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Scheduling workflows for scattered objects

Формирование календарных планов поточного строительства рассредоточенных объектов

Yu.B. Kalugin*,
R.S. Romanov,
Military Institute of rail transport troops and military communications, St. Petersburg, Russia

д-р техн. наук, профессор Ю.Б. Калугин*,
адъюнкт Р.С. Романов,
Военный институт железнодорожных войск и военных сообщений, Санкт-Петербург, Россия

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Abstract. As a rule, the task of optimal scheduling, including reducing the total duration of the project occurs when developing and adjusting schedules. The essence of flow shop scheduling problem on the scattered objects with the use methods and models calendar planning was presented. The branch and boundary method were proposed as an exact method for determining the optimal permutation including the scheme of branching and rules for determining the lower boundaries. Heuristic algorithms for determining the optimal sequence of work for scattered objects was substantiated. The general applicability of the algorithms was demonstrated with calculations including 30 variants from distinct flows. The performed studies show the possibility of reducing the planned time by about 15 %. The suggested methodology can be recommended for use by construction project managers.

Аннотация. Как правило, задача оптимального планирования, и в частности задача сокращения общей продолжительности проекта возникает при разработке и корректировке календарных графиков. Представлена сущность решения задачи выбора оптимальной последовательности поточного строительства рассредоточенных объектов. В качестве точного метода определения оптимальной перестановки предложен метод ветвей и границ, включающий схему ветвления и правила определения нижних границ. Обоснованы эвристические алгоритмы определения оптимальной последовательности работ для рассредоточенных объектов. Общая применимость алгоритмов продемонстрирована расчетами, включающими 30 вариантов различных потоков. Проведенные исследования показывают возможность сокращения запланированного времени примерно на 15 %. Предложенные методы могут быть рекомендованы для использования руководителями строительных проектов.

1. Introduction

A construction project is a complex process, which includes a large number of different tasks performed by different crews and displayed by calendar charts. When forming the schedules in case of exceeding the planned duration over deadlines requires a reduction in the total duration. In addition, with the operational management of the progress of work, it is also necessary to periodically adjust the schedule by dates [1–7].

One of the methods of reducing the planned duration of construction is the combinatorial optimization, and in particular, the formation of schedules of the minimum duration by finding the optimal sequence of work [8–11].

Numerous studies have been devoted to the problem of planning the flow organization of work (flow shop scheduling problem) [12–19]. A number of methods and algorithms (both exact and approximate) have been developed for the formation of minimum duration schedules.

The exact methods include, first of all, the method of directed search (branch and boundary method), which allows establish the optimal sequence in exponential time.

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Widespread in practice are approximation algorithms [19–25], allowing to obtain a solution close to optimal in polynomial time.

The studies [8, 9, 11, 26, 27] have shown the effectiveness of using different methods of forming the optimal sequence for the flow organization of work on nearby objects.

However, the real conditions involve the operation of construction flows and in remote areas, the relocation time between which is commensurate with the duration of the work of each specialized crew. Under these conditions, combinatorial optimization problems arise, which reduce to finding the optimal sequence of work at the scattered objects.

The purpose of this paper is to substantiate methods and algorithms for determining the optimal sequencing of objects in the stream, providing a minimum duration for scattered objects.

Objectives of the study are:

1. The theoretical foundation of the method of directed enumeration (branch and bound) for finding the optimal sequence of flow shop of scattered objects;

2. Justification of heuristic approximate algorithms;

3. The calculations of variants of formation of flows of different methods and algorithms;

4. Comparison and selection of the most effective methods and algorithms for searching the optimal sequence.

2. Methods

The problem of finding the optimal (minimum total duration) sequence of objects included in the schedule, taking into account the time of moving crews from one object to another, can be formulated as follows.

On the scattered objects $1, 2, \dots j \dots n$ in accordance with a given technology specialized crews perform various types of work $1, 2, \dots i \dots m$.

The duration of the work i on the object $j - (t_{ij})$ is determined by known methods.

The works are organized by individual-flow method (critical path method) [8].

