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Project scheduling under partially renewable resources and resource consumption during setup operations ☆

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ABSTRACT

There has been an increasing pressure on manufacturing industries to reduce energy consumption. In this study, we propose a new variant of RCPSP called RCPSP/πRC, which can deal with realistic energy constraints such as power restriction during peak hours, contract demand, and energy consumption during setup operations. First, we present an integer programming (IP) model and a constraint programming (CP) model of the RCPSP/πRC. Next, we present a heuristic mode restriction method called a mask calculation algorithm to achieve efficient searching by restricting selectable modes. Finally, through computational experiments, we evaluate the proposed methods and show their effectiveness.

1. Introduction

In recent years, global warming has become an international concern as it is believed to be responsible for the increase in carbon dioxide emissions worldwide. Additionally, due to the growth of energy demand in developing countries, tightness and destabilization of medium- to long-term supply of fossil fuel is expected. Consequently, energy-saving problems have begun attracting increasing interest. Manufacturing industries are endeavoring energy saving by introducing efficient production machinery and optimizing operation schedules. However, the environment surrounding manufacturing industries has become considerably harsh; it is expected that numerous innovative technologies will be introduced in the future (Dietmair & Verl, 2009; Fang & Lin, 2013). In this study, we discuss a production scheduling problem, where energy consumption by production equipment is taken into consideration in detail.

With regard to electric power, the energy consumption of industries may be limited to not exceed beyond a specified value, which is called a *contract demand*. A contract demand is measured in kilowatts, which is an average value over a certain period of time. Moreover, depending on the type of production machinery, the setup operation consumes considerable energy. Thus, these energy constraints must be dealt with in production scheduling problems. A large number of researches have been conducted on the resource-constrained project scheduling problem (RCPSP) within a framework containing numerous scheduling problems in manufacturing industries (Brucker, Drexl, Mohring, Neumann, & Pesch, 1999; Brucker & Knust, 2011). In the traditional RCPSP, resources are classified into two types: renewable and non-renewable. While renewable resources are available in a constant amount in each time period, the availability of non-renewable resources is limited for the scheduling horizon. Time period of the contract demand may be different from the time period of the scheduling problem. The traditional RCPSP has difficulties representing resource constraints with different time scales from the scheduling problem and cannot represent energy consumption during setup operations. The first objective of this study is to propose a new variant of the RCPSP in the area of machine scheduling problems that is able to overcome the above mentioned constraints.

The RCPSP can be extended in various ways to represent actual problems (Hartmann & Briskorn, 2010; Das, Baki, & Li, 2009; Trojet, H'Mida, & Lopez, 2011; Ranjbar, Khalilzadeh, Kianfar, & Etminani, 2012). The multi mode RCPSP (MRCPSP) introduces the concept of modes and assumes that an activity has a different duration and different resource requirements depending on the selected mode. The standard RCPSP assumes one project. In practice,

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multiple projects have to be scheduled simultaneously. This is important if two or more projects that may be processed in parallel share at least one resource. Hartmann and Briskorn (2010) provide a good survey of variants and extensions.

There are several researches on the RCPSP that considers setup operations. Drexl, Nissen, Patterson, and Salewski (2000) introduce a concept of setup time into the MRCPSP by including a time period between two consecutive activities depending on their modes. Nonobe and Ibaraki (2002) consider setup time and resource consumption during setup operations by inserting a setup operation between two consecutive activities that are processed under different modes.

The traditional RCPSP can deal with only renewable and non-renewable resources. However, Böttcher, Drexl, Kolisch, and Salewski (1999) propose the concept of partially renewable resources by generalizing renewable and non-renewable resources. The RCPSP under partially renewable resources (RCPSP/π) is applicable to diverse applications because it can constrain resource consumptions over a set of time periods. Smith, Nauss, Subramanian, and Beck (2004) apply the RCPSP/π to a staff scheduling problem. Further, Bartsch, Drexl, and Kröger (2006) apply the RCPSP/π to a scheduling problem of professional soccer leagues in Europe.

