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A method of indefinite resource factors and systemic correction of time conflicts in construction schedules

When construction work schedules are developed, numerous time parameters are taken into account. Even full account of these parameters cannot guarantee a feasible work schedule. The identification of time conflicts, arising in this case, and their solutions, is a rather labour-intensive process even in the context of computer-aided work scheduling performed using project management software. The analysis and elimination of time conflicts, presented in the article, are based on the improvement of the method of uncertain resource factors. The proposed methodology is focused on feasible construction work scheduling in the case when restrictions, associated with time characteristics, do not allow to set up a construction work timeline. The main feature of the improved method of indefinite resource factors is the simplex algorithm used to find a basic solution in the case of a negative slack, represented in the form of equations, which in the aggregate represent an invalid basic solution. Negative values of base variables, obtained in this case, allow to design integrated regulatory impacts, that allow for the systemic generation of feasible construction schedules that take account of time constraints having an adverse effect.

Keywords: *scheduling and construction management, schedule conflicts, feasible work schedule, project management software*

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INTRODUCTION

When construction work schedules are developed, numerous time parameters are taken into account to set up the required work performance timelines. Project management software is a recognized construction scheduling tool [1, 2]. The methodology of their operation is based on the extensive use of network scheduling methods and work schedule optimization. However, not only network scheduling techniques, but also time coupling methods of construction are employed to make up construction schedules [3, 4]. In the international practice, time coupling methods can be termed differently [5, 6]. In any case, work scheduling based on different principles, can be optimized by the algorithms relying on completely different concepts [7–9]. In the future, construction work schedules will be monitored and controlled in the process of implementation to ensure the pre-set construction characteristics [10]. As a result, construction work schedules are adjusted both in the course of their development and implementation. Hence, the adjustment of construction schedules maintains relevance from the beginning of construction scheduling to its final completion.

The main parameters of a construction schedule include its time characteristics, which are traditionally called “the work schedule”. Notably, events, included in the work schedule, may be delayed due to various circumstances. The reasons for the project delay may be late issuance of a construction permit, a delayed receipt of specifications for the utility connection, etc. And since the date of the facility commissioning may be unchanged, the actual time, left for the construction work, is reduced, and hence, the work schedule needs specific adjustments. A similar situation can occur in the course of construction. For example, if a regular construction process monitoring session identifies that the amount of construction work actually performed is smaller than the amount of work specified in the construction schedule, a larger amount of work should be planned for the time left before the construction completion date. As a result, a so-called time conflict may arise, and its resolution will need rescheduling.

As noted above, project management software programmes encompass scheduling, rescheduling, and monitoring tools, such as Primavera [11] and Microsoft Project (MP) [12]. In the future, we will take advantage of the MP software, since it has a supplementary function of task programming in the Visual Basic for Applications software language. Project management software, such as MP, time conflicts are resolved iteratively, and this technique involves a search through all tasks potentially affecting the conflict. In this case, each sequential iteration is accompanied by a message stating that the completion of this task is impossible at a given time due to a scheduling conflict. The following recommendations are made:

- a change in the type of restrictions;
- a removal of relationships between conflicting types of work;
- a reduction in the task performance time;
- task rescheduling within the framework of the construction work schedule.

Moreover, if a task is composite, each of the above recommendations refers to simple assignments within its structure.

The result of this approach is the step-by-step search through all works along an indefinite path that has features of the critical path method, since the generation of its time characteristics is based on the topology of previous works. If, for example, we address a construction work schedule, consisting of approximately 1,000 items of work, and only the parameters of the last one can be potentially adjusted, then software recommendations have to be analyzed hundreds of times to get the time conflict solved. This is a rather tiresome assignment for a specialist responsible for construction process scheduling. As a result, there is a need for a new approach to time conflicts, based on the replacement of step-by-step iterations with a systemic definition and analysis of corrective procedures.

