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The energy scheduling problem: Industrial case-study and constraint propagation techniques

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ABSTRACT

This paper deals with production scheduling involving energy constraints, typically electrical energy. We start by an industrial case-study for which we propose a two-step integer/constraint programming method. From the industrial problem we derive a generic problem, the Energy Scheduling Problem (EnSP). We propose an extension of specific resource constraint propagation techniques to efficiently prune the search space for EnSP solving. We also present a branching scheme to solve the problem via tree search. Finally, computational results are provided.

1. Introduction

Context of the study: Since the last two decades, hard combinatorial problems, mainly in scheduling, have been the target of many approaches combining Operations Research and Artificial Intelligence techniques (van Hoeve). These approaches are generally focused on constraint satisfaction as a general paradigm for representing and solving efficiently such problems (Salido et al., 2008). At the heart of these approaches, a panel of consistency enforcing techniques is used to dramatically prune the search space. Therefore, propagation techniques dedicated to resource and time constrained scheduling problems, viewed as special instances of *constraint satisfaction problems* (*CSPs*), have been developed to speed up the search for a feasible schedule or to detect early an inconsistency. For instance the energetic reasoning (Erschler and Lopez, 1990), the cornerstone of the present study, has enabled the joint integration of both resource and time constraints in order to prevent the combinatorics of solving conflicts between activities in competition for limited resources.

Furthermore, it is still of interest to search for propagating novel types of constraints according to real-world problems. The new environmental constraints, but also the increase of the energy cost, should prompt us to consider as a crucial and promising issue to look into the problems of emissions, wastes, and power consumption optimization in production scheduling (Subai et al., 2006). Real-time (processor) scheduling theory has often addressed energy constraints. Indeed, energy consumption management is a critical issue in computer systems, networks and embedded systems where many (on-line) algorithmic problems are raised and well studied (Irani and Pruhs, 2005). However, complexity is a major difficulty for the integration of energy constraints to production scheduling and the literature on the subject is rather sparse. For example, production scheduling for steel manufacturing has been studied, but few papers focus on energy cost (Nolde and Morari, 2010). This generally leads to the development of heuristics. For example, Boukas et al. (1990) propose a hierarchical approach for scheduling a steel plant subject to a global limitation on the power supplied to the furnaces. Harjunkoski and Grossmann (1990) use a decomposition approach to solve a steel manufacturing scheduling problem with multiple products. Finally, to the best of our knowledge, particular studies focused on constraint propagation techniques for energy considerations have been unexplored.

Problem statement: As we will see later, the production problem under study is defined as a new problem called the energy scheduling problem (EnSP). The EnSP is a generalization of the cumulative scheduling problem (CuSP) itself an extension of the parallel machine scheduling problem (PMSP). In a PMSP, a task j has to be processed on one machine among a set of m machines. The CuSP is an extension of the PMSP where each task needs a subset $k < m (k \neq 1)$ of machines. Furthermore, the industrial problem we study in this paper involves furnaces that can be modeled by parallel machines. Parallel machine scheduling has been widely studied (Cheng and Sin, 1990), especially because

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it appears as a relaxation of more complex shop or project scheduling problems, like the hybrid flow shop scheduling problem or the resource-constrained project scheduling problem. Several methods have been proposed to solve this problem. In Chen and Powell (1999), a column generation strategy is proposed. Pearn et al. (2007) propose a linear program and an efficient heuristic for large-size instances for the resolution of priority constraints and family setup times problem. Salem et al. (2000) solve the problem with a tree search method. Néron et al. (2008) compare two different branching schemes and several tree search strategies for the problem with heads and tails for makespan minimization. In Baptiste et al. (2000), a constraint programming-based approach is proposed to minimize the weighted number of late jobs. In Sadykov and Wolsey (2006), a hybrid Integer/Constraint Programming approach is proposed to solve a minimum-cost assignment problem. Among the variants presented in the latter, the most effective strategy is to combine a tight and compact, but approximate, mixed integer linear programming (MILP) formulation with a global constraint testing single machine feasibility. Many variants or extensions of the CuSP have been considered, for which feasibility tests and adjustment rules have been issued, based for example on the energetic reasoning (Erschler and Lopez, 1990).

