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The multi-mode, resource-constrained project scheduling problem in construction: state of art review and research challenges

Problem harmonogramowania przedsięwzięć z ograniczoną dostępnością zasobów i z czynnościami wielotrybowymi w budownictwie: stan wiedzy i kierunki rozwoju

Abstract

In this article, the author analyses the state of the research of the multi-mode, resource-constrained, project-scheduling problem (MRCPSP). Both general and construction-industry-specific applications were studied and compared– in particular, algorithms and methodologies used for solving the different variations of this scheduling problem. Based on the analysis, the author suggests future research ideas.

Keywords: MRCPSP, construction management, project scheduling, algorithms

Streszczenie

W artykule analizowane jest zagadnienie problemu harmonogramowania przedsięwzięć budowlanych z ograniczoną dostępnością zasobów i z czynnościami wielotrybowymi (MRCPSP). Autor bada literaturę dotyczącą problemów MRCPS oraz dotychczasowych zastosowań w przemyśle budowlanym. W szczególności przedstawiono stosowane algorytmy obliczeniowe oraz metodykę podejścia do poszczególnych odmian tego problemu. Na podstawie analizy wskazano możliwe kierunki rozwoju.

Słowa kluczowe: MRCPSP, zarządzanie w budownictwie, harmonogramowanie przedsięwzięć, algorytmy

1. Introduction

Schedules are one of the most important tools for planning and controlling construction projects. During different sub-stages of construction process, they allow construction managers to: prioritise and allocate time for different tasks; represent the dependencies between them; manage resources, both renewable (labour, machinery, materials) and non-renewable (funds). [24]. To create a schedule, one has to determine the order of tasks and their start times – this has to be performed in such a way that specific objectives of the project are achieved whilst at the same time, fulfilling organisational conditions and conforming to planning constraints [11, 17, 26, 43]. Some of the construction project planning objectives include: minimising the duration of the project; minimising or providing evenness of the resources consumption; maximising the construction project economic value for the contractor [11, 43]. Organisational conditions may include, for example, availability of construction activities performance modes, or the need to ensure the continuity of work performed by various groups of workers. Basic planning constraints are linked to technological dependencies between the activities, and the availability of the time and resources needed to implement them.

The resource-constrained, project-scheduling problem (RCPSP) is commonly known and well described in scientific literature. In its classic form, RCPSP aims to minimise the makespan or total duration of a project subject to precedence relations between the activities and the limited renewable resource availabilities [40]. The problem is known to be NP-hard [2].

The multi-mode, resource-constrained, project-scheduling problem (MRCPSP, or rarely MMRCPSP) is a generalised version of RCPSP. The term *multi-mode* means that the activities in the schedule can be performed in different ways (modes); each mode has a specific duration and specific resource requirements [40]. Due to such an approach, managers can take into account situations in which, for example, additional resources can be allocated to a task in order to shorten its duration. However, it is worth mentioning that with the introduction of the additional decision variables, the amount of time required to solve the problem increases. In other words, the computational time required for solving a MRCPSP is longer than that of a similar RCPSP without multiple modes. For this reason, it is of utmost importance to choose proper, efficient computational algorithms while solving MRCPS class problems.

2. Problem formulation

Based on the works of Talbot [38] or Van Peteghem & Vanhoucke [40], one of the possible ways that MRCPSP can be formulated is as follows: a project network $G\ (N, A)$ (in AON format) has N set of activities numbered from 0 (the start dummy node) to $n+1$ (the end dummy node), A is the set of activity pairs between which exists a finish-start precedence relationship (with a time lag ≥ 0). R^p and R^v are respectively sets of renewable and non-renewable resources – their availabilities are stated as a_k^p, $k \in R^p$, and a_l^v, $l \in R^v$. Each activity $i \in N$ can be performed in m_i different execution modes, $m_i \in M_i = \{1, ..., |M_i|\}$. The duration of

the activity i performed in the mode m_i is d_{im_i}. Each mode m_i requires $r^\rho_{im_ik}$ renewable, and $r^v_{im_il}$ non-renewable resources. A schedule S is defined by a vector of activity start s_i and its corresponding finish f_i times. The schedule is feasible if all precedence and resource (both renewable and non-renewable) constraints are satisfied. In its classic form, the objective of the MRCPSP is to minimise the makespan of the project, and, according to Van Peteghem & Vanhoucke, it can be conceptually formulated as follows [40]:

$$Min.s_{n+1} \tag{1}$$

s.t.

