Research Article

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Planning repetitive construction projects considering technological constraints

<https://doi.org/10.1515/eng-2018-0058>

Received Apr 22, 2018; accepted Jun 23, 2018

Abstract: Recently, there has been a growing number of construction projects that require more than one structure to be built - repetitive construction projects. These repetitive construction projects are characterized by a high degree of complexity both in terms of organisational and technological dependencies. A method is needed that will flexibly take into account the technological constraints that occur during the carrying out of repetitive construction projects. The article presents a method of priority scheduling that takes into account technological pauses that can prove useful in the planning of repetitive construction projects. The planner (usually a construction site manager) will be able to model the technological constraints occurring on the construction site in a more flexible way. The article also presents a calculation example in which the application of the developed model has been presented. The developed model proved to be effective in scheduling repetitive construction projects, taking into account technological constraints.

Keywords: Priority Scheduling, repetitive construction projects, linear programming

1 Introduction

An increased number of realization of repetitive construction projects has been observed in recent years. These are usually housing estates, multi-family residential, as well as public and commercial buildings. The carrying out of such construction projects, during which more than one building is to be built creates many difficulties. These are primarily organisational, technological and cost-related problems [1, 2]. This article addresses the issue of schedul-

ing repetitive construction projects in a flexible way, taking into account technological constraints.

Many methods have been developed to support planners in preparing schedules repetitive construction projects. Methods such as: Line of Balance [3], Time-Location Matrix Model [4], Horizontal and Vertical Logic Scheduling for Multistory Projects [5], Time-coupled method [6] as well as other ones [7–13] are still developed. Scheduling construction works during which many structures are to be built is complicated, which is why many methods have also been developed to support decision making [14].

The article [15] presents the concepts of priority scheduling. Priority scheduling assumes that the planner can determine the validity of restrictions in a flexible way by ranking them. The constraints that are higher in the ranking are considered as priorities and their adherence must be met, further constraints are less important and are to be met under the condition that the constraints that are higher in the ranking allow that. This article extends the priority scheduling model [15] taking into account technological constraints.

The aim of the article is to develop a mathematical model that will allow technological constraints to be adhered to in a flexible way while planning the carrying out of repetitive construction projects. The aim of the article is not to eliminate technological breaks, but to set the dates of initiation and completion of works in order to meet (as much as possible) the assumed technological breaks.

2 Priority scheduling model considering technological constraints

The definition and assumptions that were adopted to develop the model have been presented below.

We are given a repetitive construction projects carried out using a flow-shop system. There are m tasks to be completed by m specialised brigades on n structures. The duration of each task is deterministic and is assumed to be

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known. Once started, tasks cannot be interrupted. The following sets of index pairs have been determined below:

$\hat{O} = \{(1, 1), (2, 1) \dots (n-1, 1), (1, 2) \dots (n-1, m)\}$ - helpful in determining flexible time couplings between the tasks performed by a brigade on different structures;

$\hat{B} = \{(1, 1), (2, 1) \dots (n, 1), (1, 2) \dots (n, m-1)\}$ - helpful in determining flexible time couplings between the tasks performed by different brigades on a single structure;

$\hat{W} = \{(1, 1), (2, 1) \dots (n, 1), (1, 2) \dots (n, m)\}$ - the set of index pairs for all tasks.

For such assumptions and defined sets a linear programming model has been developed:

Data: $t_{i,j}$

Parameters: $tc_{i,j}^{od}, tc_{i,j}^{og}, tc_{i,j}^{bd}, tc_{i,j}^{bg}, cw_{i,j}^{od}, cw_{i,j}^{og}, cw_{i,j}^{bd}, cw_{i,j}^{bg}$

Decision variables: $S_{i,j}, F_{i,j}, ck_{i,j}^{od}, ck_{i,j}^{og}, ck_{i,j}^{bd}, ck_{i,j}^{bg}$