METHODS

The approach we propose, focused on adjusting construction schedules, is based on the application of the method of indefinite resource factors. Therefore, to learn more about the essence of this method, it is necessary to focus on an algorithm for calculating work performance schedules, also known as the method of indefinite resource coefficients. In [13], the case of the Lakhta Center multifunctional facility ("Lakhta Centre") is addressed to describe the algorithm for assigning prescriptive completion time to unique construction projects. The algorithm is focused on the calculation of the total construction time, provided that each work item is completed within the minimum possible time $t_{\min}$ by the maximum manpower $R_{\max}$. Here, the estimated construction time will be equal to the minimum value of $T_{\min}$, and the assignment of the prescriptive completion time T_d should be more important. As a result, the remainder of T_d and $T_{\min}$ will be positive. This remainder represents a time slack that may be employed to extend the period for the performance of particular work items. The method of indefinite resource factors calculates the time, needed to perform particular items of work, according to formula (1):

$$t = t_{\min} + at_{\min}, \tag{1}$$

where a is the unknown resource factor, used to calculate the period added to the minimum time, which is identified by a linear relationship.

The functional relationship between the resource factor and the value of unknown resources R is determined by the formula:

$$a = (R_{\max}/R) - 1. \tag{2}$$

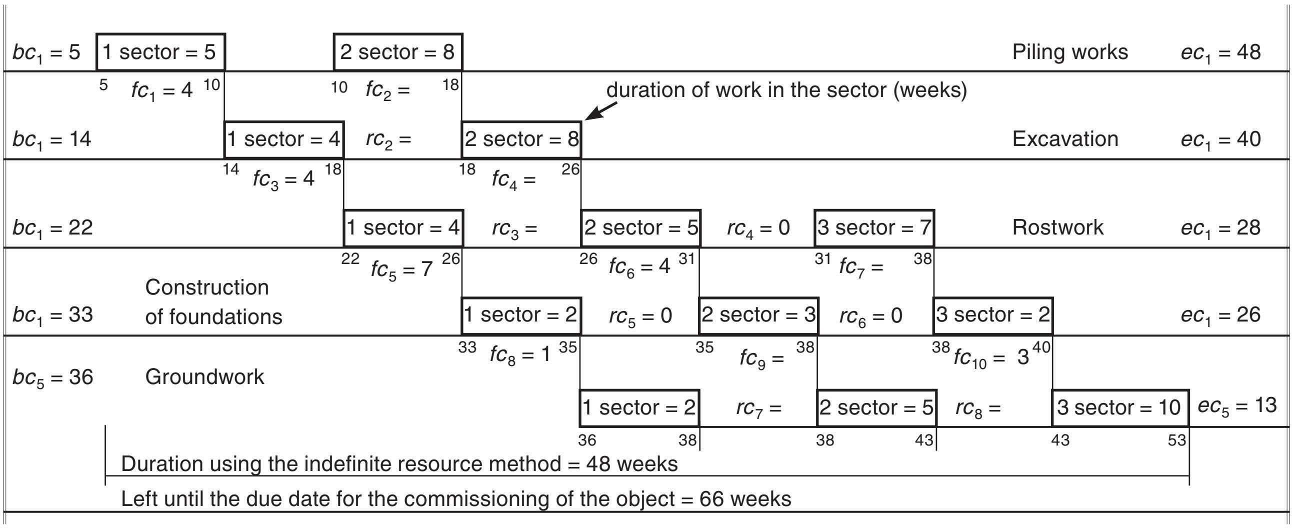
If the time, designated for the performance of each type of work, included in the construction schedule, is presented in this way, the workforce minimization will be equivalent to the maximization of the total time, designated for the performance of each item of work.

An excerpt from the Lakhta Centre construction schedule, presented in [13], is shown in Fig. 1.

The system of equations, describing the Lakhta Centre organizational and technological diagram (OTD), is provided below:

$$\begin{aligned}
&1)\ bc_1 + 13a_1 + rc_1 + ec_1 = 53;\\
&2)\ bc_2 + 12a_2 + rc_2 + ec_2 = 54;\\
&3)\ bc_3 + rc_3 + rc_4 + ec_3 = 50;\\
&4)\ bc_4 + 7a_4 + rc_5 + rc_6 + ec_4 = 59;\\
&5)\ bc_5 + 17a_5 + rc_7 + rc_8 + ec_5 = 49;\\
&6)\ bc_1 + 5a_1 + fc_1 + 12a_2 + rc_2 + ec_2 = 49;\\
&7)\ bc_1 + 13a_1 + rc_1 + fc_2 + 8a_2 + ec_2 = 45;\\
&8)\ bc_2 + 4a_2 + fc_3 + 16a_3 + rc_3 + rc_4 + ec_3 = 46;\\
&9)\ bc_2 + 12a_2 + rc_2 + fc_4 + 12a_3 + rc_4 + ec_3 = 42;\\
&10)\ bc_3 + 4a_3 + fc_5 + 12a_4 + rc_5 + rc_6 + ec_4 = 55;\\
&11)\ bc_3 + 9a_3 + rc_3 + fc_6 + 5a_4 + rc_6 + ec_4 = 52;\\
&12)\ bc_3 + 16a_3 + rc_3 + rc_4 + fc_7 + 2a_4 + ec_4 = 58;\\
&13)\ bc_4 + 2a_4 + fc_8 + 17a_5 + rc_7 + rc_8 + ec_5 = 47;\\
&14)\ bc_4 + 5a_4 + rc_5 + fc_9 + 15a_5 + rc_8 + ec_5 = 46;\\
&15)\ bc_4 + 7a_4 + rc_5 + rc_6 + fc_{10} + 10a_5 + ec_5 = 49.
\end{aligned} \tag{3}$$

