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Crashing Construction Project Schedules by Relocating Resources

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ABSTRACT A variety of schedule compression techniques are used to get delayed construction projects ‘‘back on tracks’’. This paper presents a new optimization approach to schedule crashing by relocating some of the workers from non-critical to critical processes (changing composition of crews using the initial pool of workers) and employing additional resources. The authors describe their idea in the form of a mixed-integer linear problem. A numerical example illustrates the merits of the proposed approach. The method may become a practical support in construction scheduling decisions.

INDEX TERMS Construction project management, construction project scheduling, resource allocation, resource-constrained project scheduling problem, schedule optimization.

NOMENCLATURE

A. Acronyms:

AON	Activity-on-Node
CPM	Critical Path Method
FS	Finish-to-Start
LOB	Line-of-Balance
LSM	Linear Scheduling Method
MILP	Mixed Integer Linear Problem
PDM	Precedence Diagramming Method
PERT	Program Evaluation and Review Technique
RSM	Repetitive Scheduling Method
SCHEME	Space zoning Concept-based scHEduling ModEl

B. Parameters:

G	directed graph modeling the construction project
n	construction processes number
M	sufficiently large number
K^s	predefined limit of the total cost of the subcontracted works
T	predefined deadline of the construction project (defined by the number of working days for completion)
$t_{i,w}$	the duration of an individual process i in a particular variant w

C. Indices:

h, k	auxiliary indices describing construction processes
i	construction processes
j	construction processes, which is a team donor for process i,
v	auxiliary index of construction processes variants
w	construction processes variants

D. Sets:

E	set of pairs of construction processes
V	set of processes
V^c	set of processes that cannot be team donors nor recipients
V^s	set of the processes that are potential team recipients
V^w	set of the processes that are potential team donors
W_i	set of variants for a process i
W_i^c	set of variants to be delivered by subcontractors and , by default, not involving any team transfers
W_i^p	set of basic variants (processes executed by a complete crew with no team transferred in or out)
W_i^s	set of process variants supported by extra team
W_i^w	set of process variants supporting other processes with own team

E. Variables:

D_i	integer variable modeling the duration of process i
s_i	integer variable modeling the start date of process i

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$x_{i,w}$	binary variable modeling the decisions which variant to select; equals 1 if the process i is to be executed in variant w, equals 0 otherwise
$x_{i,w,j}$	binary variable modeling the decisions on resource allocation: equals 1 if process i is to be executed in variant w by a crew reinforced with an extra team taken from process j, equals 0 otherwise

I. INTRODUCTION

Construction projects constitute a particular challenge for managers. The factors that contribute to their unpredictability include the susceptibility of construction processes to weather, uniqueness of designs, high employee turnover rates, various supply-related logistic problems, and high plant failure rate [1]–[9].

While these projects are commonly understood as exceptionally difficult to deliver on time, project owners are rigorous about deadlines specified in the contract. First, they need to conform to the bank loan conditions (schedule changes are not welcome, especially in terms of postponing the completion date). Second, the clients desire to benefit from the projects as quickly as possible. Therefore, they tend to set short and fixed due dates with no tolerance of the ''unexpected obstacles'' likely to be encountered by the contractor.

Given limited project budgets, short times for completion, scarce human resources, and high risk, the problem of compressing construction schedules is far from trivial. The well-established methods, such as CPM, PDM, LSM, PERT prove inadequate for such challenges[10]–[19]. Especially with repetitive projects, the main disadvantages of these methods are imprecise visualization (even with small projects, the bar charts or network diagrams are difficult to handle) and failure to capture the continuity of work and the dynamics of production rates[12]–[14], [20]–[22].

Inappropriate scheduling methods and tools mean more than the planner's lack of comfort: they imply oversimplifications and omissions. These result in scheduling errors and the contractor's accepting unrealistic deadlines. What follows are contractual penalties, the client's disappointment, and harm to the contractor's reputation. Inadequate scheduling tools fail to prevent the planner from misallocating resources, and the resulting workflow disturbance reduces labor productivity, increases the cost of works, and damages the workforce morale. For this reason, the research and project management community strives to develop more practical planning methods.

The authors attempt to provide a tool to assist construction managers in scheduling fast-track projects as well as in crashing schedules to make up for delays. The idea is to allow modifications of crew composition, so using some members of crews performing non-critical processes to reinforce the crews busy with critical tasks. This way, the critical tasks can be delivered quicker, though at the expense of other tasks. The overall project duration is reduced, while the pool of resources stays fixed. However, for greater flexibility, employing extra resources is also allowed.

