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SCHEDULING OF REPETITIVE CONSTRUCTION PROCESSES WITH CONCURRENT WORK OF SIMILARLY SPECIALIZED CREWS

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Abstract. The highest degree of construction works harmonization can be achieved when planning a repetitive project with processes replicated many times in work zones of identical size. In practice, structural considerations affect the way of dividing the object under construction into zones differing in terms of scope and quantity of works. Due to this fact, individual processes are being allotted to different non-identical zones. Most methods intended for scheduling repetitive processes were developed with the assumption that the work zones are identical and that a particular process cannot be concurrently conducted. To address this gap, the authors put forward a mathematical model of the problem of scheduling of repetitive processes that are repeated in different work zones with the following assumption: several crews of the same type are available, thus particular process can run simultaneously in different locations. The aim of optimization is minimizing the idle time of all crews under the constraint of not exceeding the contractual project duration. The proposed mixed binary linear programming model can be solved using software available in the market or developed into a dedicated system to support decisions. To illustrate the benefits of the model, an example of scheduling interior finishing works was provided.

Keywords: construction project scheduling, repetitive processes, mixed-linear program, resources constraints, schedule optimization, idle time reduction.

Introduction

The project time and cost optimization have been the object of research for decades. The research generated an impressive body of literature (Carr & Meyer, 1974; Johnston, 1981; Reda, 1990; Sakalauskas & Felinskas, 2006; Liu et al., 2019; Haghighi et al., 2019). In the case of construction project planning, the most frequent schedule optimization objective are to minimize the total duration and/or cost. The project duration can be reduced by a dexterous arrangement of the tasks' start and completion dates. In this process, the planner accounts for constraints, such as the task precedence relations resulting from the logic of works and construction methods (the precedence relations being of hard or soft character (Jaskowski & Sobotka, 2012; Jaskowski & Biruk, 2018), or resource availability (Sakalauskas & Felinskas, 2006; Bożejko et al., 2014). The total project cost can be reduced by selecting process modes, so methods of delivering particular tasks that affect the time, cost, and resource engagement. Another way is to reduce the idle time of resources. All these optimization objectives can be considered separately or in combinations, and the aim of the scheduling process can be reducing the cost, cutting the project time, or finding a best time-cost trade-off (Geiger, 2006; Błaszczyk & Nowak, 2009; Žujo et al., 2017; Haghighi et al., 2019; Tran et al., 2019).

Construction projects are complex by nature. They engage multiple resources, including workers of various trade profiles. Therefore, the division of labor is necessary and the processes need to be entrusted to individual specialists, crews of workers or organizational units disposing of machine sets (later referred to as crews).

To facilitate seamless cooperation of these multiple resources as members of the project team and concurrent realization of project activities (and thus reduce the time of completing the project as a whole) it is often necessary to divide the erected object into smaller parts (work zones) (Cho et al., 2013). The crews then move from one work zone to the other to complete their specific activities. One crew leaves the work zone after completing their work, so the next crew can start with a consecutive process in this location. This arrangement makes construction

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works similar to industrial production, and the scheduling methods can draw from classic flow-shop models used in manufacturing (Hyari & El-Rayes, 2006; Podolski, 2017). Construction projects that can be divided into work zones where the same sets of processes are to be conducted are referred to as Repetitive Construction Projects (Hegazy et al., 2014). According to the character of projects, these are sometimes divided further into linear projects (e.g. roads, pipelines), non-linear vertical projects (e.g. high-rise buildings, where a work zone is a story) and non-linear scattered (e.g. complexes of buildings, where the work zone is a whole building or a section of a building).

Two groups of methods are used to schedule construction projects. The first group is based on the graph and network theory. They apply to non-unit projects that involve non-repetitive processes. This group includes the classic CPM (Critical Path Method) and PERT (Program Evaluation and Review Technique). The other group, often referred to as Repetitive Scheduling Methods (Photios & Yang, 2016), have been developed to facilitate scheduling projects that involve processes replicated in a number of work zones; in their case, using network models would be inefficient (the networks would be too complex to be optimized, especially in terms of maintaining continuity of work).

A large portion of repetitive (or linear) scheduling methods proposed in the literature are based on an assumption that the project can be divided into similar work zones where the same set of processes is to be conducted, and where the amount of work related to a particular process is the same in each zone (Khisty, 1970; Carr & Meyer, 1974; O'Brien, 1975; Birrell, 1980; Arditi & Albulak, 1986; Al Sarraj, 1990; Reda, 1990; Ammar & Elbeltagi, 2001; Hegazy & Wassef, 2001).

Few methods allow for differences in the amount of work in zones while assuming that the set of processes and their sequence must be the same in each zone and excluding the possibility of employing a number of crews to perform the same process simultaneously in different zones (Selinger, 1980; Johnston, 1981; Chrzanowski & Johnston, 1986; Moselhi & El-Rayes, 1993; Harris & Ioannou, 1998; El-Rayes & Moselhi, 2001). In particular, El-Rayes and Mosheli (1998) analyzed a case of a number of crews working in parallel on the same type of process in different locations; their algorithm allowed for three types of constraints: logical precedence relationships, crew availability, and crew work continuity.