The first 5 equations in system (3) are the resource equations. These equations consolidate all workers engaged in the same type of work, which is a standard practice for an organization using continuous construction methods. Other equations sequentially include all linear relationships that determine the dependence of subsequent work on prior work. Each of the fifteen equations has unknown resource coefficients that determine potential increases in the initially accepted minimum term of work performance. Resource relationships, presented in the equations, determine the duration of breaks scheduled within the framework of sequential work performance for selected sectors. Initial relationships determine the time between the project launch date and the date of introduction of pre-set resources into the construction process. Final relationships



Designation:

be — initial connections; *rc* — resource links between sectors (fronts) one type;

ec — end connections; *fc* — frontal connections between sectors of different types.

Fig. 1. An excerpt from the organizational and technological diagram for constructing Lakhta Centre [13]

determine the time frame between the completion date of work types and the final construction completion date.

The solution to the system of equations (3), focused on minimizing the labour resources, is reduced to the problem resolvable using the linear programming method, similar to the one described in [14]. As a result, the following objective function is added to the system of linear equations (3).

$$Z = 13a_1 + 12a_2 + 16a_3 + 7a_4 + 17a_5 \rightarrow \max. \tag{4}$$

In Fig. 1, the estimated project term is 48 weeks, while the corresponding prescriptive term is 66 weeks. Hence, the slack time, needed to minimize resources, is equal to 18 weeks. The feature of the task to be accomplished is the initial generation of an acceptable basic solution at the first stage to be followed by the minimization of labour resources at the second stage. Therefore, at the first stage of the optimization problem resolution, only relationships are used as the base variables, leaving resource variables as free ones to ensure the minimum estimated time for the performance of initially agreed-upon work performance terms, which should be less than the prescribed ones. If this condition is met, then the slack time for each equation is not negative; each equation has one base variable, while other variables are equal to zero and are considered as the free ones. Fig. 1 shows slack time values in the equations, which, ultimately, determine the terms of corresponding relationships. The resulting work schedule is shown below the rectangles that specify work sectors and their minimum terms.

It is rational to assume that this problem cannot be solved using the method described above, if less than 48 weeks remain before the construction project completion date. This method needs more improvements to solve problems arising in the context described in the previous paragraph.

RESULTS AND DISCUSSION

Let's consider a 45-week reduction in construction time before commissioning. If this schedule is made using the critical path method, this supplementary constraint can be taken account of. If we use the method of indefinite resource coefficients, this constraint will also be resolved automatically in the process of finding an acceptable basic solution. The improvement of this method consists in the fact that a certain order of input of base variables is added to algorithm. If all resource relationships are moved to the end of the original simplex matrix, then system (3) is solved by means of searching for the next base variable with a forced return to the beginning to obtain a solution having zero values of resource relationships. This solution is shown in Fig. 1, and the search for an acceptable basic solution is addressed in [15]. If front relationships are placed at the end of the matrix simplex, their values will be equal to zero in the solution. In addition to these solutions, an alternative critical path solution can be obtained. In this alternative solution, non-zero values of resource and front relationships will be simultaneous, and this fact is addressed in monographs [3, 4].