The novelty of the approach consists in the following:

- The model assumes that the crews can be split into teams and stay operational even if a team is relocated to other tasks. A typical assumption in construction scheduling is that of fixed crew composition. This approach may foster the learning effect. However, if crews are composed of a number of teams, and allocated to a task of small workload, their work becomes inefficient. It is thus considered practical to allow transferring out a part of the crew and use it efficiently elsewhere.
- The proposed approach integrates two concepts of project crashing – by employing extra resources (subcontracting), and by relocating in-house resources. The idea of relocating teams helps reduce the project duration with no need to hire additional resources or change construction methods to faster but more costly ones. This way, acceleration generates no extra cost.
- The idea of setting the upper limit to the cost of subcontracted works helps manage in-house resources rationally. Many existing models for schedule crashing rely on subcontracting (increasing the resource pool). They consider the direct cost of subcontracting but ignore hidden costs associated with reducing the productivity of in-house resources and their standby pay.

The paper is organized as follows: the next section provides an overview of the schedule compression methods presented in the literature. Then, the authors propose their approach to reducing project duration: the assumptions are described and the optimization model is mathematically formalized. Further on, the model is applied to a simple notional case to illustrate its merits. The last section summarizes the results, discusses the limitations of the model, and indicates directions for future work.

II. LITERATURE REVIEW

For practical reasons, minimizing project duration is probably the most frequently addressed problem in construction project scheduling [23]–[34]. The body of literature on fast-track project planning and schedule crashing techniques is rich. The methods can be roughly divided into the following groups:

- using assembly-line approach and a steady rhythm of work of crews (to eliminate disturbance in the flow of works and eliminate unproductive time),
- adding extra resources or changing the execution modes of selected processes (to quickly complete the key processes that affect project duration),
- using flexible processes precedence relations,
- allowing some processes to be split for greater flexibility in defining sequence of works and resource allocation,
- others, including combinations of some or all of the above.

A. INTRODUCING THE ASSEMBLY LINE APPROACH AND A STEADY RHYTHM OF CREW WORKS

The assembly line approach assumes dividing the scope of a project into units with similar resource requirements.

It breaks down complex processes into simple repetitive activities that may be performed by specialized crews, and focuses on continuity of their work: allows them to move from one unit to another without interrupting the work of other specialized crews [17], [35], [36].

A number of methods based on this idea were developed, for instance RSM by Harris and Ioannou [19]. The authors introduced the concept of the controlling sequence, which has the same practical significance as the critical path in the CPM method and can be used to determine the duration of a project. Yang and Ioannou [37] computerized the RSM, thus providing users with a means to quickly test various scheduling strategies. An interesting development of this idea was proposed by Maravas and Pantouvakis [38], who created a fuzzy RSM. Possible differences between repetitive units and the variation in crew performance were described in the form of fuzzy sets to allow for their naturally non-deterministic character.

Cho *et al.* [39] attempted to plan a construction schedule using the space zoning concept based on network model-based scheduling methods. Workspace zoning helps not only reduce the construction time by iteration and overlapping related activities but also avoid congestion and interference between tasks or resources. In their SCHEME, they employed simulations to model erection of steel structures. Tests on a number of real-scale cases proved that the model is capable of precisely reflecting the character of steel structure erection projects, and that space-zoning produces better results in reducing construction duration than in cases of nonspace-zoning.

Lee *et al.* [40] used the TACT and enhanced-TACT methods (extensions of LOB) to reduce the time required to execute repetitive construction projects. Both these methods unify the execution time of tasks and synchronize the execution time of repetitive tasks by means of a uniform workload. The eTACT method in relation to the TACT method is supplemented with a work planning template. Studies have shown that this approach reduces the duration of construction projects by as much as 25%.

Another direction of development of construction scheduling methods improving schedule reliability in a risky environment [41], [42].

B. ADDING EXTRA RESOURCES OR CHANGING THE EXECUTION MODE OF SELECTED PROCESSES

Adding resources generates extra cost but speeds up construction processes. The best time-cost trade-off is often looked for using a linear [43], [44] or nonlinear [45], continuous or discrete [46], [47] cost function.

The schedule compression method by Bakry *et al.* [48] assumes dividing processes into smaller units. Then the planner identifies the parts of processes whose acceleration is the most cost-effective. This acceleration is achieved by overtime at working days, by switching to introducing shift work, by working on weekends, or by employing extra crews.