With identical work zones (of the same amount of work related with a process – referred in literature as units), the order in which they are occupied by crews is irrelevant for the total duration of a project. However, if the amount of work related with a process differs zone to zone and these differences do not stay in the same proportion for each process, then the sequence of zones becomes a key factor affecting the project duration. The problem of determining the optimal order of zones was addressed, among others, by Hejducki and Mrozowicz (2001), who assumed the same sequence of zones for each process, and later by Fan and Tserng (2006) and Fan et al. (2012) who applied soft logic in defining precedence relations among processes of the same type in different work zones. However, all these authors assumed that exactly the same set of processes is to be conducted in each work zone, and no process can be conducted at the same time in different work zones.

Huang and Sun (2005, 2006a, 2006b) considered non-unit repetitive projects that involved different scopes of works carried out by groups of crews in work zones that differed in size. For each process, the number of work zones could be different; heir approach assumed that projects repeat in activities, and not in zones. Varied working crews could be employed to deliver processes of the same type. Relationships that describe the process precedence logic were generalized compared to the earlier repetitive scheduling methods, and the activity precedence relationships could differ zone to zone. The assumption was that there exists no hard logic relationship between activities of the same type repeated on units, so any sequence of the crews' going from zone was acceptable. The authors developed a algorithm to minimize the total project duration while assuring crew work continuity. It considered the time and cost for routing (mobilizing / demobilizing) the crews. The algorithm requires that the planner predefines allocation of crews to particular processes in all work zones and partial order of zones by setting their priorities. These initial decisions may have a significant impact on the scheduling results. Therefore, the algorithm does not facilitate optimization in terms of selecting crews to perform processes in particular zones and determining their sequence.

1. Considerations in scheduling repetitive processes

While scheduling projects that consist of processes repeated on different work zones, the planner typically allows for the following facts:

1. Different processes call for different resources (specialized crews, machine sets). A particular process is going to be replicated in consecutive work zones. Although the nature and methods of the work are generally the same in each zone, the quantity of work and some details regarding its execution may differ (for example the span of floor beams, the story height). Therefore, the duration of the same process in different work zones is not constant, and the resource involved in the process does not move from one zone to another in a fixed rhythm. El-Rayes and Moselhi (1998) refer to repetitive processes that differ zone to zone in duration as „non-typical repetitive activities" and argue that they are common in the construction practice.
2. Theoretically, the duration of a particular process in all work zones, as well as the duration of several processes in the same work zone, could be equalized by continuous adjustment of the rate of work

by modifying the size and composition of the crews or machine sets. However, in the practice of construction, this is not viable. As a result, with the durations of processes in work zones not following any pattern, it is difficult to schedule out the resource idle time, or the continuity of work is obtained to the detriment of the total project duration (Biruk & Jaśkowski, 2009). However, a solution may be expanding the pool of resources: hiring more crews of the same type. These crews, similarly specialized, but not necessarily of the same productivity, enable the planner to schedule a process to run simultaneously in a number of work zones. In the remainder of the paper, the term "process" will be replaced with a "group of processes" or "activity group" meaning the same type of work to be performed in all work zones by different crews, whereas a "process" or "activity" is going to be used to describe a particular type of work to be conducted in a particular work zone by a particular crew.

3. The „classic" repetitive processes scheduling methods presented in the literature assume that the sequence of processes is fixed and the same for all zones. Moreover, the next process can start no earlier than its predecessor has been completed. However, as observed in practice, different processes may require a different approach to defining work zones. Thus, it is necessary to take into account modified precedence constraints resulting from different division of the building into zones for particular processes (e.g. the assembly of all floor panels on the building story can be started after the completion of more labor-intensive walls on two parts of the story).
4. The sequence of a process-related crew moving from zone to zone can be, in many cases, arbitrarily defined: the logic of works does not constrain it. However, these precedence relationships affect the total duration of the project. Thus, the links among processes of the same group are rather of a soft character (Jaskowski & Sobotka, 2012; Jaskowski & Biruk, 2018), but structural considerations may impose hard-type relationships at least in some work zones.
5. In many cases, it is necessary to account for additional time for the mobilization and demobilization – preparation of a tasks or completion activities in a work zone (e.g. time for assembling and disassembling equipment), as well as the time to move from zone to zone. These auxiliary activities (further referred as preparation) – if performed during the working shift – should be treated as additional tasks that engage resources, but not occupy the work zone (a successive process may start in a work zone at the moment of leaving by the crew performing the preceding process).

Considering the character of construction works, the authors formulate the problem of scheduling repetitive processes as follows:

1. The planner strives to assure continuity of work for the resources without allowing the project's duration to exceed the contractual time for completion.
2. The planner must assure that the sequence of processes in each work zone is following the logic that arises from the build methods, the way of dividing the object into work zones, and spatial arrangement of the work zones.
3. Concurrent execution of the same type of processes is acceptable, as it is possible to hire a number of similarly specialized crews to work on the same processes in different work zones at the same time.
4. If the project involves mechanized processes whose duration in particular work zones takes less than one working day, the time for preparation needs to be accounted for in the planning process.

2. Mathematical model of the scheduling problem

Table 1 provides the list of symbols, parameters and variables used in the mathematical model.