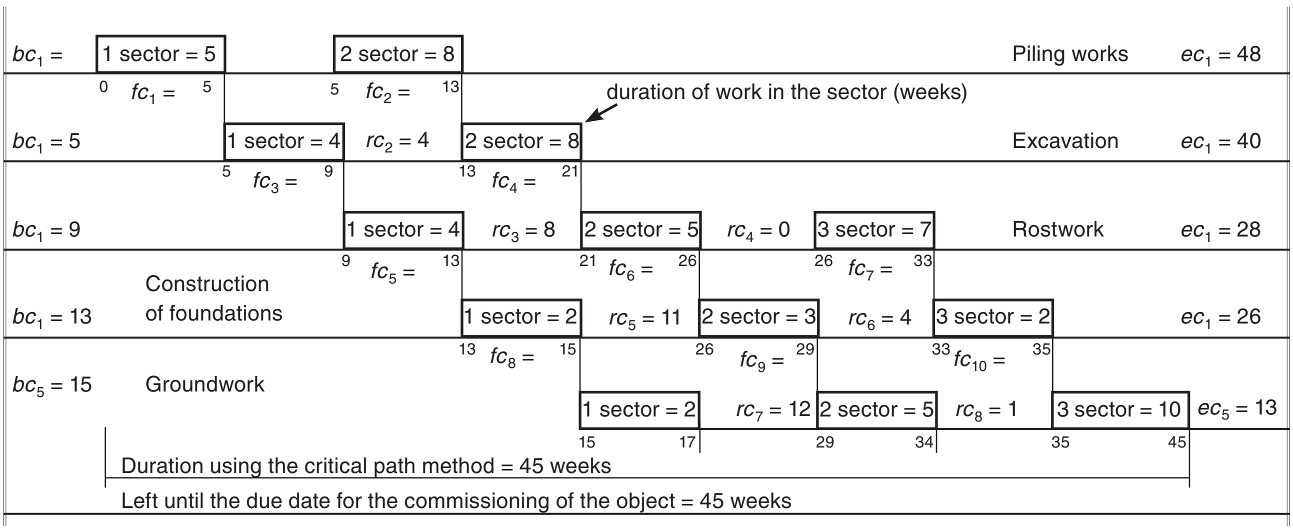
The solution to the original problem, that encompasses a reduction in the time before the facility commissioning to 45 weeks, is shown in Fig. 2.

Fig. 2 shows that the solution is in full compliance with the calculated linear organization of construction, conduced according to the method of continuous work performance, set forth in monographs [3, 4]. Here, the results obtained using the critical path and continuous work performance methods fully coincide. It has been theoretically proven that the total work performance time, calculated using the critical path method, is considered to be minimal [1]. Let's consider the construction time reduction to 42 weeks. The calculation results are shown in Fig. 3.

Fig. 3 shows that the number of base variables is equal to 14, one fewer than the number of equations. The resulting system of equations is inconsistent, and the work schedule shown in Fig. 3 is not fully defined. Let's consider an equation missing a base variable.

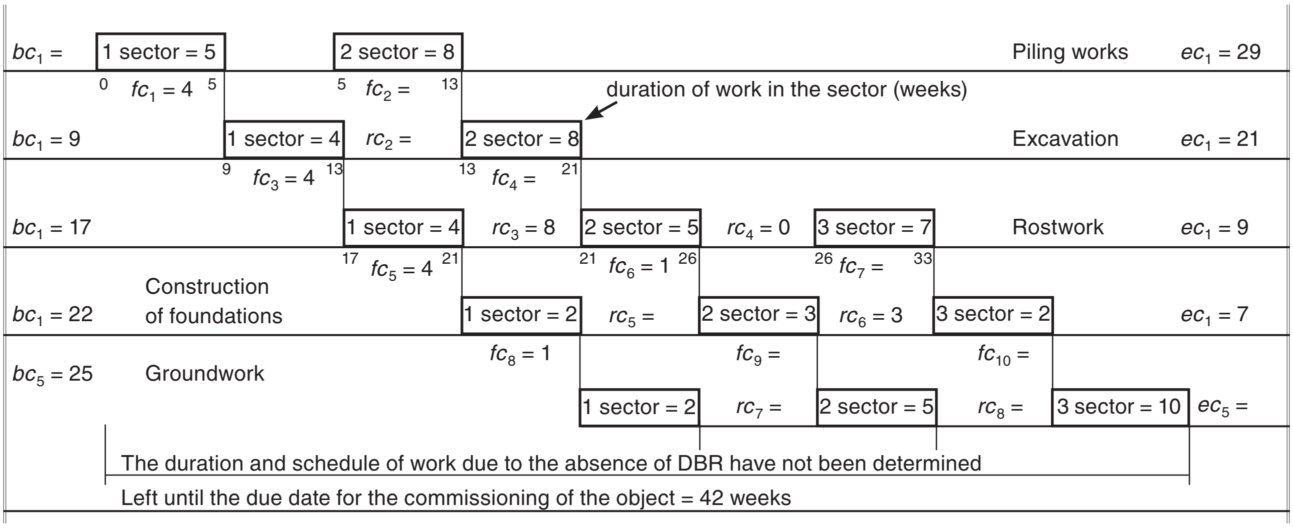
$$\begin{aligned} &-bc_1 - 13a_1 - rc_1 - fc_2 - 8a_2 - fc_4 - 12a_3 - rc_{41} - \\ &- fc_7 - 2a_4 - fc_{10} - 10a_5 - ec_5 = 3. \end{aligned} \tag{5}$$