Jun and El-Rayes [49] developed a system to accelerate construction projects by shift work. Adding an evening and night shifts are a popular method to overcome project delays despite cost increase, occupational health and safety risks, and crew productivity issues. A multicriteria analysis adopted in this system helps the planners accelerate the execution of construction projects while minimizing its negative effects.

Xu *et al.* [50] considered the way to reduce the construction project's overall time and cost, the cost of accelerating processes, and the environmental impact – at the same time. Their method allows the acceleration of process execution (up to a certain limit) with the increase of the costs. The main advantage of the proposed method is that it provides a systematic and practical approach to decision-making, supporting the decision-makers in controlling their schedules.

Tomczak and Jaśkowski put forward models that help improve the work continuity of the general contractor's in-house crews, both in non-repetitive [10], [51], and repetitive projects [52]. Their MILP models assumed that subcontractors can be employed to help smooth the general contractor's resources, thus optimizing the use of in-house labor and improving the harmonization of works throughout the project.

Changing the execution mode of a process (providing the same "product" using different – more expensive but faster - construction methods) constitutes another way to reduce the duration of a construction project. Among the authors who used this approach, Aziz [53] developed a strategy based on multicriteria optimization aimed at finding the best bid for repetitive construction projects. By considering multiple process modes, this system minimizes project duration, tender price and the project's demand for working capital, while maximizing the project's present value.

García-Nieves *et al.* [54] developed a mathematical model minimizing the duration and tardiness of repeatable construction projects. The model was meant to assists the planner in selecting modes of process execution in search for ways of reducing project duration. The user could specify tasks to be split (if necessary), set fixed precedence relationships, and define optimum crew sizes. The authors applied their method to find optimal schedules in a project under seven scenarios of resource availability and continuity conditions.

C. CHANGING PROCESS PRECEDENCE RELATIONS

Fan *et al.* [55] constructed a model to minimize the total cost of a project based on the idea of soft relationships between processes. In contrast to the most common network modeling approach, the authors observed that the process order does not need to be decided once and for all: the construction practice prompted that it is technically viable to change (e.g. reverse) sequence of some works. With some flexibility in the definition of the predecessor-successor relations, the spectrum of viable schedule options becomes larger. Earlier on, Fan and Tserng [36] used models with soft process relationships to minimize the project duration while ensuring resource use continuity.

Wang [56] examined the impact of the uncertainty of process duration on the project schedule as well as the impact of changing the logic of the project network on the overall duration. For this purpose, the author developed a new simulation model.

Jaśkowski and Sobotka [57] introduced soft relationships to construction project modeling to increase scheduling flexibility and facilitate compressing schedules. They proved that applying soft logic to network project models increases the number of viable options, extends the value range of the optimization criteria, and allows the planner to find a solution with reduced duration without compromising the project budget.

D. SPLITTING PROCESSES

Another way to compress schedules is to allow some noncritical processes to be split. As their execution is suspended, their resources can be temporarily redirected to reinforce the crews performing other, critical processes. This way, the critical tasks may be accelerated and the whole project delivered faster. The disadvantage of this solution is a possible extra cost and work to protect the effects of unfinished processes against damage.

The model presented by Altuwaim and El-Rayes[58] allowed interrupting secondary construction processes to reduce the overall project duration and to improve the continuity of works. Their procedure consisted of four phases: early schedule calculation, work-continuity float calculation, ensuring strict work continuity, and assessing schedule performance. The merits were illustrated by an example of a repetitive project. The model enables the planner to generate a wide range of schedules with a reduced completion time and analyze them in terms of the total project cost.

Similarly, Long and Ohsato [59] considered splitting and suspending tasks of repetitive projects to create schedules with minimized time and/or cost. Their method respects all constraints of the initially defined network model and constraints on resource continuity. The relationships between the time and cost of processes can be linear, nonlinear, or discrete. The method's performance was demonstrated using examples of the construction of a bridge (a case used for testing in other publications) and a notional project consisting of five work units with eighteen processes in each of them.

Amini and Heravi [60] developed a model that allows interrupting processes with higher production rates to allocate their resources to other processes in order to reduce project duration. The presented method is flexible in terms of the number and duration of pauses in the course of the process execution – they can be defined according to the planner's preferences.

A model by Ammar [61] also permitted suspending processes while maintaining resource continuity; it was intended specifically for repetitive projects and used the LOB approach.