$$s_i + d_{im_i} \le s_j \qquad\qquad \forall (i,j) \in A \tag{2}$$

$$\sum_{i \in S(t)} r^\rho_{im_ik} \le a^\rho_k \qquad\qquad \forall k \in R^\rho, \forall m_i \in M_i \tag{3}$$

$$\sum_{i=1}^{|N|} r^v_{im_il} \le a^v_l \qquad\qquad \forall l \in R^v, \forall m_i \in M_i \tag{4}$$

$$m_i \in M_i \qquad\qquad \forall i \in N \tag{5}$$

$$s_0 = 0 \tag{6}$$

$$s_i \in \mathrm{int}^+ \qquad\qquad \forall i \in N \tag{7}$$

where

$S(t)$ – the set of activities in progress in the period $[t-1; t]$.

Each activity i is performed in exactly one mode (equation 5). If a schedule fulfils all the equations, it is called optimal; if equation 1 is not met, the schedule is called feasible [40].

3. Classification of MRCPSPs

In common practice, the goal of the MRCPSP is to minimise the makespan of the project. However, in common practice, clients (including developers) strive to minimise not only time, but also the cost of the construction project in order to maximise the rate of return. Similarly, contractors are trying to optimise these project parameters. The lower the cost, the higher the profit; the shorter the duration, the lower the risk of not fulfilling the deadlines, the lower the risk of inflation, and the lower the risk of encountering a shortage of skilled labour [43]. The dependencies between time and cost of a project are taken into account in *multi-mode, resource-constrained, time-cost, trade-off* problems (MRC-TCT or RC-TC), [25].

There are other variations of the problem – these include: P-MRCPSP (P at the beginning stands for *pre-emptive*) in which activities can be pre-empted at any point in time and restarted at no additional cost [40]; MRCPSP *with discounted cash flows* (MRCPSPDCF); and more depending on the approach chosen by researchers (types of trade-offs, objective functions, constraints, and conditions).

According to Sprecher & Drexl, the generalised problem is obtained by replacing the makespan minimisation with any regular measure of performance and can be referred to as the *generalised resource-constrained, project-scheduling problem* (GRCPSP), [35].

4. Approaches to solving the problem

The procedures used to solve MRCPSP (and scheduling problems in general) can be classified as: *exact*, *heuristic*, and *metaheuristic* [18, 41, 43].

The exact procedures include, among others, *linear programming* (LP), *dynamic programming* (DP), *branch and bound method* (B&B). The heuristic methods include priority rule-based heuristics. These methods are fairly easy to use; however, their use might be slightly problematic when it comes to more complicated schedules. The use of heuristic methods does not guarantee finding the optimal solution to a given problem [30, 31].

Practical problems in construction can be easily qualified as NP-hard (*non-deterministic, polynomial-time hard*) problems. The time needed for solving these problems grows exponentially with the increase of the problem's size [9, 31] – this is why mathematical and heuristic methods do not enable finding solutions to complicated construction problems within an acceptable period of time [11]. In the view of many authors, metaheuristic algorithms seem to be the most appropriate measures for scheduling and task sequencing [21, 30, 31].

The metaheuristic approach does not guarantee finding the optimal solution and the obtained results are often subject to their input parameters; however, they seem perfect for solving complicated, NP-hard class problems because they enable computing suboptimal (acceptable) solutions within an acceptable time frame [31].