Let us assume that a construction project consists in completing n groups of processes that belong to the set G ($G = \{1, 2, \ldots, n\}$). The processes of each group are conducted repeatedly in different work zones. Each group of processes $i \in G$ is assigned a set of work zones U_i ($U_i = \{1, 2, \ldots, m_i\}$) where the processes from the group need to be executed. Therefore, each process is described as (i, j): it belongs to the group of processes $i \in G$ and is to be conducted in work zone $j \in U_i$.

A set of direct predecessors $P_{i,j}$ is defined for each process (i, j); the set comprises processes related with the process in question by "hard" relationships that result from the build method, structural considerations, and the way of dividing the object into work zones. A set S comprises processes whose set of direct predecessors is empty ($P_{i,j} = \varnothing$); these processes can be started as soon as the project starts or later.

Each group of processes $i \in G$ is allotted a set of renewable resources R_i – crews of workers or machine sets, later referred to as crews. The time $t_{i,j,r}$ of a particular crew $r \in R_i$ executing a particular process (i, j) is estimated in advance and treated as input.

The variables corresponding to the start dates of processes are marked with the symbol $s_{i,j}$, $\forall i \in G, \forall j \in U_i$. The start date is understood as the moment when a crew starts demobilizing in the preceding work zone; after the demobilizing the crew moves to the next zone, mobilizes there, and then the actual process may start.

The decisions on assigning a particular crew to a particular process in a particular work zone are modeled by binary variables $x_{i,j,r} \in \{0,1\}$: they equal 1 if process (i, j) is to be conducted by crew r, and 0 otherwise.

Crews cannot be assigned to more than one process at a time. If the same crew r ($x_{i,u,r} = 1 \land x_{i,v,r} = 1$) is allotted to a pair of processes (i, u) and (i, v), where $u < v$, the processes have to be scheduled in sequence. This sequence is modeled by binary variables $y_{i,u,v} \in \{0,1\}$ ($y_{i,u,u} = 0$).

Table 1. Symbols and notations

Symbol	Description
	General symbols
G	set of groups of processes (activity groups)
U_i	set of work zones for group of processes i
$P_{i,j}$	set of direct predecessors for process from group i in zone j
S	set of processes whose set of direct predecessors is empty
R_i	set of renewable resources (crews) to execute processes from group i
	Model parameters
n	the number of groups of process
m_i	the number of zones where processes of group i are to be executed
$t_{i,j,r}$	time of a particular crew r executing a particular process from group i on unit j
M	a sufficiently large number
	Model variables
$s_{i,j}$	start dates of process from group i in zone j
$x_{i,j,r}$	a binary variable to model the decision on assigning a particular crew r to a particular process from group i on unit j
$y_{i,u,v}$	a binary variable to model the decision on the sequence of zones u and v to repeat the process from the group i
τ_i	the preparation time for a crew realizing the process from the group i ; preparation means mobilization/demobilization/moving from zone to zone
$p_{i,j,r}$	an auxiliary variable; if process from the group i is to be delivered by crew r in zone j, the variable equals the start date of this process, otherwise it equals 0
$s_{i,r}^{\min}$	the earliest start of a process from group i entrusted to crew r; this date corresponds to the start of the crew's r engagement in the project
$z_{i,r}^{\max}$	the latest finish of a process from group i entrusted to crew r; this date corresponds to the finish of the crew's r engagement in the project
$D_{i,j}$	the duration of process from group i in zone j
$\xi_{i,r}$	the auxiliary binary variable: it equals 1 if a process from group i is conducted by crew r in any work zone, and equals 0 otherwise

Variable $y_{i,u,v}$ equals 1 if process (i, u) is to precede process (i, v), and 0 otherwise.

The time for preparation is considered a quality of a group of processes, and for each crew $r \in R_i$ that changes location from zone u to zone v (or begins / finishes work in any zone) it equals τ_i.

Selecting crews and defining process start dates is aimed at reducing resource idle time. The total idle time of a particular crew is calculated as the difference between the period of the crew's being engaged in the project (limited by the dates of the crew's starting their first process in the project and finishing the last process entrusted to them), and sum of durations of all processes allotted to this crew increased by the crew's total time for preparations (moving from zone to zone and/or mobilizing/demobilizing in all zones).

To facilitate the calculation of the crew's start and finish dates (the dates of the crew's starting their first process in the project and finishing the last), an auxiliary variable was introduced into the analysis, created for each crew $r \in R_i$ and each process (i, j) the crew can potentially execute:

$$p_{i,j,r} = s_{i,j} \cdot x_{i,j,r}, \quad \forall i \in G, \ \forall j \in U_i, \forall r \in R_i . \tag{1}$$

If process (i, j) is to be delivered by crew r, the variable $p_{i,j,r}$ equals the start date of process (i, j). Otherwise, it equals 0.