E. COMBINATION OF THE ABOVE AND OTHER METHODS

Huang *et al.* [62] put forward a way to solve a discrete time-cost trade-off problem using soft logic. A genetic algorithm implemented in their model selects the optimal sets of process execution modes, sets the start dates of the processes, and defines the process sequence within each unit (work zone). The method's performance was demonstrated on the example of scheduling works in two construction sites.

Ford *et al.* [63] undertook to reduce construction duration without increasing the total cost by conducting constructability reviews. They modeled and analyzed the impact of constructability reviews on the design phase, construction phase, and project duration. The basic rationale for the constructability reviews is that they improve the performance of project schedules by identifying and fixing errors before the construction begins, thereby reducing the duration of the construction phase. The presented results illustrate how medium-sized constructability reviews reduce project duration and explain the potential impact of the project-construction approach on the effectiveness of constructability reviews.

F. SUMMARY

The authors of all works described above agree that the "classic" scheduling procedures fail to answer problems specific to construction projects. Therefore, it is necessary to develop tools to support construction site managers in resolving emerging issues. It seems that the opportunity to reduce the time of construction projects through changes in traditional work organization has not been explored yet. This paper is an attempt to exploit this gap to improve the quality and effectiveness of time planning of construction projects.

III. THE METHOD

One of the most frequently used methods of modeling engineering problems is linear programming [64]. The authors put forward a mixed-integer linear program (MILP) to reduce the project duration, as to find a schedule that meets a predefined deadline (defined by the number of working days for completion, T), by manipulating resources. To use the full potential of the model, the deadline should be tight.

The model assumes that at least some crews are composed of smaller operating units, further referred to as teams. As construction workers are usually trained in more than one trade, the crews are considered multi-skilled. This means that they are qualified to deliver several types of processes. The key assumption is that a set of workers (a team drawn from a crew) can be relocated from one process to another. This way, the former process slows down, and the latter (a critical process directly affecting the project duration) accelerates.

Another assumption is that extra resources (subcontractors) can be employed to deliver some processes. Subcontractors are intended to be hired only if the cost of using them does not exceed a predefined limit. Thus, the model helps take advantage of the general contractor's resources to the highest possible degree – if economically justified.

The scheduling steps are as follows. First, the project logic needs to be expressed as AON network: the project is to be modeled by a graph $G = \langle V, E \rangle$ with one start node and one end node. $V = \{1, 2, \ldots, n\}$ denotes the set of processes, while the graph arcs $E \subset V \times V$ reflect the process sequence. The relationships are considered fixed (hard-type only).

The next step requires the planner to compile a list of crews that are available for the project and capable of performing the particular processes, and decide which crews are reasonable to be divided into teams. Then, the planner is to identify the processes that potentially could do with an extra team to reinforce their crews (the set V^s), and another set of processes that are the possible "team donors" (the set V^w). The remaining processes (where transferring teams in or out is not possible or not justifiable) belong to the set V^c. Therefore, $V = V^c \cup V^s \cup V^w$.

This makes some processes possible to be delivered in more than one variant. The variants are defined by the resources allocated to them (one crew or the other, with backing from an extra team or, in contrast, weakened by taking a team away, or a subcontractor), and naturally differ in durations and costs.

Let the complete set of variants for a process i be W_i. The subset of variants to be delivered by subcontractors and, by default, not involving any team transfers, is denoted by $W_i^c \subset W_i$. Then come the variants that employ in-house crews:

- W_i^p is the subset of "basic" variants where the process is executed by a complete crew without any team transferred in or out;
- $W_i^s \subset W_i$ is a set of process variants with support from an extra team;
- W_i^w is a set of process variants with resources "weakened" by transferring out part of the crew.

Only one variant can be selected for a process in the final schedule.

In its current form, the model covers only one type of precedence relations, namely FS. It does not enable defining different calendars for the project and the resources and operates only in working days. Therefore, for each of the variants that come in question, the process durations need to be expressed as a number of working days for completion.

Let the duration of an individual process i in a particular variant w be denoted by $t_{i,w}$. A variable s_i represents the start date of process i (i.e. the number of the day the process is started). The decisions which variant to select is modeled with the use of a binary variable $x_{i,w} \in \{0, 1\}$. The variable $x_{i,w}$ assumes the value of 1 if the process i is to be executed in variant w, and equals 0 otherwise. Another binary variable, $x_{i,w,j}$, is needed to capture decisions on resource allocation: if process i is to be executed in mode w by a crew reinforced with an additional team taken from process j, then the binary variable $x_{i,w,j}$ equals 1, and 0 otherwise.