Each crew can simultaneously perform work only on one object.

Combining the work of crews on one object is not allowed.

The possible start time of i on object j (earliest start time – T_{ij}^{EST}) is defined by the following expression:

$$T_{ij}^{EST} = \max[(T_{(i-1),j}^{EFT}); (T_{i,(j-1)}^{EFT} + t_{(j-1),j}^{red})], \tag{1}$$

$T_{(i-1),j}^{EFT}$ is earliest finish time activity $(i-1)$ on the j-th object;

$T_{i,(j-1)}^{EFT}$ is earliest finish time activity i on the $(j-1)$-th object;

$t_{(j-1),j}^{red}$ is the time for the redeployment of the team from the object $(j-1)$ to an object j.

It is necessary to determine the optimal sequence of work P_{opt}, taking into account the time of relocation of crews from object to object, in which the total duration of the individual flow T_o will be minimal:

$$P_{opt} \subset Q, \tag{2}$$

Q is the set of all possible alternatives.

Along with this

$$Q: \begin{pmatrix} \forall i = 1 \div m \\ \forall j = 1 \div n \\ \forall P_{opt} = T_o \to \min \end{pmatrix}. \tag{3}$$

This type of problems can be solved by various optimization methods, the main of which is the branch and bound method [8, 14, 16, 28, 29]. Fundamental in this respect has been the work of Professor Afanasiev [8].

2.1. Using the branch and boundary method to find the optimal sequence for including scattered objects in a flow

The most important step of the branch and boundary method is to determine the prospects of further branching (in this case, the lower boundary).

The value of the lower boundary will be equivalent to the limit possible minimum duration of work (LPMD) [8].

The definition of the lower bounds for the considered sequence P is realized as follows:

1) Is determined for the sequence lower limit of the flow duration when passing the critical path through each type of work

$$g^P = \max g_i^P, (i = 1, ..., m). \tag{4}$$

2) For a sequence P, the lower limit of the flow duration when passing a critical path through each object is determined

$$k^P = \max k_j^P, (j = 1, ..., n). \tag{5}$$

3) As the lower bound (estimates of the prospects of the sequence P for further branching), the maximum of the obtained values is taken $g^P; k^P$ (taking into account the time for the redeployment of commands)

$$\eta_{S_j}^P = \max(g_i^P, k_j^P) + \sum t^{red}. \tag{6}$$

4) To further branching at the level S_j of the sequence is taken with a minimum value $\eta_{S_j}^P$.

The branching scheme and the order of implementation of the first stage of the algorithm (development of the tree to the level S_n) are shown in figures 1 and 2.

At the second stage of the algorithm (Figure 3) a comparison of estimates of the development prospects of the corresponding subsets with the flow duration calculated at the first stage is made T.

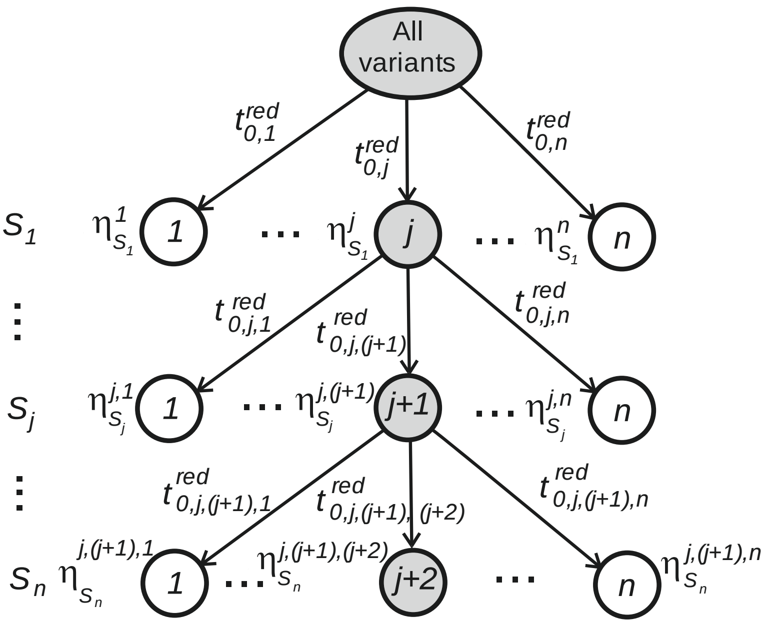

Figure 1. Branching scheme.