Goal function:

$$FC = \sum_{(i,j) \in \hat{O}} (ck_{i,j}^{od} \cdot cw_{i,j}^{od} + ck_{i,j}^{og} \cdot cw_{i,j}^{og}) + \sum_{(i,j) \in \hat{B}} (ck_{i,j}^{bd} \cdot cw_{i,j}^{bd} + ck_{i,j}^{bg} \cdot cw_{i,j}^{bg}) + F_{n,m} \rightarrow \min \quad (1)$$

Constraints:

$$F_{i,j} = S_{i,j} + t_{i,j}, \text{ for } (i,j) \in \hat{W} \quad (2)$$

$$S_{i+1,j} \leq F_{i,j} + tc_{i,j}^{od} - ck_{i,j}^{od}, \text{ for } (i,j) \in \hat{O} \quad (3)$$

$$S_{i+1,j} \geq F_{i,j} + tc_{i,j}^{og} + ck_{i,j}^{og}, \text{ for } (i,j) \in \hat{O} \quad (4)$$

$$S_{i,j+1} \leq F_{i,j} + tc_{i,j}^{bd} - ck_{i,j}^{bd}, \text{ for } (i,j) \in \hat{B} \quad (5)$$

$$S_{i,j+1} \geq F_{i,j} + tc_{i,j}^{bg} + ck_{i,j}^{bg}, \text{ for } (i,j) \in \hat{B} \quad (6)$$

$$S_{i,j}, F_{i,j}, ck_{i,j}^{od}, ck_{i,j}^{og}, ck_{i,j}^{bd}, ck_{i,j}^{bg} \geq 0 \quad (7)$$

The developed model requires knowledge of the duration of tasks being performed on all structures by all brigades ($t_{i,j}$).

The parameters of the model are: $tc_{i,j}^{od}, tc_{i,j}^{og}$ - the value of the limiting lower and upper flexible time couplings between work on successive structures, as well as their respective unit weights $cw_{i,j}^{od}, cw_{i,j}^{og}$ allowing the calculation of the value of the influence of failure to ensure a flexible coupling on the goal function; $tc_{i,j}^{bd}, tc_{i,j}^{bg}$ - the value of limiting upper and lower flexible time couplings between the work of successive brigades and their respective unit weights $cw_{i,j}^{bd}, cw_{i,j}^{bg}$ allowing the calculation of the value of the influence of failing to ensure a flexible coupling on the goal function.

The decision variables in the model are: $S_{i,j}, F_{i,j}$ - the time of initiation and completion of work on structure i by brigade j ; $ck_{i,j}^{od}, ck_{i,j}^{og}, ck_{i,j}^{bd}, ck_{i,j}^{bg}$ - auxiliary variables that allow us to determine by how much did the lower and upper flexible time coupling for performing tasks on structures, as well as the lower and upper flexible time coupling for the work of brigades miss their marks.

The goal function (1) is a sum of several components. The first element determines the value of the failure to ensure lower and upper flexible time coupling between structures. The second element allows us to determine the value of the failure to ensure lower and upper flexible time coupling between the tasks of successive brigades. The third element is the deadline for all work ($Z_{n,m}$ signifies the time of completion of the last work). The objective function will be minimized. This will allow us to set such deadlines for the work of brigades on the structure that best meet the technological constraint with the shortest project completion time.

The model has the following constraints. Formula (2) makes it possible to link the initiation and completion dates of all tasks performed during the carrying out of the project. Formulas (3-6) retain the dependencies of the CPM network, taking into account lower and upper flexible time couplings for both structures and brigades, and allow us to determine whether flexible couplings have not been ensured (ck variables). All variables take on non-negative values (7).

Both the constraints and the goal function are linear, which makes this a linear programming model. The model developed by the authors has been implemented in the Python programming language. The Simplex algorithm was used to analyse the model.