As mentioned in the assumptions, subcontracting is possible but constrained. The cost of process i in mode w equals $k_{i,w}$ (defined only for the subcontracted works) and the total cost of the subcontracted works may not exceed a predefined limit of K^s.

The mathematical model of the problem was formulated as follows.

$$\min P : P = \sum_{w \in W_i^w} \sum_{i \in V^w} x_{i,w}, \tag{1}$$

$$\begin{aligned} D_i = &\sum_{w \in W_i^c} t_{i,w} \cdot x_{i,w} + \sum_{w \in W_i^p} t_{i,w} \cdot x_{i,w} \\ &+ \sum_{w \in W_i^s} \sum_{j \in V_j^s} t_{i,w} \cdot x_{i,w,j}, \quad \forall i \in V, \end{aligned} \tag{2}$$

$$\begin{aligned} &\sum_{w \in W_i^c} x_{i,w} + \sum_{w \in W_i^p} x_{i,w} \\ &+ \sum_{w \in W_i^s} \sum_{j \in V_j^s} x_{i,w,j} = 1, \quad \forall\, i \in V, \end{aligned} \tag{3}$$

$$s_1 = 0, \tag{4}$$

$$s_i + D_i \le s_j, \quad \forall\ (i,j) \in E, \tag{5}$$

$$\begin{aligned} &s_h + D_h \le s_j + M \cdot (2 - x_{j,v} - x_{i,w,j}), \\ &\forall\, v \in W_j^w, \quad \forall\, w \in W_i^s, \\ &\forall\, j \in V^w, \forall\, h : (h,i) \in E \\ &\wedge \forall\, h \in V, \forall\, i \in V^s, \end{aligned} \tag{6}$$

$$\begin{aligned} &s_j + D_j \le s_k + M \cdot (2 - x_{j,v} - x_{i,w,j}), \\ &\forall\, v \in W_j^w, \quad \forall\, w \in W_i^s, \\ &\forall\, j \in V^w, \forall\, k : (i,k) \in E \\ &\wedge \forall\, k \in V, \quad \forall\, i \in V^s, \end{aligned} \tag{7}$$

$$x_{i,w} = \sum_{w \in W_i^w} \sum_{j \in V^s} x_{j,w,i}, \quad \forall\, i \in V^w, \tag{8}$$

$$s_n + D_n \le T, \tag{9}$$

$$\sum_{i \in V} \sum_{w \in W_i^c} k_{i,w} x_{i,w} \le K^s, \tag{10}$$

$$s_i \ge 0, \quad \forall\, i \in V, \tag{11}$$

$$\begin{aligned} &x_{i,w} \in \{0, 1\}, \\ &\forall\, w \in W_i^w, \quad \forall\, w \in W_i^c, \\ &\forall\, i \in V^w, \quad \forall\, i \in V^c. \end{aligned} \tag{12}$$

The equations are explained below.

1) The objective function (1) is minimizing the number of instances of the teams' relocation. This is to obtain acceptable schedules while keeping modifications of crew composition to the minimum: changes in a crew's work routines are likely to generate disruption. The constraints on the project completion date and the cost of subcontracted work are described by conditions (9) and (10), respectively. We intentionally treat them as constraints and not the objective functions: if they were made objective functions, the result would be too many transfers of teams between the crews and a general

disorder. The set of variants w selected for the final schedule (so the variants whose $x_{i,w} = 1$) that involve team transfers (so belonging to the set of W_i^w) should be minimized. Please note that W_i^w is actually a set of processes whose resources have been weakened by transferring a team out (they are team donors). However, condition (8) makes the number of team donors equal the number of team recipients.