The model of the problem of selecting crews for particular processes and calculating the processes' start and finish dates, with the assumption that the total project duration cannot be greater than a predefined time for completion (T), is formulated as follows:

$$\min P: \ P = \sum_{i \in G} \sum_{r \in R_i} \left(z_{i,r}^{\max} - s_{i,r}^{\min} - \sum_{j \in U_i} \left(t_{i,j,r} \cdot x_{i,j,r} \right) - \tau_i \cdot m_i \right); \tag{2}$$

$$D_{i,j} = \sum_{r \in R_i} t_{i,j,r} \cdot x_{i,j,r}, \quad \forall i \in G, \forall j \in U_i; \tag{3}$$

$$\sum_{r \in R_i} x_{i,j,r} = 1, \ \forall i \in G, \forall j \in U_i; \tag{4}$$

$$s_{i,j} \ge 0, \ \forall (i,j) \in S; \tag{5}$$

$$s_{k,l} + \tau_k + D_{k,l} \le s_{i,j} + \tau_i, \ \forall (k,l) \in P_{i,j}; \tag{6}$$

$$s_{i,u} + D_{i,u} + \tau_i \le s_{i,v} + M \cdot \left(1 - y_{i,u,v}\right) + M \cdot \left(2 - x_{i,u,r} - x_{i,v,r}\right),$$
$$\forall i \in G, \forall r \in R_i, \forall u \in U_i, \forall v \in U_i; \quad (7)$$

$$s_{i,v} + D_{i,v} + \tau_i \le s_{i,u} + M \cdot y_{i,u,v} + M \cdot \left(2 - x_{i,u,r} - x_{i,v,r}\right),$$
$$\forall i \in G, \forall r \in R_i, \forall u \in U_i, \forall v \in U_i; \quad (8)$$

$$z_{i,r}^{\max} + \tau_i \cdot \xi_{i,r} \le T, \ \forall i \in G, \forall r \in R_i; \quad (9)$$

$$\xi_{i,r} \le M \cdot z_{i,r}^{\max}, \ \forall i \in G, \forall r \in R_i; \quad (10)$$

$$z_{i,r}^{\max} \le M \cdot \xi_{i,r}, \ \forall i \in G, \forall r \in R_i; \quad (11)$$

$$z_{i,r}^{\max} \ge p_{i,j,r} + t_{i,j,r} \cdot x_{i,j,r} + \tau_i \cdot x_{i,j,r},$$
$$\forall i \in G, \ \forall j \in U_i, \forall r \in R_i; \quad (12)$$

$$s_{i,r}^{\min} \le p_{i,j,r} + M \cdot \left(1 - x_{i,j,r}\right),$$
$$\forall i \in G, \ \forall j \in U_i, \forall r \in R_i; \quad (13)$$

$$p_{i,j,r} \le M \cdot x_{i,j,r}, \ \forall i \in G, \forall j \in U_i, \forall r \in R_i; \quad (14)$$

$$p_{i,j,r} \le s_{i,j}, \ \forall i \in G, \ \forall j \in U_i, \forall r \in R_i; \quad (15)$$

$$p_{i,j,r} \ge s_{i,j} - M\left(1 - x_{i,j,r}\right), \ \forall i \in G, \ \forall j \in U_i, \forall R_i; \quad (16)$$

$$s_{i,r}^{\min} \le M \cdot \sum_{j \in U_i} x_{i,j,r}, \ \forall i \in G, \ \forall r \in R_i; \quad (17)$$

$$s_{i,r}^{\min} \ge 0, \ \forall i \in G, \forall r \in R_i; \quad (18)$$

$$s_{i,j} \ge 0, \ \forall i \in G, \forall j \in U_i; \quad (19)$$

$$p_{i,j,r} \ge 0, \ \forall i \in G, \ \forall j \in U_i, \forall r \in R_i; \quad (20)$$

$$x_{i,j,r} \in \{0,1\}, \ \forall i \in G, \forall j \in U_i, \forall r \in R_i; \quad (21)$$

$$y_{i,u,v} \in \{0,1\}, \ \forall i \in G, \forall u \in U_i, \forall v \in U_i; \quad (22)$$

$$\xi_{i,r} \in \{0,1\}, \ \forall i \in G, \quad (23)$$

where M is a sufficiently large number, and $z_{i,r}^{\max}$, $s_{i,r}^{\min}$ represent, respectively, the latest finish and the earliest start of a process from group i entrusted to crew r; these dates correspond to the finish and start of the crew's engagement in the project.

The model comprises the following components: the objective function (2), the constraints (3)–(17), and the boundary conditions (18)–(23). The objective function (2) minimizes the total idle time of all crews.

Equation (3) serves calculating duration $D_{i,j}$ of any process from group i in zone j. Variables $D_{i,j}$ have been introduced to simplify Eqns (6)–(7).

According to Eqn (4), any process in any zone can be entrusted to only one crew.

Equation (5) describes the condition that processes with no predecessors may start as soon as the project starts. Equation (6) facilitates calculating the start dates of processes that have predecessors and allows for relationships between the processes that define their sequence.

Equations (7) and (8) enable the planner to calculate start dates of processes that cannot be conducted in parallel due to being entrusted to the same crew. However, if they are not allotted to the same crew r $(2 - x_{i,u,r} - x_{i,v,r} \ne 0)$, then conditions (7) and (8) are automatically met, and the processes may run simultaneously. Otherwise, if $y_{i,u,v} = 1$ and, at the same time, $x_{i,u,r}, x_{i,v,r} = 1$, then, according to Eqn (7), process (i, v) can start after process (i, u) is completed, and condition (8) is fulfilled. If $y_{i,u,v} = 0$, then according to condition (8), process (i, u) can start after process (i, v) is completed, and condition (7) is met.