If all signs are changed to the opposite on both sides of the equation, then the equation changed in this way can be defined as follows: it is the sum of activirelationships located along the critical path. The resulting negative time slack is the difference between



Designation:
be — initial connections; *rc* — resource links between sectors (fronts) one type;
ec — end connections; *fc* — frontal connections between sectors of different types.

Fig. 2. Lakhta Centre construction schedule featuring a shorter time period left before the facility commissioning (45 weeks)



Designation:
be — initial connections; *rc* — resource links between sectors (fronts) one type;
ec — end connections; *fc* — frontal connections between sectors of different types.

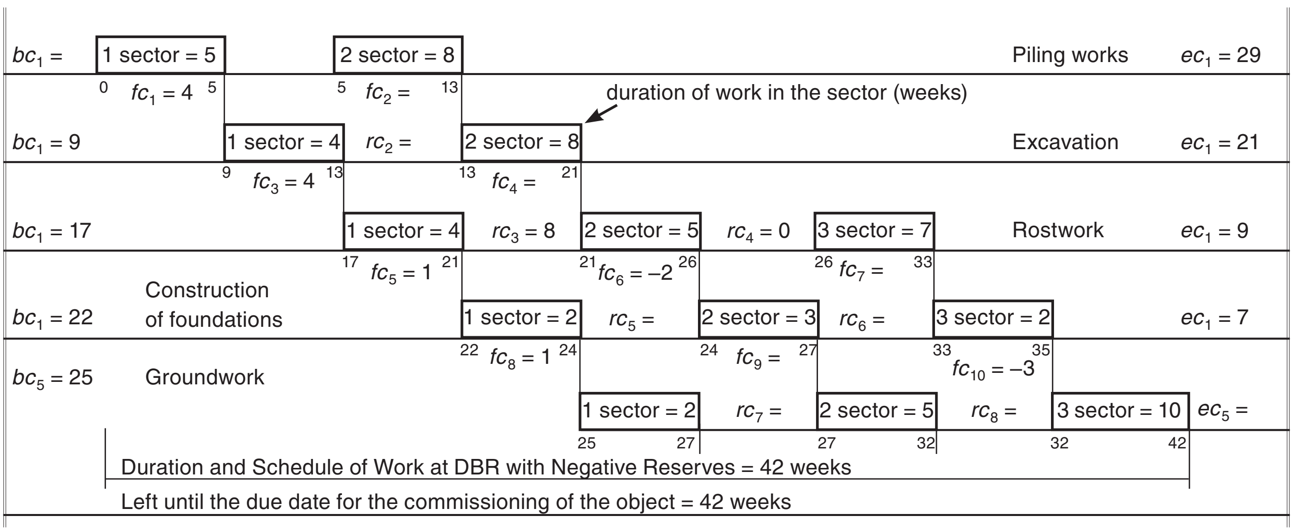
Fig. 3. Lakhta Centre construction schedule featuring a shorter time period left before the facility commissioning (42 weeks)

the prescribed work time and the sum of critical items of work. As a result, the absence of a base variable allows to propose the following procedure to improve the algorithm for finding a basic solution.

As for non-basic equations, it is necessary to change all signs to the opposite and reapply the standard algorithm to a new system of equations. A replacement for an invalid basic solution is needed because negative time slacks are used to achieve a new solution. When attaining an invalid basic solution, we obtain negative values of base variables, as shown in Fig. 4.