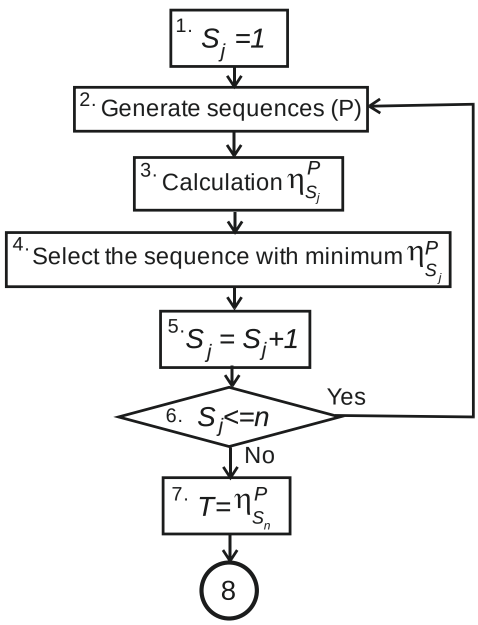

Figure 2. Implementation of the first stage of the algorithm.

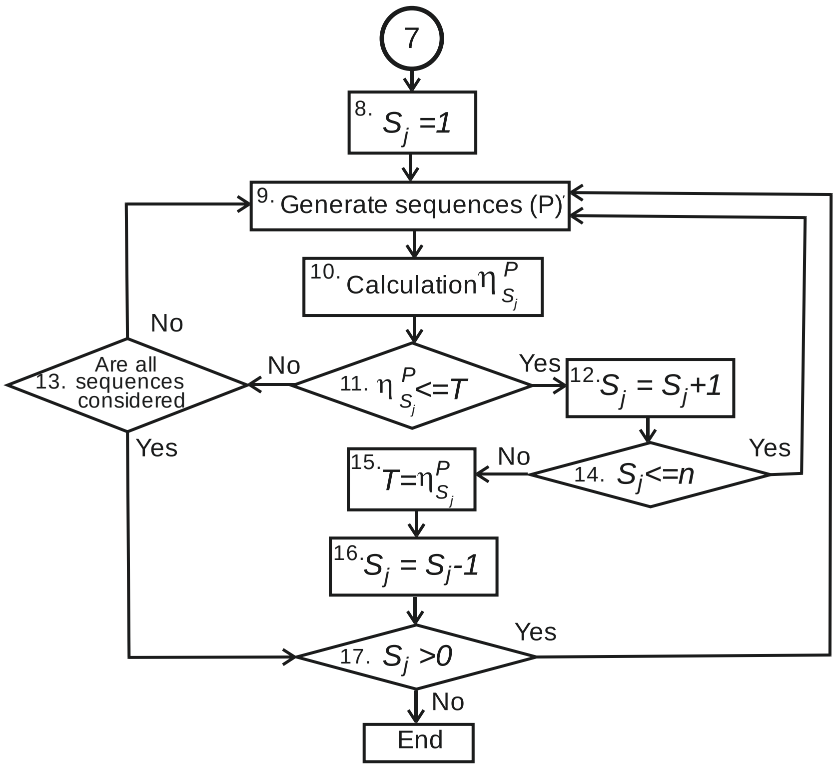

Figure 3. Implementation of the second stage of the algorithm.

Of particular importance is the calculation of the lower limits of the flow duration when passing the critical path through each type of work performed and each object [8].