According to condition (9), no crew is allowed to complete their work (including demobilization) later than the project due date. Demobilization is to be considered only if the crew was allocated to at least one process ($z_{i,r}^{\max} > 0$). Because of that, another auxiliary binary variable was necessary: $\xi_{i,r}$ that, according to Eqns (10) and (11), equals 1 if $z_{i,r}^{\max} > 0$ (so a process from group i is conducted by crew r in any work zone), and equals 0 otherwise.

Equations (12) and (13) enable the planner to define the dates of the crews' first and last appearance in the project. Although these formulas are inequalities, they allow for the determination of the extreme values due to the form of the objective function: the maximum time for completion of the crew work is minimized, and the minimum time for starting is maximized.

Equation (1) is non-linear. Therefore, as simple linear programming solvers were intended to be used, it was substituted by linear relationships (14), (15), and (16). If $x_{i,j,r} = 1$ then variable $p_{i,j,r}$ assumes the value of $s_{i,j}$ $(p_{i,j,r} \le s_{i,j} \wedge p_{i,j,r} \ge s_{i,j})$. If $x_{i,j,r} = 0$, then, according to (14) and (19), $p_{i,j,r}$ also equals 0 $(p_{i,j,r} \le 0 \wedge p_{i,j,r} \ge 0)$.

Condition (17) means that the start date of the work of a crew that was not selected for any process is 0.

The solution of this model prompts the planner the optimal dates of realization of particular activities in work zones, the optimal allocation of processes to particular crews (or the optimal selection of crews for processes), and the optimal sequence of the crew's moving from zones to zone. The latter is likely to be different for each group of processes. The model takes the linear form with continuous and binary variables. Therefore, the solution can be produced by general-purpose solvers available on the market (e.g. LINGO, AIMMS, AMPL, CPLEX, Gurobi). The model can also be the basis for creating a computer application devoted solely to supporting repetitive scheduling.

The model is easily adaptable to different objective functions: minimizing the total project completion time with the predefined maximum permitted idle time of the crews, or finding a trade-off between the project duration and the crew idle time.

While constructing the model, the authors' assumptions were similar to those by Huang and Sun (2005, 2006a, 2006b). However, the algorithm by Huang and Sun did not provide the planner with optimal schedules and required a heuristic (or trial-and-error) definition of partial units ordering for each activity group and resource allocation.

Another difference between the proposed model and the model by Huang and Sun (2006a) lies in the approach to the "preparation time" – the time for the crew's mobilizing and demobilizing in a particular location together with the time for changing the work zones. Huang and Sun (2006a) assumed that mobilization/demobilization time is different for different crews, and the time of moving from one zone to the next (routing) differs process to process and zone to zone. Maintaining this differentiation would significantly increase the complexity of the proposed model (e.g. by the need to introduce non-linear dependencies). Therefore, the authors decided to assume that preparation time is characteristic only for a process, and that it does not differ zone to zone or crew to crew. This assumption can be acceptable in practice if the work zones are located in the same construction site, the distances between them are relatively short, the process execution times are expressed in full days, and the transfer from zone to zone takes place at the beginning or at the end of the working shift.

3. Examples

To check the model's consistency and advantages, the authors analyzed two simple test cases used by Huang and Sun (2005, 2006a) – notional projects with three groups of processes to be conducted in four to five work zones with four crews.

Figures 1 and 2 illustrate the relationships between the processes. Table 2 lists the input values: durations of processes, preparation times of the crews', and possible assignments of crews to processes.

The heuristic algorithm by Huang and Sun (2005, 2006a, 2006b) aimed at minimizing the total project duration while eliminating crew idle time (no idle time was allowed). Therefore, the objective function of the proposed linear programming model was modified to minimize the total duration. In Example I, the minimum project duration found by means of the proposed algorithm was 23 days, so 3 days less than the minimum duration by Huang and Sun (2005). The minimum duration for Example II was 28 days, equal to the result by Huang and Sun (2006a).

The optimal solutions of the models minimizing the crews' idle time were obtained by means of LINGO 14.0. The optimal schedules are presented in Figures 3 and 4. In the analyzed cases, the results were the schedules with the minimum idle time of the crews of 0 days (all crews work continuously).

The solution of Example I (Figure 3) was better than the reference solution by Huang and Sun (2005). As for Example II (Figure 4), the total duration of 28 days was the same, but the sequence of processes in each group occurred to be different than in the reference solution by Huang and Sun (2006a).