Figure 1 shows the concept of flexible time couplings. In a case in which the difference between the date of the initiation of a task on structure $i+1$ by a given brigade and the date of a task's completion on structure i falls between the values $tc_{i,j}^{od}$ and $tc_{i,j}^{og}$ (or in the case of tasks being performed on a single structure by successive brigades: $tc_{i,j}^{bd}$ and $tc_{i,j}^{bg}$) this does not affect the value of the goal function (Figure 1a). In a case in which the aforementioned difference is smaller than the value of the lower flexible coupling by $tc_{i,j}^{od}$ by $ck_{i,j}^{od}$ time units, the goal function will be increased by the quotient of the value of the failure of ensuring to maintaining this coupling ($ck_{i,j}^{od}$) and the determined $cw_{i,j}^{od}$ weight (Figure 1b). Also in the case of failure to keep the upper flexible coupling by $ck_{i,j}^{og}$ time units, the goal function will be increased by the quotient $ck_{i,j}^{og} \cdot cw_{i,j}^{og}$ (Figure 1c). Flexible couplings between tasks carried out on one site by successive brigades can be interpreted in a similar manner. By adopting appropriate val-

ues of cw parameters, constraints can be flexibly complied with according to the priorities set by the planner.

Figure 1: Graphical interpretation of flexible time couplings.

The developed model will be used to schedule repetitive construction projects with technological constraints. The set T will contain work indices after which the technological pause is to take place. Suppose that between task $P_{k,l}$ and task $P_{k,l+1}$, where $l \in T$, there must be a technological pause of at least s_l . $\tilde{L}_1$ will be a sufficiently large number (determined experimentally, it must be a number by at least 2 orders of magnitude greater than the maximum duration of any task) and $\tilde{L}_2$ will be much larger (by at least 2 orders of magnitude) than $\tilde{L}_1$ ($\tilde{L}_2 \gg \tilde{L}_1$). With these assumptions, an appropriate set of weights was prepared:

$$tc_{i,j}^{od} = 0, cw_{i,j}^{od} = \tilde{L}_1, \text{ for } (i, j) \in \hat{O} \quad (8)$$

$$tc_{i,j}^{og} = \tilde{L}_1, cw_{i,j}^{og} = \tilde{L}_1, \text{ for } (i, j) \in \hat{O} \quad (9)$$

$$tc_{i,j}^{bd} = 0, cw_{i,j}^{bd} = \tilde{L}_1, \text{ for } (i, j) \in \hat{B} \wedge j \in T \quad (10)$$

$$tc_{i,j}^{bd} = s_j, cw_{i,j}^{bd} = \tilde{L}_2, \text{ for } (i, j) \in \hat{B} \wedge j \in T \quad (11)$$

$$tc_{i,j}^{bg} = \tilde{L}_1, cw_{i,j}^{bg} = \tilde{L}_1, \text{ for } (i, j) \in \hat{B} \quad (12)$$

The weights described in condition (8) will allow the meeting of the general conditions in the CPM network - none of the tasks carried out on structure $i + 1$ will start before completion of work on structure i . Weights (9) and (12) will ensure that there are no upper limits between

the date of initiating a successive work and the completion date of a previous work - this applies to tasks performed on subsequent structures (condition 9) as well as to tasks performed by subsequent brigades (condition 12). The weights presented in condition (10) will allow the meeting of general conditions in the CPM network - none of the tasks carried out by brigade $j + 1$ will commence before the end of brigade j 's work on structure i (this does not apply to tasks that require technological pauses). The weights described in condition (11) will cause the pause between the work of successive brigades on a structure will be equal to at least s_j . It should be noted that due to the fact that $\tilde{L}_2 \gg \tilde{L}_1$ adherence to technological pauses will be more important than maintaining general limitations in the CPM network. Such a developed set of weights will be called set A.