2) This auxiliary equation defines the duration of process i. By defining this variable separately, we could make other equations concise and the model more readable. D_i is the sum of the products of the durations of all possible variants of process i and binary variables $x_{i,w}$ and $x_{i,w,j}$. As only one of the binary variables at a time can equal 1 (see equation (3)), the duration is modeled properly.
3) This constraint assures that one and only one variant of a process is selected for execution. If for a given $i \in V$, one of the binary variables equals 1, then all others must be 0. Thus the sum of binary variables $x_{i,w}$ and $x_{i,w,j}$ must be 1 for each $i \in V$. Indirectly, this constraint assigns a set of teams to process i.
4) This is a boundary condition that forces the first process to begin at the date of 0. Conventionally, projects start on day 0, so this equation is to follow this rule.
5) This equation assures that sequential relationships between individual processes are respected. These relationships come from the project's precedence network. This constraint prevents reversing process order and, at the same time, assures that a predecessor i is completed before its successor j starts. This holds for all process pairs (i, j) that belong to arches of the directed graph G that represents the project logic.
6) By this constraint, process j, a team donor for process i, must start after i's predecessors are completed. This equation ensures that the team transferred from process j to the crew executing process i will not be allocated to more than one process at the same time. Literally, if process i is to be executed in variant w ($x_{i,w,j} = 1$), and if i needs to be reinforced by a team taken from process j executed in variant v ($x_{j,v} = 1$), and if process h must be delivered before i ($(h, i) \in E$), then process h must finish before j starts. This prevents using the same team simultaneously in processes h and i.
7) This equation means that process j (the team donor) must be completed before the successors of i start. This constraint assures that the team transferred out of the j's crew to help with process i will not be allocated to more than one process at the same time. If process i is to be executed in variant w ($x_{i,w,j} = 1$) and reinforced by a team taken from process j executed in variant v ($x_{j,v} = 1$), and if process k must start after completion i ($(i, k) \in E$), then process i must end before k starts. This prevents using the team taken from j to reinforce k.
8) This condition ensures that the number of processes supported by an extra team equals the number of those whose crews were weakened: if a team is taken from some crew, it cannot "disappear" but must be used elsewhere. Thus if process i belongs to the set of possible team donors (V^w) and is conducted in variant w ($x_{i,w} = 1$), then the sum of processes (or rather the binary variables representing them) that are potential recipients of a team from i executed in variant w must also be 1. Yet if process i belongs to V^w and $x_{i,w} = 0$, then all processes that can potentially be reinforced by a team taken from i in variant w also need to equal 0. In other words, the sum of donors equals the sum of recipients.
9) This requirement to complete the project before the deadline is introduced as the model's constraint. It enforces that the finish date of the last process of the project network (day n) must occur no later than on day T, a directive date of project completion.
10) The total cost of subcontracted works cannot go beyond a predefined limit. The constraint reads: the sum of costs of processes i decided to be executed according to variant $w \in W_i^c$ that means subcontracting is no greater than the cost limit K^s.
11) This boudary condition assures that the integer variable of s_i is non-negative.
12) This boundary condition defines the binary character of $x_{i,w}$.

IV. EXAMPLE AND DISCUSSION

Let us consider a notional project to illustrate the merits of the model. The project consists in the erection of two buildings. The construction of each building comprises eight processes. The general contractor has two crews, GC-1 and GC-2, with the latter possible to split into two teams, GC-2-1 and GC-2-2. If necessary, one of them may assist the GC-1 in executing selected work packages. There are also five subcontracted crews, marked A to E. The network model of the project and the options of resource allocation are summarized in Figure 1. The process execution times, calculated according to resource allocation decisions, are listed in Table 1. Table 2 presents the costs of processes if entrusted to subcontractors. The total cost of subcontracted works must not exceed € 900,000.

The problem has been approached three times. The first analysis concerns the "reference option". It does not use the method described in the paper: no teams can be exchanged between crews and employing subcontractors is not possible – except for processes beyond the in-house crews' scope of competence (i.e. processes 2, 9, 10, and 17 described in Table 2). The project duration is to be minimized respecting the cost limit on subcontracted works (€ 900,000), the original sequence of processes, and the resource availability constraints. In this option, the objective function needed to be defined differently than in the proposed model (1-12), namely:

$$\min P : P = s_n. \tag{13}$$

TABLE 1. **Process execution times by resource variants.**

Building No.	Process No.	Process	Execution processes' durations [in working days]								
			GC-1	GC-1+GC-2-2	GC-2	GC-2-1	A	B	C	D	E
	1	Start									
Building A	2	Earthworks					3				
	3	Foundations	7	5					8		
	4	Foundation walls	14	11						16	
	5	Ground flooring	7	5							
	6	Walls	14	11						7	
	7	Floor	10	7					2		
	8	Walls of the attic	7	5						8	
	9	Roof						10			
Building B	10	Earthworks								1	
	11	Foundations			4	9			5		
	12	Foundation walls			7	14				9	
	13	Ground flooring			4	9					
	14	Walls			7	14				8	
	15	Floor			5	10			7		
	16	Walls of the attic			4	9				5	
	17	Roof									5
	18	Finish									

The second approach is a partial application of the method described in the paper: the teams may be relocated between crews, but it is still not possible to employ subcontractors for works that are technically possible to be executed by the in-house resources (just like in the "reference option").