The zone sequence (the order in which the crews move from zone to zone) affects the duration of processes repeated in work zones differing in size if the amount of work related to a process is not proportional to the zone size, or if the relationship between the amount of work and the size of the work zone exists, but differs process to process. This fact was considered by many researchers dealing with repetitive scheduling (e.g. Hejducki & Mrozowicz, 2001; Fan & Tserng, 2006; Fan et al., 2012) and flow shop scheduling. The above examples illustrated the fact that the zone sequence affects the total project duration also with equal size of the zones (all activities in an activity group were assumed to have identical duration)

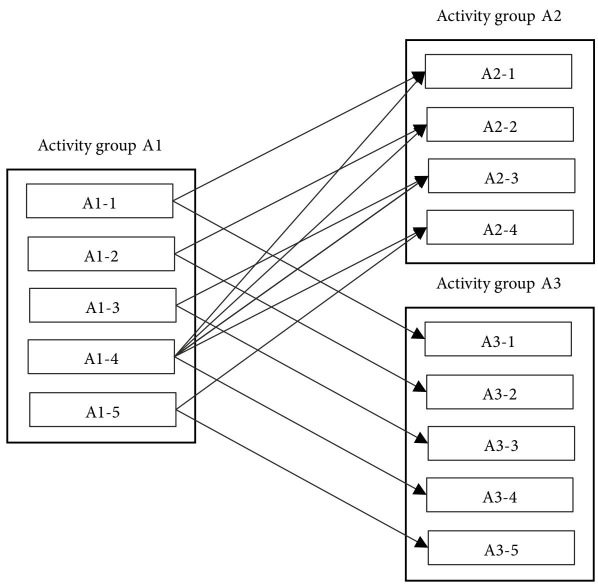

Figure 1. Logical relationship between activities in work zones (Example I from Huang and Sun (2005))

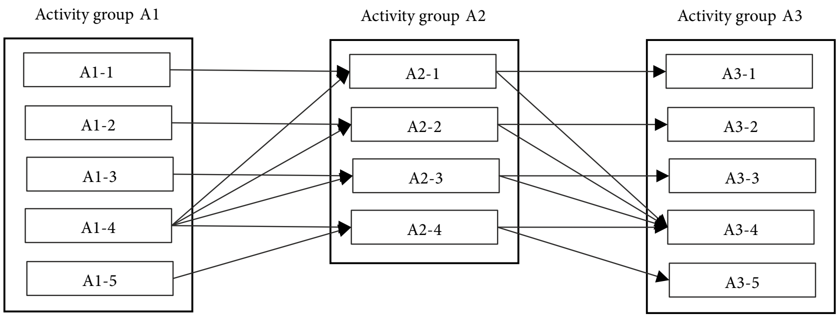

Figure 2. Logical relationship between activities in work zones (Example II from Huang and Sun (2006a))

if the relationships between the processes are of a complex character. It should be stressed that the Huang and Sun approach (2005, 2006a, 2006b) requires that the planner arbitrarily defines activities priorities in each activity group as well as allocates resources. As confirmed by their solution to Example II – worse than optimal – the use of the trial-and-error method based on intuition and experience does not guarantee finding the optimal solution.

Another test case was prepared, this time of the authors' design. The project involves internal works in a small school building, whose floor plan is presented in Figure 5. The data on process durations are listed in Table 3.

The project comprises the following groups of processes:

1. Erection of plasterboard partition walls on steel frame and filled with acoustic insulation (all internal walls visible in Figure 6),
2. Placing dry screed overlay,
3. Installing dry lining of walls, suspended ceilings of gypsum boards, and painting all surfaces,
4. Laying wooden floors in classrooms and in the office, and
5. Laying ceramic floor tiles in the laboratory and the bathrooms.

For each of the groups of processes 1), 2) and 3), two identical crews are potentially available – of the same productivity. There are also two flooring crews – one specialized in wooden floors and allocated to group 4), the other consisting of tillers and allocated to group 5).

The processes from different groups are going to be repeated in a different number of work zones: rooms-zones differ in the type of flooring, and they "share" partition walls, so the walls are assigned only to one of the pair of neighboring zones. The relationships between the processes are illustrated in Figure 6.

As dry screeds were selected for the building and there are two crews available to lay them, the screeds can be installed in the halls and rooms at the same time: there is no chance of damaging fresh screed while using the hall to access the rooms. If wet screeds or plasters were to be considered, constraints on the sequence of zones, adopted to avoid damage to fresh surfaces, could be introduced by setting appropriate values to variables $y_{i,u,v}$.

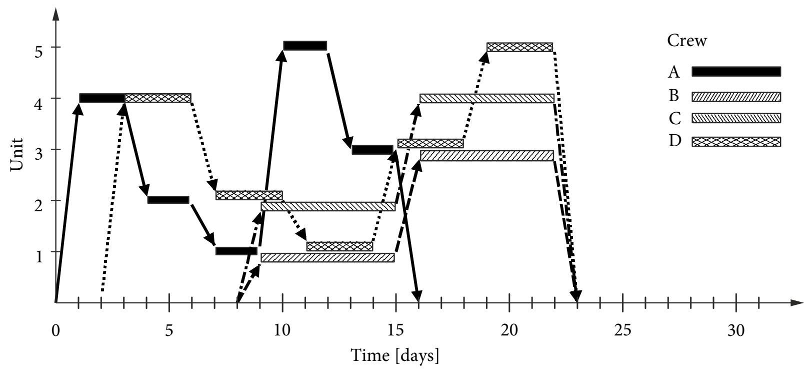

Figure 3. Optimal schedule for Example I (case based on Huang and Sun (2005))