As a result, a solution is obtained that has two negative front relationships are present: these are the fc_6 relationship, which has a value of -2, and the fc_{10} relationship, which has a value of -3 weeks. In fact, the presence of negative relationship values indicates that the dependent event should be rescheduled to an earlier date. In the practice of construction scheduling, such a combination of work is used quite often, since not all subsequent work items must necessarily be launched upon completion of prior work items. If such an assumption is acceptable from the standpoint of construction technology, negative time lags can be entered into the construction schedule to allow for further adjustments to the work performance schedule. Table shows adjustments made in the MR software, which translate into a construction schedule which can be perfectly feasible in 42 weeks.

The result shows that the proposed time conflict resolution method can generate system information, used to make management decisions aimed at resolving time conflicts. Simultaneously, the



Designation:
be — initial connections; *rc* — resource links between sectors (fronts) one type;
ec — end connections; *fc* — frontal connections between sectors of different types.

Fig. 4. The basic solution featuring negative timeframes for the relationships

The MR spreadsheet showing the resolution to a time conflict using negative time lags

ID	Connections	Task name	Duration	Start	Finish
0		Tower	42 week	11.10.21	29.07.22
1		Piling works	13 week	11.10.21	07.01.22
2		1 sector	5 week	11.10.21	12.11.21
3	2	2 sector	9 week	15.11.21	07.01.22
4		Excavation	16 week	15.11.21	04.03.22
5	2	1 sector	4 week	15.11.21	10.12.21
6	5; 3	2 sector	8 week	10.01.22	04.03.22
7		Rostwork	24 week	13.12.21	27.06.22
8	5	1 sector	4 week	13.12.21	07.01.22
9	8; 6	2 sector	5 week	07.03.22	08.04.22
10	9	3 sector	7 week	11.04.22	27.05.22
11		Construction of foundations	22 week	10.01.22	10.06.22
12	8	1 sector	2 week	10.01.22	21.01.22
13	12; 9OH — 2 weeks	2 sector	3 week	28.03.22	15.04.22
14	13; 10	3 sector	2 week	30.05.22	10.06.22
15		Groundwork	27 week	24.01.22	29.07.22
16	12	1 sector	2 week	24.01.22	04.02.22
17	16; 13	2 sector	5 week	18.04.22	20.05.22
18	17; 14OH — 3 week	3 sector	10 week	23.05.22	29.07.22

solution shown above is not limited to merely fixing negative time lags. A regulatory action can be more universal. For example, given the analysis of an equation that does not have a base variable, it is possible to determine such reductions in the work performance time that lead to the elimination of negative slacks. This approach is consistent with maximizing resource ratios. A similar comprehensive procedure can be launched by combining extended work performance timeframes with negative time lags. Further studies will provide relevant materials.

CONCLUSION

The study, presented in the paper, aimed at improving the method of indefinite resource factors, focuses on an acceptable schedule of construction work if restrictions imposed on time characteristics prevent the calculation of a construction schedule. The main feature of the proposed method of indefinite resource coefficients is the use of a simplex algorithm for finding a basic solution in the context of equations describing negative time slacks, which together represent an invalid basic solution. Negative values of base variables, obtained in this case, allow to make a governing influence, that enables the development of a feasible schedule, with regard for adverse time limits.

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Метод неопределенных ресурсных коэффициентов и системная коррекция временных конфликтов в календарных графиках

При формировании календарных графиков строительства принимается во внимание множество временных параметров, полный учет которых не всегда приводит к нахождению допустимого расписания работ. Поиск источников, возникающих при этом временных конфликтов и вариантов их устранения является достаточно трудоемким процессом даже в условиях автоматизированного календарного планирования в программах управления проектами. Представленные в статье анализ и устранение временных коллизий базируются на совершенствовании метода неопределенных ресурсных коэффициентов. Целевая направленность предлагаемой методики направлена на формирование допустимого расписания строительных работ в случае, когда ограничения, связанные с временными характеристиками, не позволяют рассчитать календарный график строительства. Основной особенностью предлагаемого совершенствования метода неопределенных ресурсных коэффициентов является использование симплекса алгоритма поиска базисного решения при отрицательных резервах времени уравнений, которые в совокупности представляют недопустимое базисное решение. Полученные при этом отрицательные значения базисных переменных позволяют сформировать такие комплексные регулирующие воздействия, применение которых дает возможность системного формирования допустимого календарного графика с учетом неблагоприятных временных ограничений.

Ключевые слова: *календарное планирование и управление строительством, временные коллизии календарных графиков, допустимое расписание работ, программы управления проектами*

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