The lower bound of the flow duration when passing the critical path through the i-th type of activity is determined by the mathematical expression (7):

$$g_i = T_{ir}^{EFT} + \sum_{j \in N \setminus \tilde{N}} t_{ij} + \min \sum_{j \in N \setminus \tilde{N}} t_{(i+1),j}, \quad (7)$$

T_{ir}^{EFT} is earliest finish time activity i on the r-th object; (earliest finish time activity i on objects already included in the subset $\tilde{N}, (r = |\tilde{N}|)$;

$\sum_{j \in N \setminus \tilde{N}} t_{ij}$ is the duration activity of the i crew on the remaining objects;

$\min \sum_{j \in N \setminus \tilde{N}} t_{(i+1),j}$ is minimum from the sums activities of the remaining crews (starting from $(i+1)$) on one of the remaining (not included in the subset $\tilde{N}$) object;

N is set of all objects.

The lower bound of the flow duration when passing the critical path through each object is defined as follows.

1. Calculation T_{1r}^{EFT} is earliest finish time activity 1 on the last $(r-th)$ fixed object (from already included in the subset $\tilde{N}, (r = |\tilde{N}|)$;

2. From a subset of loose objects one (j) is selected and taken as the considered object (the object through which the critical path can pass).

3. Loose objects are sorted as follows.

If the first type of activity on the $j*$-th object is longer than the duration of the last type of activity $(i_{1j^*} > i_{mj^*})$, then this object falls below the considered (unfixed) and is included in the subset S (subsequent),

Otherwise $(i_{1j^*} < i_{mj^*})$, the object rises and is placed above the considered one, that is, it is included in the subset P (previous).

4. The total duration of the first crew on the objects preceding the considered $(j-th)$ object, and the last crew – on the objects subsequent to the considered are determined.

5. From the condition of continuity of work of crews on the considered object (the object is not idle) the minimum possible duration of performance of all types of works is defined.

As a result, the lower bound of the duration of the flow during the passage of the critical path through the $j-th$ object is determined using the expression (8):

$$k_j = T_{1r}^{EFT} + \sum_{i=1}^{m} t_{ij} + \min\left(\sum_{p\in P;\, p\neq j} t_{1p};\ \sum_{s\in S;\, s\neq j} t_{ms} \right); \tag{8}$$

T_{1r}^{EFT} is earliest finish time activity 1 on the last $(r-m)$ fixed object (from already included in the subset $\tilde{N}$;

$\sum_{i=1}^{m} t_{ij}$ is the minimum possible duration of all types of activity on the $(j-th)$ object;

$\sum_{p\in P;\, p\neq j} t_{1p}$ is the total duration of the first crew on the objects preceding the considered $(j-th)$ object;

$\sum_{s\in S;\, s\neq j} t_{ms}$ is total duration of the last crew on the objects subsequent to the considered $(j-th)$ object.

The implementation of the presented approach using dependencies (4-8) and the corresponding branching scheme has shown its effectiveness for determining the optimal sequence of work on scattered objects.

At the same time, the development and improvement of heuristic methods of combinatorial optimization is of some interest.

2.2. Heuristic search algorithms for rational sequences of activities on scattered objects

For solve the problem of this type, heuristic algorithms are implemented, allowing for polynomial time to search for a rational sequence of work at scattered objects, taking into account the duration for the relocation of crews. The basis of these algorithms are methods and models of combinatorial optimization and integer programming [30, 31].

In this case, all objects are represented by a complete undirected graph consisting of n vertices connected by arcs, where $1, 2, \ldots j \ldots n$ is the numbers of objects, and the arcs connecting the vertices show different sequences of work (routes of crews) (Figure 4).

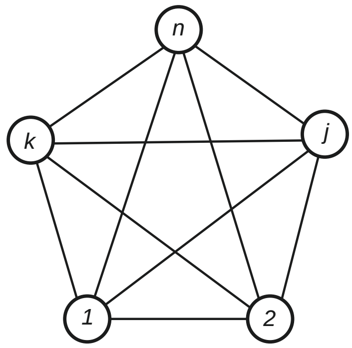

Figure 4. Complete undirected graph.

Algorithms with all their varieties are as follows.