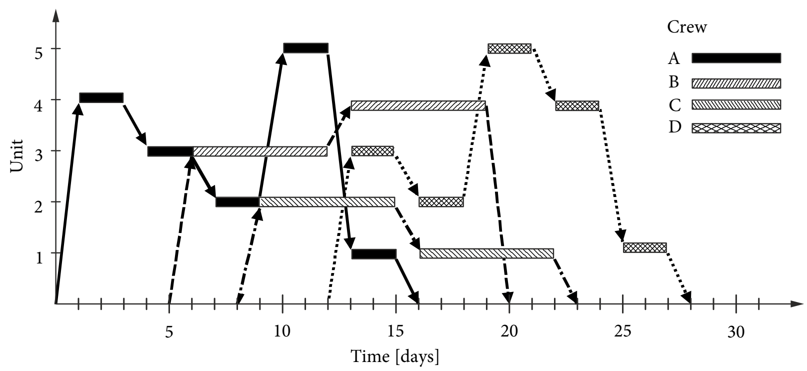

Figure 4. Optimal schedule for Example II (case based on Huang and Sun (2006a))

Table 2. Example data (example project from Huang and Sun (2005, 2006a))

Activity group	Number of activities (zones)	Activity duration (for each zone) in days (Huang & Sun, 2005)	Activity duration (for each zone) in days (Huang & Sun, 2006a)	Preparation time, days	Crews symbols
A1	5	2	2	1	A
A2	4	6	6	1	B, C
A3	5	3	2	1	D

Table 3. Example III data for school building interior finishing works

Unit number	Unit symbol and location	Duration for plasterboard partition walls [days]	Duration for dry flooring screeds [days]	Duration for plastering and painting [days]	Duration for wooden flooring [days]	Duration for ceramic cladding [days]
1	C1 – classroom 1	9	8	12	11	–
2	C2 – classroom 2	8	7	11	9	–
3	C3 – classroom 3	7	6	10	8	–
4	L1 – laboratory 1	6	5	8	–	6
5	L2 – laboratory 2	5	4	7	–	5
6	O – office	4	3	5	6	–
7	S – sanitary	3	2	4	–	3
8	H1 – hall 1	–	4	6	–	5
9	H2 – hall 2	–	3	4	–	3
Number of crews		2	2	2	1	1

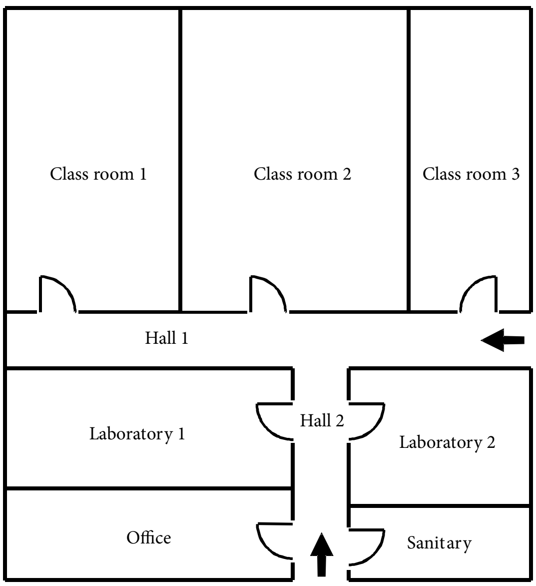

Figure 5. School floor layout (Example III)

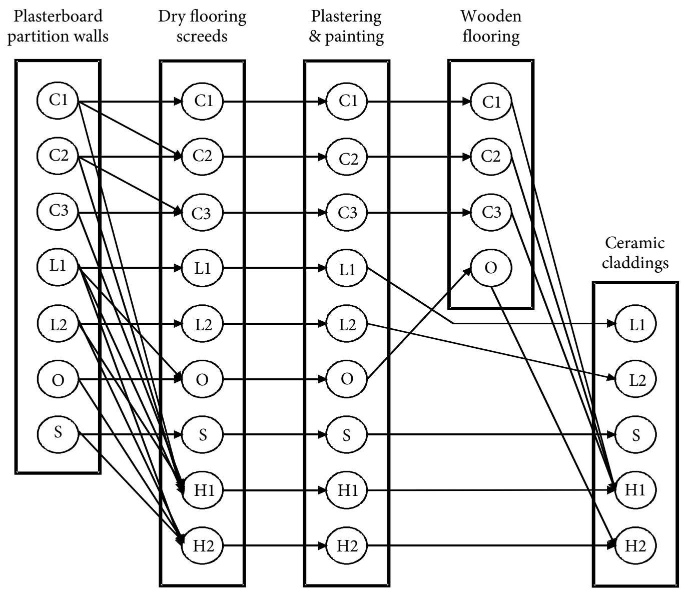

Figure 6. Precedence relations among processes in work zones of Example III (interior decoration works in a school building)

