2021	07.02.2021
26	Found. 1	105	08.02.2021	23.05.2021
27	Stru 1	608	24.05.2021	21.01.2023
28	Finish.1	56	20.01.2023	16.03.2023
29	Dorm. 2	821	30.09.2022	28.12.2024
30	Prep. 2	28	30.09.2022	27.10.2022
31	Found. 2	84	28.10.2022	19.01.2023
32	Stru. 2	644	20.01.2023	24.10.2024
33	Finish.2	63	28.10.2024	29.12.2024
34	Educational buildings	726	03.01.2022	29.12.2023
35	School preparation	35	03.01.2022	06.02.2022
36	School	284	07.02.2022	17.11.2022
37	Kindergarten preparation	28	25.10.2022	21.11.2022
38	Kindergarten	228	22.11.2022	07.07.2023
39	Art centre preparation	21	15.06.2023	05.07.2023
40	Art centre	178	06.07.2023	30.12.2023

Fig. 4. Integrated urban development scheduling in Project Expert


Effectiveness of investments

Project duration: 60 months

Calculation period: 60 months

Reference

PARAMETERS	RUBLES	USD
Discounting rate, %	12,00	12,00
Payback period, PB, months	47	47
Discounted payback period, DPB, months	48	48
Average rate of return, ARR, %	25,67	25,67
Net present value, NPV	23	23
Profitability index, PI	1,03	1,03
Internal rate of return, IRR, %	14,01	14,01
Modified internal rate of return, MIRR, %	12,36	12,36
Business value (DDM)	1 216	1 216

Fig. 5. Estimated project efficiency parameters calculated in Project Expert

given sequence of building various projects included in the scheme. Obviously, calculating a schedule for a different sequence will yield different results, but it can be carried out using a similar algorithm. It follows from the practice of planning urban developments that the total number of projects included therein will be of the same order as in the example presented[7]. Therefore, it can be shown that the formation of work schedules for all possible construction sequences is quite a solvable task, even when using the method of the full sorting of options.

In the example presented, the maximum volume of full-scale sorting of construction schedules will be determined as a product of the number of options for each of the selected streams (flows). The first flow has 4 facilities, so this translates into 24 permutation options; for the second flow we have 2 permutations, and for the third flow — 6 permutations. As a result, we have 288 optional project development sequences, and this number defines the limit of this problem's computational complexity. In practical planning we actually have all sorts of time and other constraints, significantly reducing the scope of the problem of finding the optimal priority order [17]. This fact points to the effectiveness of the full search/sorting algorithm.

CONCLUSION

The methodology of generation, analysis and optimization of the work schedule under integrated development of a residential area has been devised, its step-by-step execution coming down to the following procedures.

The organizational-technological plan of development is worked out, including the estimation or calculation of work durations, establishing the links between them and restrictions on the event occurrence times, these data then being entered into the Microsoft Project software.

Given the choice of the workflow method of construction organization, Microsoft Project searches for an acceptable basic solution relying on description of the organizational and technological plan via a system of linear equations.

Optimization calculation aimed at minimization of specific investment costs is carried out for the obtained solution in Microsoft Project.

The cost effectiveness of the optimized scheduling under integrated urban development is assessed in the Project Expert programme.

The admissibility of implementing the optimized schedule is checked by visualizing its development using a Revit-like BIM modelling programme.

Due to a relatively small number of options determining the possible development priorities, all the preceding procedures are carried out for each of them, the best option being selected on the basis of cost-effectiveness criteria.

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Формирование оптимизированного расписания строительства при комплексном освоении территории

Комплексное освоение селитебной территории обеспечивает благоприятное и комфортное проживание и использование городского пространства. Одним из элементов, необходимым для реализации комплексной застройки, является создание обобщенного расписания работ. Этой цели служит представленная в статье методика формирования, расчета и оптимизации расписания работ при комплексной застройке селитебной территории. Пошаговое выполнение разработанной методики сводится к выполнению следующих процедур.

Разрабатывается организационно-технологическая схема застройки, включающая расчет (оценку) продолжительности работ, установление связей между ними и ограничений на сроки свершения событий. Далее с учетом введенных данных и выбора метода поточной организации работ, осуществляемых в программе Microsoft Project, проводится поиск допустимого базисного решения, которое основано на решении системы линейных уравнений, описывающих организационно-технологическую схему строительства. После получения допустимого базисного решения в программе Microsoft Project проводится оптимизационный расчет, направленный на минимизацию удельных инвестиционных затрат. Экономическая эффективность оптимизированного расписания, ориентированного на комплексное освоение территории, оценивается в программе Project Expert. Далее проверяется допустимость реализации оптимизированного расписания работ посредством визуализации застройки в программе BIM-моделирования типа Revit. Сравнительно небольшое число вариантов, определяющих возможные очередности освоения объектов, позволяет на основе полного перебора вариантов оценить каждый из них по выбранным критериям экономической эффективности и выбрать оптимальный вариант.

Ключевые слова: *календарное планирование строительства, организационно-технологическая схема строительства, временные ограничения календарных графиков, допустимое расписание работ, оптимизированное расписание работ, программы управления проектами*

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