Computers & Industrial Engineering 91 (2016) 139–153

Contents lists available at ScienceDirect

Computers & Industrial Engineering

journal homepage: www.elsevier.com/locate/caie

Payment models and net present value optimization for resource-constrained project scheduling

Pieter Leyman[a,1], Mario Vanhoucke[a,b,c,*]

[a] Faculty of Economics and Business Administration, Ghent University, Tweekerkenstraat 2, 9000 Ghent, Belgium
[b] Vlerick Business School, Reep 1, 9000 Ghent, Belgium
[c] UCL School of Management, University College London, Gower Street, London WC1E6BT, United Kingdom

ARTICLE INFO

Article history:
Received 1 June 2015
Received in revised form 7 October 2015
Accepted 10 November 2015
Available online 19 November 2015

Keywords:
Net present value
Payment models
Resource-constrained project scheduling
Metaheuristics

ABSTRACT

This manuscript focuses on the single- and multi-mode resource-constrained project scheduling problem with discounted cash flows (RCPSPDC and MRCPSPDC) and three payment models. The contribution of the paper is twofold. First, we extend a new scheduling technique, which moves activities in order to improve the project net present value. This more general version is applicable to multiple problem formulations and provides an overarching framework in which these models can be implemented. The changes in activity finish times take other activities and the possible changes in the finish times of these other activities into account, by forming a set of activities which is subsequently moved in time. The scheduling technique is implemented within a genetic algorithm metaheuristic and employs two penalty functions, one for deadline feasibility and one for non-renewable resource feasibility. Second, we test the proposed approach on several datasets from literature and illustrate the added value of each part of the algorithm. The influence of data parameters on the project net present value is highlighted. The detailed results provided in this paper can be used as future benchmarks for each of the six models discussed.

1. Introduction

Over the past decades the resource-constrained project scheduling problem (RCPSP) has been extensively discussed in literature (Herroelen, De Reyck, & Demeulemeester, 1998; Kolisch & Hartmann, 2006). Whereas the RCPSP focusses on minimizing the total project duration, several alternative objectives exist (Hartmann & Briskorn, 2010). An important distinction to be made between the existing scheduling objectives is whether the objective is regular or not. Regular objectives such as project duration minimization are non decreasing functions of activity finish times. This does not hold, however, for non-regular objectives such as the maximization of project net present value (NPV) and the minimization of resource idle time.

In this paper, we focus on the maximization of the project NPV and discuss the RCPSP with discounted cash flows (RCPSPDC) and its multi-mode variant the multi-mode resource-constrained project scheduling problem with discounted cash flows (MRCPSPDC). Furthermore, we apply three payment models to these two problem formulations. The three payment models discussed are payments at activities' completion times (PAC), progress payments (PP) and payments at event occurrences (PEO). These payment models determine the timing and amounts of cash inflows received and are based on different assumptions. Cash outflows are assumed to occur upon activity finish time for all models. The PAC model assumes cash inflows are received upon activity completion. This in turn implies a net cash flow can be calculated for each activity. In the PP and PEO models however, cash inflows occur at regular or irregular times throughout the project duration and are based on the project progress up until the payment time.

The problems discussed are relevant from a practical point of view since several possibilities exist for the receipt of cash flows during the project runtime. The manner in which these cash flows are received is however often beyond the control of the party responsible for executing the project. This highlights the need to analyze the effect of different payment models on the project schedule and its resulting NPV. Furthermore, individual activities may be executable in different modes, i.e. with different combinations of activity duration and resource demand. This way, additional flexibilities exist for the project schedule, which however also increase the problem complexity (Kolisch & Drexl, 1997) and

* Corresponding author at: Faculty of Economics and Business Administration, Ghent University, Tweekerkenstraat 2, 9000 Ghent, Belgium. Tel.: +32 92643569; fax: +32 92644286.

E-mail addresses: pieter.leyman@ugent.be (P. Leyman), mario.vanhoucke@ugent.be, mario.vanhoucke@vlerick.com, m.vanhoucke@ucl.ac.uk (M. Vanhoucke).

[1] Tel.: +32 92648981; fax: +32 92644286.

http://dx.doi.org/10.1016/j.cie.2015.11.008
0360-8352/

as such require more complex algorithms to properly solve the problem.

The remainder of this paper is organized as follows. In Section 2 we give an overview of the existing literature and Section 3 discusses the single- and multi-mode RCPSPDC along with the investigated payment models. In Section 4 we go into detail about our proposed scheduling approach, as part of the metaheuristic presented in Section 5. The results of our computational experiments are discussed in Section 6. Finally, in Section 7 we formulate our conclusions.

2. Literature overview

In this section we provide a literature overview of the problems under consideration. We however only include research done after the general literature overview on NPV optimization of Herroelen, Van Dommelen, and Demeulemeester (1997). The distinction is made between the RCPSPDC (single-mode) and the MRCPSPDC (multi-mode).