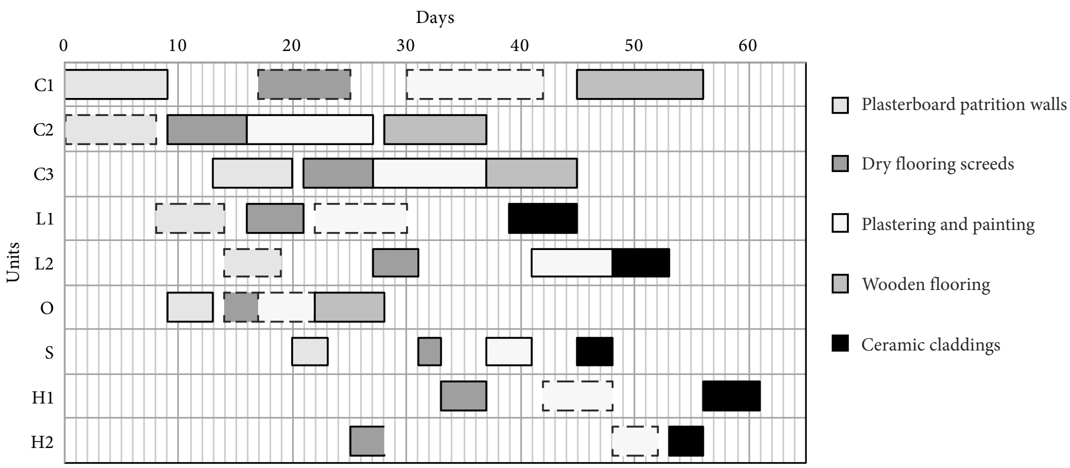

Figure 7. Project schedule in Example III (optimal solution: T = 61 days without crews idle times). Bars with dotted outlines represent processes delivered in parallel by the other crew

The preparation times τ_i were ignored (assumed to be 0) as the building is small, and moving from zone to zone can be quick.

The minimum duration of the project was calculated to be 61 days. With this figure as the maximum acceptable duration, the optimum schedule (of minimum crew idle time) is presented in Figure 7. The total crew idle time was in this case 0.

Conclusions

The origins of mathematical methods for optimizing construction projects schedules are commonly associated with the development of the CPM/PERT in the late nineteen-fifties. Analyzing the literature on the subject, two research directions can be identified. One was aimed at accounting for a variety of practical constraints, conditions, and goals specific to construction projects (e.g. resource availability, time-widows, repeatability of processes) and allowing for various optimization objectives. The other focused on developing scheduling decision-support tools. These are both accurate algorithms, which ensure obtaining optimal schedules, and dedicated heuristic algorithms, or customized meta-heuristic algorithms. In the latter two cases, finding the optimal solution is not guaranteed; instead, the planner is provided with a "relatively good" solution obtainable with reasonable computational effort for solving real-life scheduling problems.

In construction, the purpose of optimizing schedules is usually to minimize the project completion time. Construction projects typically involve the employment of many crews of various trades. The size of a built facility is many times larger than the space occupied by a particular crew. Therefore, to reduce the duration of the whole set of works the built facility is divided into smaller parts (work zones). The way an object is divided into work areas depends on its shape, type of structure, and construction methods. Division into work zones facilitates planning the work: crews may work in parallel repeating their specialty work in subsequent locations. The best effects are obtained by ensuring continuous work of the crews – eliminating the costly idle time. For this reason, employing traditional network methods (CPM, PERT) to repetitive scheduling is difficult: they do not account for resource constraints. In real-life cases, the zones differ in size and quantities of particular works to be conducted within them, which limits the use of traditional repetitive scheduling methods. As the construction practice involves constraints and requirements that differ from the assumptions adopted in classic scheduling methods, instances of these methods being applicable without modification are rare.

The proposed approach assumes that the construction crews employed for a project are of a fixed composition. Their expected productivity is also considered a known constant, and is used to plan the duration of processes. As the crew is not scalable to each particular process it is assigned to, the durations of processes in subsequent non-uniform work zones are different. Similarly, the durations of different processes in the same work zone are different. The aim of analyses was to provide a method to harmonize the construction work and eliminate the idle time of crews. In order to better synchronize the work of the crews, differences in duration of processes are alleviated by hiring several equally skilled crews to simultaneously work in separate work zones.

Therefore, the authors undertook to analyze the problem of scheduling repeatable processes with the following assumptions:

1. The work zones are differing in the amount of work and the scope of processes. The processes do not have to be conducted in all zones; for each process, the number of work zones may be different.
2. The composition of crews is fixed, so duration of processes conducted by them in different work zones may differ.
3. There is a possibility of parallel work of a number of crews of the same trade in different work zones.
4. The relationships defining the sequence of processes in zones are complex – they may differ zone to zone.
5. Crews do not need to move from zone to zone in the same order (different order is possible for different processes), this order may also be imposed by the planner.
6. As moving from zone to zone may require some activities (mobilization and demobilization) and consume some time, extra time for such preparations can be introduced into the model.
7. The aim of the optimization is to minimize the crew idle time without exceeding the predefined time for completion for the whole project and generating an optimal schedule defining start and finish dates of processes in zones that optimally allocates processes to crews and optimally sequences the crew's moving from zone to zone.

The focus of the paper is the mathematical formalization of this scheduling problem. Though it has been discussed in the literature for many years, and some dedicated scheduling support algorithms have been created, no formal model was presented.

The authors are aware that mathematical models of complex real-life problems are very complex themselves, containing hundreds of variables and conditions, which increases computational effort. A natural direction of further research is then developing heuristic or metaheuristic algorithms that generate acceptable solutions quicker but compromise on quality. Nevertheless, the insight into optimal solutions of simple test cases is necessary to verify the created algorithms. The advantage of the linear programming model presented in this paper is the possibility to find such solutions using commonly known solvers.

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