2.3. An approach based on finding the shortest Hamiltonian contour

Step 1. For each pair of objects (j and k) is determined by the duration of the work in the forward and reverse direction (T_{jk} and T_{kj}).

Step 2. The ratio coefficient between the sum of pair durations of works and the true duration of the schedule is determined.

For a regular flow, it will be:

$$k_r = \frac{(m+1)(n-1)}{(m+n-1)}. \tag{9}$$

Calculations performed for 30 examples of non-rhythmic flow with random integer work durations from 1 to 5 with m = 4 and n = 5 showed that k_r it changed in the range from 1.87 to 2.85. The average value was 2.36. For a regular flow with m = 4 and n = 5, k_r = 2.5, which allows using expression (9) for the calculation k_r.

Step 3. For each pair of objects (j and k), the corrected duration of the work in the forward and reverse direction is determined – T^*_{jk} and T^*_{kj}:

$$T^*_{jk} = \frac{T_{jk}}{k_r}, \tag{10}$$

$$T^*_{kj} = \frac{T_{kj}}{k_r}, \tag{11}$$

Step 4. For each pair of objects (j and k) is determined by the corrected duration of the work in the forward and reverse direction, taking into account the duration of the redeployment from object to object (t^{red}_{jk}):

$$T^{**}_{jk} = T^*_{jk} + t^{red}_{jk}, \tag{12}$$

$$T^{**}_{kj} = T^*_{kj} + t^{red}_{kj}. \tag{13}$$

Step 5. On a graph with the lengths of arcs of equal T^{**}_{jk} and T^{**}_{kj} known methods are used to determine the shortest Hamiltonian circuit, which will determine the required sequence.

2.4. The approach based on the calculation of the potentials of the vertices of the graph

Steps 1–4 are similar to the steps above.

Step 5. For each pair of objects (j and k) the difference between the corrected durations of work T_{jk}^{**} and T_{kj}^{**} is determined. This distinction and constitute the so-called potential of vertex j on the edge jk and the potential of vertex k on the edge kj.

Step 6. After determining all vertex potentials on each edge of the graph, the total potentials of each vertex are calculated.

Step 7. The desired sequence of inclusion of objects in the flow is determined by increasing the potential of the vertices.

The combined approach is to determine the initial and final flow objects in the amount of 15–20 % of their total number (reference points) by the method of potentials.

For the remaining objects, the rational sequence is determined based on the shortest Hamiltonian contour.

3. Results and Discussion

The described methods and algorithms have been implemented for 30 different tasks of non-rhythmic flow with integer random duration of work from 1 to 5 and the duration of redeployment from 0.5 to 2.5 in increments of 0.25 (m = 4; n = 5).

The results of optimization using the above methods and approaches are presented in Table 1. Here 1 is the branch and bound method; 2 is the approach based on finding the shortest Hamiltonian contour; 3 is the approach based on calculating the vertex potentials of the graph; 4 is the combined approach.

Table 1. Optimization results by different methods.

# task's	Average time for 120 variations	Method	P_{opt}	T_{opt}	$\Delta T(\%)$	Undetermined variants (%)	Calculation time (h)
1	32.56	1	45213	25.75	21	0	6.0
		2	45213	25.75	21	0	2.0
		3	25413	28.50	12	7	1.0
		4	21543	28.0	14	3	1.5
2	36.40	1	21345	29.25	20	0	6.0
		2	31254	30.75	16	2	2.0
		3	23145 32145	33.75 33.25	7 9	17 11	1.0 1.0
		4	21345	29.25	20	0	1.5
3	37.50	1	43521	31.0	17	0	6.0
		2	34521	33.0	12	6	2.0
		3	54321	31.25	17	1	1.0
		4	54321	31.25	17	1	1.5
4	36.23	1	31254	30.75	15	0	6.0
		2	52134	31.50	13	2	2.0
		3	23154 23514	36.25 40.50	0 -12	48 96	1.0 1.0
		4	21354	34.50	5	18	1.5
5	36.06	1	43125	31.50	13	0	6.0
		2	21345	33.25	8	6	2.0
		3	32451 34251	35.75 32.25	1 10	45 2	1.0 1.0
		4	34521	33.00	8	5	1.5
6	35.50	1	34521	30.00	15	0	6.0
		2	54312	35.25	1	39	2.0
		3	42531	31.75	11	7	1.0
		4	43521	31.00	13	4	1.5
7	38.18	1	54312	32.25	16	0	6.0
		2	31254	35.75	6	11	2.0
		3	54321 54312	33.25 32.25	13 16	1 0	1.0 1.0
		4	54312	32.25	16	0	1.5
8	34.76	1	52134	29.50	15	0	6.0