The first publications in the field of operational research that tackled the problem of solving MRCPSP were the articles by Słowiński [32] and Talbot [38] published in the nineteen-eighties. The authors used the above-mentioned exact methods for schedule optimisation (respectively: linear programming and enumerative algorithm).

Over the next few years, a series of other exact methods were proposed. Speranza, Vercellis, Hartmann, Sprecher, and Drexl [8, 34, 35, 37] among others used the branch and bound method for classic MRCPSPs; Demeulemeester & Herroelen used the same method for solving a discrete time/resource trade-off problem [5]. In the year 2006, Zhu et al. proposed the use of the *branch-and-cut* (B&C) algorithm [44]. Unfortunately, none of these methods can currently be used for solving complicated construction project scheduling problems since they are unable to find optimal solutions in reasonable computational times [40]. Because of that, heuristic and meta-heuristic methods are being constantly developed.

In particular, Talbot [38], and Sprecher & Drexl [36] introduced time constraints for their branch and bound algorithms. Boctor [3, 4] tested the possibility of introducing and combining different heuristic scheduling rules and proposed an heuristic algorithm basing on the *critical path method* (CPM). Several articles were published which presented the results of solving MRCPSPs with the use of local search algorithms [14], a random sampling approach [6], multi-pass heuristics basing on priority rules [22], and *constraint programing* (CP), [25].

Along with the development of computer technology and the adaptation of ever newer optimisation techniques, metaheuristic methods were more and more often used for solving scheduling problems. Their advantage over the heuristic methods (the prefix *meta* means *next level/over* in ancient Greek) is based on their greater versatility – it is easier to adapt them to specific cases. This process often requires extensive knowledge and long-term tests.

Although use of the metaheuristic algorithms does not guarantee finding the optimal result (just like in the case of heuristics), it does, however, enable a significant reduction of computational time. This fact is especially important while solving complex problems, such as practical problems in the field of construction [9, 30].

Among the approaches for solving MRCPSPs with the use of metaheuristics, several algorithms were proposed: *genetic algorithms* (GA) [1, 7, 23, 24, 28, 40]; *simulated annealing* (SA) [12, 33]; *tabu search* (TS) [19, 27, 30, 31]; *particle swarm optimisation* (PSO) [10, 13, 42]; *ant colony optimisation* (ACO) [39], or hybrid algorithms [29].

Regarding the structure of the models that were built in order to simulate real-life projects, most of the articles listed above contain examples with 10-100 activities, 1-5 execution modes for each activity, and 1-10 types of both renewable and non-renewable resources. The project makespan or total duration minimisation is the most commonly chosen optimisation criterion (basic MRCPSP). In very few papers, authors are using other criteria such as cost, contractual penalties, or indicators of the economic efficiency of the investment such as NPV [13, 20]. On rare occasions, authors also use multi-stage or multi-pass schedule optimisation models.

It is worth mentioning that the vast majority of the authors cited above do not test their algorithms on construction projects. In the case of most articles published after 1997, the authors verify their algorithms with the use of a PSLIB dataset [15]. The dataset was generated with the project generator ProGen which is a generator of RCPS problems developed by Kolisch et al. [16]. PSLIB can be used to check the general parameters and the efficiency of the scheduling optimisation methods; however, the randomly generated set of problems is not representative of the problems encountered in the field of construction management.

5. Conclusions

MRCPSP is a field of science which originates from operational research – it is still being developed and transferred to other branches, such as logistics, manufacturing, and construction. Researchers are constantly proposing new models in order to simulate the specific conditions of construction projects. However, the few acceptable solutions proposed so far require the constant support of computer programming experts – this significantly impedes their widespread use in the construction industry.

There is no commercial software currently on the market to support construction project management that enables solving instances of the MRCPSP (not to mention its more sophisticated variants like the above-mentioned MRC-TCT).

Development of the models – which would represent the specifics of the construction projects and at the same time allow for their simple implementation in the practice of

scheduling – would fill the currently existing knowledge gap. These models would be able to significantly expand the possibilities for the optimisation of the schedules during the planning phase of construction projects.

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