The third analysis presents a complete application of the method described in the paper. It allows relocation of the teams and employing subcontractors almost freely – with the only constraint of not exceeding the total cost of subcontracted works, so applying the whole optimization model described in the previous section.

All three cases were solved using Lingo14.0 [65]. The model included 119 constraints and 98 variables. Calculations were performed using an Intel Core i5, 2 GHz CPU PC, with a single solution delivered in 0.2 seconds.

The first analysis was devoted to a "baseline option" without the possibility of relocating the GC-2-2 work team to support the GC-1 crew and without subcontracting processes that physically could be entrusted to in-house crews. Its shortest duration was 72 days, with the cost of subcontracted works € 580,000.

TABLE 2. **The execution costs of the individual processes realised by the subcontractor crews.**

Building No.	Process No.	Process	Execution processes' cost [in 1000 €]				
			A	B	C	D	E
	1	Start					
Building A	2	Earthworks	90				
	3	Foundations			100		
	4	Foundation walls				80	
	5	Ground flooring					
	6	Walls				150	
	7	Floor			120		
	8	Walls of the attic				50	
	9	Roof		250			
Building B	10	Earthworks				70	
	11	Foundations			70		
	12	Foundation walls				60	
	13	Ground flooring					
	14	Walls				120	
	15	Floor			90		
	16	Walls of the attic				30	
	17	Roof					170
	18	Finish					

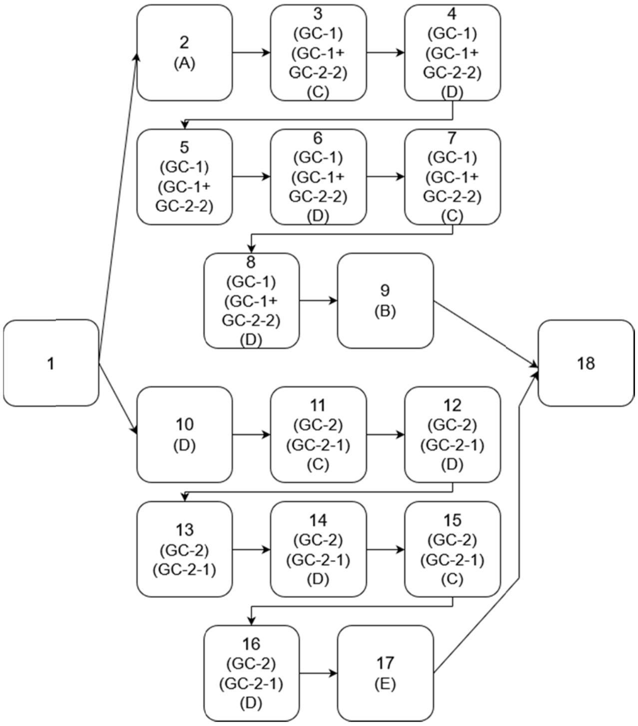

FIGURE 1. **The network model of the project with possible execution options.**

Then the relocation of teams was enabled. The model prompted that team GC-2-2 should be taken from processes 12 and 13 to reinforce processes 4 and 5. As a result, the duration of the project was reduced by five working days using the same pool of resources as the "reference option."

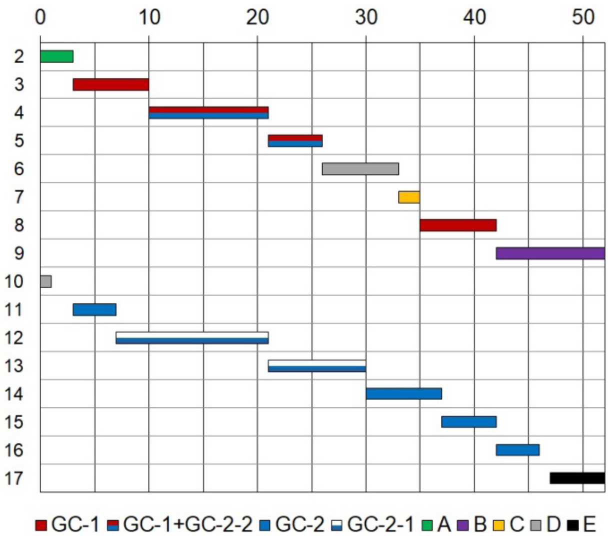

FIGURE 2. A Gantt chart for the optimum schedule of the sample construction project.