A set of weights which will cause the technological pause to be exactly as long as parameter s_l was developed as well:

$$tc_{i,j}^{od} = 0, cw_{i,j}^{od} = \tilde{L}_1, \text{ for } (i, j) \in \hat{O} \quad (13)$$

$$tc_{i,j}^{og} = \tilde{L}_1, cw_{i,j}^{og} = \tilde{L}_1, \text{ for } (i, j) \in \hat{O} \quad (14)$$

$$tc_{i,j}^{bd} = 0, cw_{i,j}^{bd} = \tilde{L}_1, \text{ for } (i, j) \in \hat{B} \wedge j \in T \quad (15)$$

$$tc_{i,j}^{bd} = s_j, cw_{i,j}^{bd} = \tilde{L}_2, \text{ for } (i, j) \in \hat{B} \wedge j \in T \quad (16)$$

$$tc_{i,j}^{bg} = \tilde{L}_1, cw_{i,j}^{bg} = \tilde{L}_1, \text{ for } (i, j) \in \hat{B} \wedge j \in T \quad (17)$$

$$tc_{i,j}^{bg} = s_j, cw_{i,j}^{bg} = \tilde{L}_2, \text{ for } (i, j) \in \hat{B} \wedge j \in T \quad (18)$$

Conditions (13-16) are analogous to (8-11). The condition (17) has been modified while condition (18) has been added to impose an upper limit on the length of the technological pause - now it will last exactly s_j . This set of weights will be called set B.

The proposed models assume that every day is a work-day.

3 Calculation example

To verify the model's usefulness, a calculation example of the carrying out of works on 5 structures by 4 specialized brigades was developed. Each brigade must perform the following works on every structure: B1 - excavation, B2 - building a strip foundations, B3 - erection of foundation walls, B4 - erecting a floor slab above the basement.

$t=[5, 8, 6, 7]$	$tc^{od}=[0,0,0,0]$	$tc^{bd}=[0,7,14]$	$tc^{og}=[L1,L1,L1,L1]$	$tc^{bg}=[L1,L1,L1]$
$[6, 6, 5, 8]$	$[0,0,0,0]$	$[0,7,14]$	$[L1,L1,L1,L1]$	$[L1,L1,L1]$
$[8, 7, 4, 8]$	$[0,0,0,0]$	$[0,7,14]$	$[L1,L1,L1,L1]$	$[L1,L1,L1]$
$[6, 10, 5, 9]$	$[0,0,0,0]$	$[0,7,14]$	$[L1,L1,L1,L1]$	$[L1,L1,L1]$
$[5, 9, 6, 8]$		$[0,7,14]$		$[L1,L1,L1]$
$L1=10000$	$cw^{od}=[L1,L1,L1,L1]$	$cw^{bd}=[L1,L2,L2]$	$cw^{og}=[L1,L1,L1,L1]$	$cw^{bg}=[L1,L1,L1]$
$L2=1000000$	$[L1,L1,L1,L1]$	$[L1,L2,L2]$	$[L1,L1,L1,L1]$	$[L1,L1,L1]$
	$[L1,L1,L1,L1]$	$[L1,L2,L2]$	$[L1,L1,L1,L1]$	$[L1,L1,L1]$
	$[L1,L1,L1,L1]$	$[L1,L2,L2]$	$[L1,L1,L1,L1]$	$[L1,L1,L1]$
		$[L1,L2,L2]$		$[L1,L1,L1]$
				$[L1,L1,L1]$

Figure 2: Weights set according to the weight set A.

Figure 3: The solution obtained using weight set A. $O_i B_j$ – work performed on structure i by brigade j , S – tasks initiation time, F – tasks completion deadline, t – task completion time.

The completion times of individual tasks by the brigades on each structure have been shown in Table 1. A technological pause of at least 7 days must be maintained between the task of Brigade B2 (strip foundations) and B3 (erection of foundation walls). Meanwhile, a technological pause of at least 14 days must be maintained between the task of B3 and B4 (constructing a floor slab over the basement).

Table 1: The duration of the tasks performed by each brigade (B1 – B4) on each structure (O1 – O5).