# task's	Average time for 120 variations	Method	P_{opt}	T_{opt}	ΔT(%)	Undetermined variants (%)	Calculation time (h)
		2	52134	29.50	15	0	2.0
		3	15342	34.00	2	36	1.0
			15324	34.75	0	49	1.0
		4	12534	31.00	11	3	1.5
9	35.33	1	52134	29.50	17	0	6.0
		2	52134	29.50	17	0	2.0
		3	53241	35.25	0.2	44	1.0
		4	54321	31.25	12	2	1.5
10	33.73	1	52134	27.50	18	0	6.0
		2	31254	32.75	3	31	2.0
			45213	33.75	0	50	2.0
		3	51342	31.50	7	11	1.0
		4	54312	29.25	13	1	1.5
11	32.62	1	54312	27.25	16	0	6.0
		2	52134	27.50	16	1	2.0
		3	53241	31.25	4	26	1.0
		4	54321	28.25	13	2	1.5
12	34.00	1	21345	27.25	20	0	6.0
		2	31254	27.75	18	1	2.0
		3	23145	29.75	13	8	1.0
		4	21345	27.25	20	0	1.5
13	32.84	1	52134	28.50	13	0	6.0
		2	23451	31.50	4	21	2.0
		3	23154	31.25	5	18	1.0
		4	25134	28.75	12	1	1.5
14	34.05	1	52134	28.50	16	0	6.0
		2	45213	30.75	7	10	2.0
		3	51324	32.25	5	17	1.0
			51342	31.50	7	10	1.0
		4	52134	28.50	16	0	1.5
15	31.50	1	43125	26.50	16	0	6.0
		2	25431	29.50	6	9	2.0
		3	41235	30.25	4	10	1.0
			41325	29.00	8	5	1.0
		4	43125	26.50	16	0	1.5
16	33.48	1	45213	27.75	17	0	6.0
		2	12543	31.00	7	12	2.0
		3	51423	32.50	3	26	1.0
			54123	29.25	13	2	1.0
		4	54213	29.50	12	4	1.5
17	32.43	1	21345	26.25	19	0	6.0
		2	13452	29.50	9	11	2.0
		3	21345	26.25	19	0	1.0
			21354	27.50	15	2	1.0
		4	21345	26.25	19	0	1.5
18	29.49	1	12543	25.00	15	0	6.0
		2	12543	25.00	15	0	2.0
		3	12543	25.00	15	0	1.0
		4	12543	25.00	15	0	1.5
19	31.85	1	52134	25.50	20	0	6.0
		2	25134	27.75	13	2	2.0
		3	35214	29.00	9	7	1.0
		4	31524	26.75	16	1	1.5
20	34.21	1	43521	28.00	18	0	6.0
		2	54321	29.25	14	4	2.0
		3	45321	29.50	14	6	1.0
		4	45231	28.25	17	1	1.5
21	38.54	1	52134	33.50	13	0	6.0
		2	34521	36.00	7	7	2.0
		3	35241	40.00	-4	77	1.0
			53241	39.25	-2	64	1.0
		4	34521	36.00	7	7	1.5
22	30.46	1	45213	26.75	12	0	6.0
		2	25431	27.50	10	2	2.0
		3	42315	29.25	4	22	1.0
		4	43125	27.50	10	2	1.5
23	33.98	1	52134	25.50	25	0	6.0
		2	52134	25.50	25	0	2.0
		3	51234	28.50	16	4	1.0
		4	52134	25.50	25	0	1.5

