



Discrete Optimization

Solving the Weighted Capacitated Planned Maintenance Problem and its variants



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ABSTRACT

This paper introduces, analyzes, and solves the Weighted Capacitated Planned Maintenance Problem (WCPMP) and its practically relevant variants. The problem pursues the finding of a maintenance schedule that incurs minimum total fixed and variable cost. Each executed maintenance activity guarantees the operability of the respective component for an interval of predetermined length. Moreover, a feasible schedule has to obey period-dependent predetermined time limitations for the scheduled maintenance activities. After providing a literature classification of the WCPMP and proving that the unweighted CPMP is strongly \mathcal{NP} -hard, the complexity status of further problem variants is established. For instance, a solution procedure is proposed for the WCPMP that guarantees an optimal solution in strongly-polynomial time if the number of maintenance activities is a constant. Moreover, the algorithm becomes pseudo-polynomial if the number of periods is a constant. In order to deal with strongly \mathcal{NP} -hard variants, a multi-state Tabu Search approach is proposed. Its efficiency is evaluated in a computational study.

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1. Introduction

By increasing the reliability of a production system through the reduction of downtimes, stoppages, breakdowns, and failures, the scheduling of maintenance activities may improve its productivity, efficiency, and quality. However, since these maintenance activities block scarce resources that are needed for the production process, their usage has to be limited. Depending on whether a maintenance activity is carried out after the occurrence of a failure or not, *ex post* (i.e., corrective maintenance) is distinguished from *ex ante* (i.e., planned maintenance). The present paper focuses on planned maintenance. For this purpose, the *Weighted Capacitated Planned Maintenance Problem* (WCPMP) is introduced and analyzed. By assuming activity-depending coverages of each executed maintenance activity, the WCPMP seeks to find a feasible maintenance plan that minimizes the total cost of maintenance for a planning horizon with a predetermined number of periods. The coverage of an executed maintenance activity defines the maximum number of succeeding periods for which operability is usually guaranteed with a high probability. Despite this deterministic assumption, the approach can be also applied to reschedule the maintenance activities in case of unexpected failures. Such a maintenance activity may be associated with repair, overhaul, replacement, inspection,

cleaning, calibration or lubrication. The cost and time consumption of a scheduled maintenance activity are taken into account while the total available maintenance time per period is limited. The WCPMP distinguishes between fixed and variable cost. Fixed maintenance cost is period dependent and arises if at least one maintenance activity is scheduled. This applies, for instance, to administrative costs or in case of using external specialized maintenance personnel or machinery resources of third parties whose allocation costs are frequently independent on the number of executed maintenance activities in the respective period. In contrast to this, variable costs depend on the scheduled maintenance activities, such as, for instance, costs for deployed personnel and material resources. The WCPMP pursues the finding of a feasible maintenance schedule with minimum total fixed and variable cost such that every period is covered by some scheduled maintenance activity and the period dependent maximum available maintenance time is never exceeded.

The WCPMP has many real-world applications. Whenever processes are considered that, due to costly downtimes or safety restrictions, require a high reliability, the application of this deterministic approach is reasonable. For instance, such applications can be found in the automotive industry where high service level agreements have to be fulfilled (Boysen, Emde, Hoeck, & Kauderer, 2015). The definition of deterministic coverages due to safety restrictions are adequate for maintenance planning in the airline industry. Here, certain inspections must be carried out (Gopalan, 2014) or critical security components are replaced whenever a

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maximum flying hour limit is reached (Knotts, 1999). A similar restriction can be found in locomotive maintenance, where a maximum travel distance requires a visit to a fuel station or a maintenance base (Vaidyanathan, Ahuja, & Orlin, 2008). If fixed cost significantly exceeds variable cost, the WCPMP relaxes to the *Capacitated Planned Maintenance Problem* (CPMP) (Kuschel, 2017) by setting uniform fixed cost and zero variable cost. This frequently applies to the process industry where downtimes are extremely expensive while maintenance activities can only be carried out in between batches (Schwindt & Trautmann, 2000). The technical reason for this is that the production system is a closed system where the chemical reactions cannot be preempted. If the maximum available maintenance time is not a bottleneck, the WCPMP relaxes to the *Weighted Uncapacitated Planned Maintenance Problem* (WUPMP) that is introduced in Kuschel and Bock (2016) and Kuschel (2017).

There are also real-world applications that require stochastic maintenance approaches. However, such approaches usually presuppose the reliable knowledge of detailed time-to-failure distributions of installed components/devices. The definition of such distributions requires the collection or measure of detailed degradation data (Lu & Meeker, 1993), which might not always be easily available or its measurement is costly (e.g., if maintenance is introduced as a novelty, data is withheld by component manufacturers or is difficult to convert to the installed process). In these cases, the WCPMP can provide a valuable alternative to existing stochastic maintenance approaches since its application requires only a reasonable estimation of the number of succeeding periods for which operability is usually guaranteed with a high probability after an executed maintenance activity, i.e., a reliable estimation of the corresponding non-failure fractile. Specifically, this lower bound of periods can be derived very pragmatically by using either expert knowledge or by simplifying the stochastic process if we use bounds on the coverages, guaranteed values, or introduce a tolerance in which a failure is acceptable.