2.1. Single-mode

A recent overview of the RCPSPDC with the PAC model is given by Leyman and Vanhoucke (2015). To the best of our knowledge only three papers exist which discuss other payment models for the RCPSPDC. The first is the paper of Sepil and Ortac (1997), in which the authors apply the PP model to the RCPSPDC and propose three different heuristic rules. These rules are applied in a single-pass greedy forward algorithm and determine the priority given to the different feasible activities at a specific time instance. The first heuristic gives priority to the activities with the highest NPV, whereas the second one applies a pairwise comparison of the NPV of all feasible activities. Finally, the third priority rule takes the slope of the activity profit curves into account. The other two papers of Möhring, Shulz, Stork, and Uetz (2001, 2003) tackle project scheduling problems with irregular objective functions and propose a uniform methodology for solving resource-constrained project scheduling problems based on minimum cuts. The focus of both papers lies on the mathematical problem formulation and a Lagrangian relaxation based approach to solve the problems to optimality. The authors conclude that the relaxed problem can be solved efficiently by minimum cut computations.

2.2. Multi-mode

Table 1 provides details of the research done for the MRCPSPDC since the literature overview of Herroelen et al. (1997).

- The objective of each paper can be found in the second (NPV) and third (Dur) column. Four papers combine NPV maximization and duration minimization in a single objective. The two asterisks (*) indicate that Mika, Waligóra, and Weglarz (2005) only work with positive cash flows for the NPV objective, whereas Kazemi and Tavakkoli-Moghaddam (2010) include a robustness measure as part of their duration minimization objective.
- Columns four to seven display the payment models used in the different research papers. These models constitute the PAC, PP, PEO and lump sum payment (LSP) variants.
- In columns eight to ten the required resource types are displayed. These resources include renewable resources (RR), non–renewable resources (NRR) and capital (Cap). The asterisks imply that a cost is assigned to these resource types and that these costs are included in the NPV objective.
- The final two columns show whether the authors additionally discuss a client-contractor trade-off (CC) and whether a bonus/penalty (B/P) structure is included with respect to the project deadline.

Based on Table 1 it can be concluded that a multitude of problem formulations exist in literature when discussing NPV optimization in a multi-mode context.

3. Problem description

In this section, we first discuss the mathematical models for both the single-mode and multi-mode RCPSPDC. We present the PAC model since this payment model is most commonly used, especially in the single-mode literature (Herroelen et al., 1997; Leyman & Vanhoucke, 2015; Vanhoucke, Demeulemeester, & Herroelen, 2001). Both mathematical models are subsequently extended to the PP and PEO payment models.

3.1. Payments at activities' completion times

We use the activity-on-the-node (AoN) representation for a network $G(N,A)$ with N the set of project activities or network nodes and A the set of precedence relations or network arcs. The activities are numbered from the start dummy 0 to the end dummy $n+1$. Each activity i ($i \in N = \{1,\ldots n\}$) has a duration d_i, a cash in- and outflow, respectively $c_{i,in}$ (>0) and $c_{i,out}$ (<0), and a RR demand r^{ρ}_{ik} of type k. Each RR of type k ($k \in R^{\rho} = \{1,\ldots,|R^{\rho}|\}$) has a constant availability of a^{ρ}_k throughout the project duration. A time-lag of zero is assumed for the precedence relations, and the project has a deadline δ_{n+1}. The finish time of each activity i is contained in the decision variables f_i.

Conceptually, the RCPSPDC with PAC can be formulated as follows:

$$\text{Maximize} \quad \sum_{i=1}^{n} (c_{i,in} + c_{i,out}) \cdot e^{-\alpha f_i} \tag{1}$$

Subject to :

$$f_i \leqslant f_j - d_j, \qquad \forall (i,j) \in A \tag{2}$$

$$\sum_{i \in S(t)} r^{\rho}_{ik} \leqslant a^{\rho}_k, \qquad \forall k \in R^{\rho}, \quad t = 1,\ldots,\delta_{n+1} \tag{3}$$

$$f_{n+1} \leqslant \delta_{n+1} \tag{4}$$

$$f_i \in int^{+} \qquad \forall i \in N \tag{5}$$

The objective function (1) maximizes the project NPV by discounting the cash in- and outflows to each activity's finish time. Hence the objective function can be simplified to $\sum_{i=1}^{n} c_{i,net} \cdot e^{-\alpha f_i}$, with $c_{i,net} = c_{i,in} + c_{i,out}$. Constraints (2) enforce the precedence constraints, whereas constraints (3) impose the renewable resource limits, with $S(t)$ the set of activities in progress at time t ($S(t) = \{i \in N : f_i - d_i \geqslant t \wedge f_i < t\}$). Constraint (4) makes sure the deadline is met, and finally constraints (5) state that the decision variables should be integers.

The RCPSPDC model from (1)–(5) can be extended to its multi–mode variant, based on the model of Van Peteghem and Vanhoucke (2014) for the multi-mode RCPSP (MRCPSP). Each activity now has a duration d_{im_i}, which differs depending on the mode m_i selected for each activity i out of a set M_i of different modes with $M_i = \{1,\ldots,|M_i|\}$. Furthermore, each mode has a unique RR demand $r^{\rho}_{im_ik}$ per resource type k and a NRR demand $r^{\nu}_{im_il}$ per resource type l. Each (N) RR of type k (l) has an availability of a^{ρ}_k (a^{ν}_l), with $k \in R^{\rho} = \{1,\ldots,|R^{\rho}|\}$ ($l \in R^{\nu} = \{1,\ldots,|R^{\nu}|\}$). Constraints (2) are adjusted to (6) and (3) to (7) to include the different modes.