	B1	B2	B3	B4
O1	5	8	6	7
O2	6	6	5	8
O3	8	7	4	8
O4	6	10	5	9
O5	5	9	6	8

For a problem formulated in this manner, a solution shown on Figure 3 has been obtained using the model developed by the authors in conjunction with weight sets A (weight shown on Figure 2).

Calculations were also performed for an analogous example, assuming that pauses are to last exactly 7 days (between tasks performed by brigades B2 and B3) and exactly 14 days (between the tasks performed by brigades B3 and B4). In order to solve this problem the authors used the model that has been developed in conjunction with weight set B (weight shown on Figure 4). The solution obtained has been shown in Figure 5.

Using weight set A, the project will be completed within 80 days. The imposed minimum technological pauses will be maintained, and in some cases will last longer. For example, on structure 2, between tasks performed by brigades B3 and B4, the pause will be 16 days (instead of 14). All constraints resulting from network dependencies were also maintained. There will be no situation in which two different task are being performed simultaneously on one structure. In the case of using weight set

$t=[$ [5, 8, 6, 7] [6, 6, 5, 8] [8, 7, 4, 8] [6, 10, 5, 9] [5, 9, 6, 8]]	$tc^{od}=[$ [0,0,0,0] [0,0,0,0] [0,0,0,0] [0,0,0,0]]	$tc^{bd}=[$ [0,7,14] [0,7,14] [0,7,14] [0,7,14] [0,7,14]]	$tc^{og}=[$ [L1,L1,L1,L1] [L1,L1,L1,L1] [L1,L1,L1,L1] [L1,L1,L1,L1]]	$tc^{bg}=[$ [L1,7,14] [L1,7,14] [L1,7,14] [L1,7,14] [L1,7,14]]
L1=10000 L2=1000000	$cw^{od}=[$ [L1,L1,L1,L1] [L1,L1,L1,L1] [L1,L1,L1,L1] [L1,L1,L1,L1]]	$cw^{bd}=[$ [L1,L2,L2] [L1,L2,L2] [L1,L2,L2] [L1,L2,L2] [L1,L2,L2]]	$cw^{og}=[$ [L1,L1,L1,L1] [L1,L1,L1,L1] [L1,L1,L1,L1] [L1,L1,L1,L1]]	$cw^{bg}=[$ [L1,L2,L2] [L1,L2,L2] [L1,L2,L2] [L1,L2,L2] [L1,L2,L2]]

Figure 4: Weights set according to the weight set B.

Figure 5: The solution obtained using weight set B. Markings as in Figure 3.

B, the project will be completed within 84 days. In this example, the break must be exactly 14 days long. This results in changing the dates of some tasks and extending the duration of the entire project (compared to the first example). All imposed restrictions were met.

4 Conclusions

The presented model of priority scheduling turned out to be possible to implement in the planning of the carrying out of repetitive construction projects featuring technological constraints. Constraints defined in a flexible manner by the decision-maker allow to shape the assumed planning situation in a free manner under assumed technological constraints. The planner only defines the technological constraints and selects the appropriate parameter weights (based on the sets that were developed) to be used in the presented optimization model. The initiation and completion dates of tasks obtained as a result of this optimization can be used to create a schedule. The planner participates

only in the collection and input of data and the development of a ranking list. Of course, in the program dedicated to the planner that will be developed in the future, the selection of parameters will be performed automatically, implemented in the program's code.

The presented model, along with a weight set, can be extended to consider additional restrictions, such as: the continuity of performing work by selected brigades, continuity of work on selected structures, imposed deadlines for the completion of structures and other items. Constraints (technological and organisational) would be determined in a flexible way in the form of a ranking list. The proposed approach does not take into account the costs that, when carrying out repetitive construction projects, are an important factor affecting the organisation of the work of brigades. The possibility of changing the order in which structures are being built was not included as well. These aspects will be the subject of further research. The possibility of shortening task completion time or of the technological breaks should also be included.

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