Several aspects of the WCPMP are discussed in the literature that mostly cover periodic maintenance, periodic maintenance inspection or combine maintenance with machine scheduling. Compared to these approaches, the WCPMP allows for a flexible scheduling of maintenance activities and a detailed capacity allocation per period. Anily, Glass, and Hassin (1998), Grigoriev, van de Klundert, and Spieksma (2006) and more recently Todosijević, Benmansour, Hanafia, Mladenović, and Artiba (2016) consider a periodic maintenance problem that minimizes linearly increasing costs between two maintenance activities. The maintenance plan consists of a repeating sequence of minimum length that maintains at most one machine per period. Barlow, Hunter, and Proschan (1963) consider the inspection of a stochastically degrading machine and determine the length of an inspection interval such that a single machine is inspected periodically. They pursue the minimization of the inspection cost and the costs that arise from the time between failure and detection. Furthermore, Vaurio (1995) consider a single machine where maintenance is carried out either periodically or due to a failure and determine the interval lengths of maintenance and inspection. The authors pursue the minimization of inspection and maintenance costs. There are also approaches in the literature that integrate maintenance activities into machine scheduling (Bock, Briskorn, & Horbach, 2012). Adiri, Bruno, and Rinnooy Kan (1989) consider a single machine with allowed job preemption where a breakdown can occur randomly. In Zammori, Braglia, and Castellano (2014), a single machine problem with sequence dependent setup times, random breakdowns, and planned maintenance intervals is considered. The authors pursue the minimization of total earliness and tardiness penalties. Maintenance approaches are surveyed in Wang (2002), Ma, Chu, and Zuo (2010), and more recently in Beichelt and Tittmann (2012).

The remainder of the paper is organized as follows: We mathematically introduce the WCPMP in Section 2. In Section 3, the computational complexity status of the WCPMP and some of its problem variants is established. In order to tackle very complex instances, we propose a Tabu Search approach in Section 4. Computational results are presented in Section 4.5.

2. Mathematical model

We define the parameters of the WCPMP as follows:

n : Number of maintenance activities (index i).

T : Number of periods in the planning horizon (index t).

π_i : Coverage of maintenance activity i , i.e., the maintenance activity i has to be executed every π_i periods. For simplicity, we assume that all maintenance activities are scheduled in the periods $t = 0$ and $t = T + 1$. Furthermore, it holds that $\pi_i \leq \pi_{i+1} \forall i$ and $\pi_i \leq T \forall i$. Instances of the CPMP and the WUPMP are trivially solvable if there exists a maintenance activity i with $\pi_i = 1$. In case of the more general WCPMP, such instances are solvable by the Generalized Assignment Problem. In the case of the aforementioned CPMP and WUPMP, we avoid trivially solvable cases by assuming $\pi_i \geq 2 \forall i$.

r_i : Time units required to execute the maintenance activity i . We define the parameters $r^{max} = \max_{i=1, \dots, n} r_i$ and $r^{sum} = \sum_{i=1}^n r_i$.

\bar{r}_t : Maintenance capacity of the period t . We introduce $\bar{r}^{max} = \max_{t=1, \dots, T} \bar{r}_t$ and $\bar{r}^{min} = \min_{t=1, \dots, T} \bar{r}_t$. Moreover, we assume that $r^{max} \leq \bar{r}^{max} \leq r^{sum}$ and $\bar{r}_t = 0$ if $\bar{r}_t < \min_{i=1, \dots, n} r_i$.

f_t : Fixed cost of executing at least one maintenance activity in period t .

$c_{i,t}$: Variable cost of executing the maintenance activity i in period t .

The following variables define a solution of the WCPMP:

y_t : Binary variable indicating that at least one maintenance activity is executed in period t (i.e., period t is open).

$x_{i,t}$: Binary variable that schedules the execution of a maintenance activity i in period t .

The objective function and constraints of the WCPMP are stated as:

$$\min \sum_{t=1}^T f_t \cdot y_t + \sum_{i=1}^n \sum_{t=1}^T c_{i,t} \cdot x_{i,t} \quad \text{subject to} \quad (1)$$

$$\sum_{\tau=t}^{t+\pi_i-1} x_{i,\tau} \geq 1 \quad \forall i = 1, \dots, n; t = 1, \dots, T - \pi_i + 1 \quad (2)$$

$$\sum_{i=1}^n r_i \cdot x_{i,t} \leq \bar{r}_t \cdot y_t \quad \forall t = 1, \dots, T \quad (3)$$

$$x_{i,t} \in \{0, 1\} \quad \forall i = 1, \dots, n; t = 1, \dots, T \quad (4)$$

$$y_t \in \{0, 1\} \quad \forall t = 1, \dots, T \quad (5)$$

The model seeks the finding of a maintenance schedule (x, y) with minimum total maintenance cost. Constraint (2) ensures the execution of a maintenance activity i every π_i periods. Constraint (3) defines the limitation of the available maintenance time and opens a period t ($y_t = 1$) if at least one maintenance activity is executed ($x_{i,t} = 1$). It is noteworthy to mention that adding the valid inequality $x_{i,t} \leq y_t \forall i; t$ tightens the LP relaxation, which then provides better lower bounds. Two previously mentioned special cases are the WUPMP ($\bar{r}_t = r^{sum} \forall t$) and the CPMP ($f_t = 1 \forall t$ and $c_{i,t} = 0 \forall i; t$).

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