TABLE 3. Comparison of results.

	Reference option	Partial application of the method	Proposed method	Method of [66]
Project duration (days)	72	67	**52**	57
Total cost of subcontracted work(€)	580,000	580,000	**850,000**	850,000

Further on, more subcontracting was allowed. Subcontractors employed in processes 6 and 7 helped reduce the project duration by 15 days. Eventually, the project was scheduled to take only 52 days, with the cost of the subcontracted works of € 850,000. Figure 2 presents a detailed Gantt chart for the optimal schedule.

The results of the calculations are summarized in Table 3. They were juxtaposed with the results obtained using another state-of-the-art method, put forward by Jaśkowski [66]; the method simultaneously minimizes three criteria of construction schedule evaluation: project duration, project cost, and cost of subcontracted work, using an evolutionary algorithm. Please note that though the method proposed in [66] allows the use of subcontractors (here to the same cost limit of € 850,000), it does not use the possibility of relocating the in-house teams from process to process. Its solution was a schedule with a project duration 5 days longer than that obtained with the proposed method.

To sum up, the application of the proposed method of resource allocation – allowing crews to be split and teams transferred in or out – helped reduce the duration of the sample project by 7% (from 72 days in the "reference option" to 67 days in the "partial option") without increasing the cost of subcontracting. An improvement based solely on work reorganization without increasing the cost appears noteworthy.

Employing subcontractors reduced the sample project completion time by further 15 days (with an increase of subcontracting cost by € 230,000). Therefore, by taking full advantage of the method, the project baseline time was reduced by 27.7%, though with a 40.0% increase in the subcontracting cost. Such a significant reduction in the duration of a project may be useful in projects with tight schedules as well as cases when the planner needs to make up for delays to avoid high contractual penalties.

V. CONCLUSION

Managing construction projects is a challenge and, due to the sheer scale, the consequences of wrong decisions are particularly costly. Unfortunately, the standard scheduling methods are not easily adaptable to the problems of construction projects. The need for reliable decision making support has not been satisfied yet. The existing ways of accelerating construction projects (allocation of additional resources, the introduction of soft relations between processes, enabling the interruption of secondary processes) usually entail additional costs.

This paper puts forward a MILP algorithm for compressing schedules by changes in the resource allocation – namely by splitting crews into teams and relocating teams to processes that are reasonable to be accelerated. Team relocation was observed in the construction practice, though not found to be reflected in schedule optimization algorithms described in the literature. A further reduction of construction duration was also enabled through subcontracting. Both methods were incorporated into one optimization model.

To illustrate the merits of the method, it was applied to optimize a test schedule. The total duration was reduced by 7% without employing extra resources. However, as the pool of resources was increased by subcontractors, the schedule was compressed by as much as 27.7% of the original duration, though with a considerable increase in subcontracting costs (40%). The developed method generated better results than another state-of-the-art method taken from the literature.

These results, though certainly not representative, show the potential of this method. It significantly increases flexibility in resource allocation. It may be applied for re-scheduling delayed projects to find a way to accelerate while being constrained by a fixed pool of resources. The method can also be used by contractors at the bidding stage to analyze how to make the best use of available resources and how to subcontract more economically while meeting the contractual deadlines.

Obviously, the example we presented was relatively small, but the method applies to real-life full-scale problems. Available solvers of linear models are efficient even if there are thousands of constraints. Naturally, in the case of very complex construction projects like infrastructure megaprojects, the method may prove insufficient. In such a case, one may use some specialized heuristics or metaheuristic algorithm to find a pseudo-optimal solution.

While the idea seems promising, the model is still crude. The algorithm is deterministic. In its current form, it conducts calculations in consecutive working days. Holidays and different calendars for particular processes or resources were not taken into account. Moreover, the project is modeled as an activity-on-node network with only finish-to-start precedence relations.

One of the future directions for its development is adapting it for repeatable projects. The model is going to be expanded to consider process relationships other than finish-to-start. As it is now purely deterministic, the next issue to be addressed is adapting it for risk. Moreover, the model needs to be integrated with the existing scheduling tools for a more user-friendly interface and useful options, such as calendars.

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