# task's	Average time for 120 variations	Method	P_{opt}	T_{opt}	$\Delta T(\%)$	Undetermined variants (%)	Calculation time (h)
24	34.07	1	43125	28.50	16	0	6.0
		2	43125	28.50	16	0	2.0
		3	42135	30.50	10	2	1.0
		4	43125	28.50	16	0	1.5
25	34.30	1	12543	30.00	13	0	6.0
		2	12543	30.00	13	0	2.0
		3	12534	31.00	10	6	1.0
			15234	31.75	7	10	1.0
		4	13254	31.25	9	8	1.5
26	30.19	1	13452	25.50	16	0	6.0
		2	31254	27.75	8	7	2.0
		3	15342	29.00	4	26	1.0
			15432	28.50	6	17	1.0
		4	13452	25.50	16	0	1.5
27	35.38	1	43125	30.50	14	0	6.0
		2	34512	35.00	1	39	2.0
		3	34521	32.00	10	4	1.0
		4	34521	32.00	10	4	1.5
28	33.85	1	45213	27.75	18	0	6.0
		2	43125	29.50	13	1	2.0
		3	43521	31.00	8	9	1.0
		4	45231	30.25	11	4	1.5
29	32.31	1	25431	27.5	15	0	6.0
			52134	27.5	15	0	
		2	23451	28.50	12	5	2.0
		3	24531	30.50	6	23	1.0
		4	23451	28.50	12	5	1.5
30	31.65	1	52134	24.50	23	0	6.0
		2	23451	29.50	7	18	2.0
		3	25143	26.00	18	2	1.0
		4	21543	26.00	18	2	1.5

Based on the calculations, Table 2 was compiled.

Table 2. Parameters of compared methods.

Average parameters for 30 tasks	Optimization method			
	Branch and bound (1)	Hamiltonian circuit (2)	Potential method (3)	Combined approach (4)
$\Delta T(\%)$	17	11	8	14
Undetermined variants (%)	0	10	19	3
Calculation time (h)	6.0	2.0	1.0	1.5

The analysis of the parameters of the compared methods and approaches shows the following.

The directed search method (branch and bound method) established optimal sequences in all cases. The average value of schedule compression was 17 %.

The approach based on the combination of the method of potentials and the shortest Hamiltonian circuit allowed to achieve the average value of schedule compression – 14 %.

At the same time, undetermined sequences of shorter duration are only 3 %.

4. Conclusions

1. When forming the schedules in case of exceeding the planned duration over deadlines requires a reduction in the total duration. One of the methods of reducing the duration of the construction flow is to find the optimal sequence of work (flow shop scheduling problem).

2. This problem is solved for scattered objects. Methods and algorithms for determining the optimal sequence of work for dispersed objects are presented.

3. The branch and boundary method is proposed as an exact method for determining the optimal permutation. The scheme of branching and rules for determining the lower boundaries of the minimum are presented.

4. Heuristic algorithms for determining the optimal sequence of work for scattered objects are substantiated.

5. Calculations of 30 variants of flow formation by different methods and algorithms are presented. The performed calculations allow us to consider the method of branches and boundaries as a priority exact method of finding the optimal sequence in the formation of the schedule of construction of scattered objects. As an approximate method, the priority is a heuristic algorithm based on a combination of the potential method and the search for the shortest Hamiltonian circuit.

6. The performed studies show the possibility of reducing the planned time by 14–17 %, which shows the effectiveness of the proposed methods to reduce the duration of construction of scattered objects.

The suggested methods can be recommended for use by construction project managers to reduce project completion time.

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Yuri Kalugin,*
+7(905)2162825; yuri_kalugin@inbox.ru

Roman Romanov,
+79675533507; sluzba2013@mail.ru

Юрий Борисович Калугин,*
+7(905)2162825; эл. почта: yuri_kalugin@inbox.ru

Роман Станиславович Романов,
+79675533507; эл. почта: sluzba2013@mail.ru