Paper objectives and organization: The objective of this paper is twofold. First, we present in Section 2 an industrial case-study involving energy constraints and objectives linked to electric power consumption, and a two-step constraint programming and mixed-integer linear programming framework to solve it, as well as a first set of computational experiments. Second, in Section 3, we focus on the energy part of the industrial problem, issuing a generic problem, the Energy Scheduling Problem (EnSP). To enhance the previous approach, we propose a formal description for the propagation of energy constraints based on an extension of the energetic reasoning. In Section 4, we present dominance rules and practical assumptions in order to reduce the search space, a branching scheme to solve the problem via tree search, as well as computational results. Section 5 highlights the conclusions of the paper and proposes some future research directions.

2. A two-step approach for the industrial problem

In this section, we present an industrial case-study where energy constraints have a great importance in scheduling. A two-step approach was developed to solve the problem.

2.1. Industrial case-study

The addressed problem comes from a pipe-manufacturing plant. The plant is divided into three main departments: foundry, drawing mill, and pipe-tubing. In these departments, melting and heating processes use a huge quantity of energy: electricity, natural gas, and steam. Electricity expenses account for more than half the annual energy costs for the plant. The electricity bill is based on the cost of the energy consumed and on penalties for power overrun, in reference to a subscribed maximal power.

The study focuses on the foundry where metal is melted in induction furnaces and then cast in individual billets. Non-regular power consumption peaks occur and cause high electricity bills. To cope with this problem, equipments such as power cutters and relays can be installed at small cost to avoid peaks, but they cause production shutdowns that are not desired. Consequently, production scheduling needs to consider energy consumption as a central element in order to maintain the production at the current level.

The foundry has five similar lines of production to perform the melting jobs. From a scheduling view-point, this facility can easily be recognized as a parallel machine problem. However, a particularity of the problem is that melting jobs have variable durations that depend on the power given to the furnace, constrained in a range $[P_{\min}, P_{\max}]$ by physical and operational considerations. Melting of job i ends when an amount E_i of energy has been supplied. Production scheduling determines the assignment and sequencing of the jobs on the furnaces, and the starting/finishing dates of these jobs that allow to supply the required energy while respecting the power limits and the time windows. The goal is to minimize the energy bill, with energy and overrun costs evaluated periodically, every 15 min.

We proposed a two-step Constraint Programming / Mixed Integer Linear Programming approach to solve this problem, considering additional constraints that may influence the energy consumption, as human resource availability for loading and unloading the furnaces. This approach is described in what follows. Further details can be found in Haït and Artigues (to appear).

2.2. Overview of the solving method

As mentioned in Section 2.1, we want to schedule melting jobs whose duration depends on the power given to the furnace. Actually, a job is composed of three sequential parts: loading, heating, and unloading (see Fig. 1). The durations of loading and unloading are known (*dl* and *du*), but heating duration depends on the following conditions:

- melting duration depends on the power given to the furnace, in a range $[P_{\min}, P_{\max}]$;
- when melting is complete, the temperature must be hold in the furnace until an operator is ready to unload it.

The goal is to minimize the cost of the schedule, depending on the energy consumed and on penalties when the overall power in the foundry exceeds a given subscribed value.

Various mixed integer linear models have been developed for this problem. First, a discrete time model has been proposed (Trépanier et al., 2005), but the huge number of binary variables made it impossible to tackle realistic problems. A continuous time model allowed the reduction of the number of binary variables (Haït et al., 2007), but the solving time was still very long. Finally, a decomposition of the problem led to much more acceptable computation times (Haït and Artigues, 2009; to appear). The main principle of the two-step approach is shown in Fig. 2.

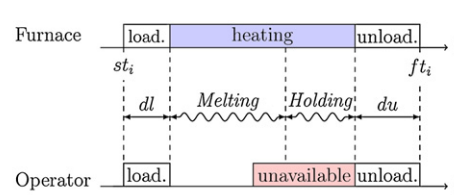

Fig. 1. Job description and corresponding operator's tasks.

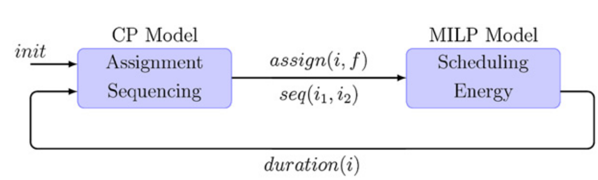

Fig. 2. Two-step approach.