By using these concepts, we can represent energy consumption during setup operations and energy constraints over a set of time periods. In this study, we propose a RCPSP under partially renewable resources and resource consumption during setup operations (RCPSP/πRC).

The second objective of this study is to propose an effective method for the RCPSP/πRC. Blazewicz, Lenstra, and Kan (1983) show that the RCPSP is $\mathcal{NP}$-hard(Garey & Johnson, 1979) in the strong sense. There are various researches on effective searching. Hartmann (1998) applies a genetic algorithm to the RCPSP. Merkle, Middendorf, and Schemeck (2002) propose an application of ant colony optimization. Bouleimen and Lecocq (2003) apply simulated annealing to the MRCPSP. Nonobe and Ibaraki (2002) apply tabu search to the RCPSP with setup operations. Alvarez-Valdes, Crespo, Tamarit, and Villa (2008) propose a scatter search and heuristic method by employing the aggressive greedy randomized adaptive search procedure and a path relinking for the RCPSP/π. Zhu, Bard, and Yu (2006) propose a branch and bound approach for the MRCPSP/π.

Constraint programming (CP) is a relatively new technique that combines local consistency algorithms with search. CP is based primarily on computer science fundamentals, such as logic programming and graph theory, in contrast to mathematical programming (MP), which is based on numerical linear algebra. A CP model is expressed in a declarative fashion, using decision variables, constraints, and objectives that must be minimized or maximized, just as in MP. A CP model supports logical constraints as well as a full range of arithmetic expressions. A CP model can also use specialized constraints, such as the "all-different" constraint that can accelerate searches. A CP engine makes decisions on variables and values and, after each decision, performs a set of logical inferences to reduce the available options for the remaining variables' domains. The process of eliminating inconsistent values from the domain of the variables is called *propagation*. CP is an exact optimization method as well as MP; a CP engine proves optimality by showing that no better solution than the current one can be found. However it is an exponential search method; one has to put a time limit for practical purposes. A number of researches have reported that a reduction of computation time is achieved by using CP. Demassey, Artigues, and Michelon (2005) propose a hybrid method between CP and integer programming (IP) to compute the lower bound for the RCPSP. Delgado, Jensen, Janstrup, Rose, and Andersen (2012) apply CP to the Container Stowage Problem for Below Deck Locations. Zeng and Mizuno (2012) discuss the separation in two-period double round robin tournaments with minimum breaks using CP. Developing a CP model using appropriate notations is important in order to benefit from the power of CP. In this study, we present a CP model of the RCPSP/πRC. An IP model of the RCPSP/πRC is also presented to help readers, who are familiar with MP, understanding the RCPSP/πRC.

In the MRCPSP, as the number of modes increases, optimization time grows drastically; therefore, eliminating redundant modes or selecting an appropriate mode is effective. Lova, Tormos, and Barber (2006) propose a heuristic method based on priority rules and mode selection rules. Coelho and Vanhoucke (2011) propose a heuristic scheduling method after a feasible mode is selected by using a satisfiability problem (SAT) solver. In this study, we propose a mode restriction algorithm using time and resource consumption for setup operations, called a *mask calculation algorithm*, for the RCPSP/πRC, and evaluate the mask calculation algorithm through computational experiments.

The remainder of this study is organized in the following manner. Section 2 formulates the RCPSP/πRC as both integer and constraint programs. Section 3 explains the mask calculation algorithm. Section 4 evaluates the proposed formulation and the mask calculation algorithm through empirical evaluation. Finally, Section 5 provides the conclusion.

2. Formulation

2.1. Notations

Let Q be the set of projects and J be the set of activities. The set of activities associated with a project $q \in Q$ is denoted by $J_q \subseteq J$. Let $\prec \subseteq J \times J$ be a precedence relation on the set of activities; then, an activity j_1 must be completed before j_2 begins if $j_1 \prec j_2$. The due date and completion time of a project q are denoted by $d_q \in T$ and $c_q \in T$, respectively, where $T = \{0, \ldots, |T|-1\}$ is the scheduling horizon. The set of modes is denoted by M.

Resources are consumed when activities are processed. The set of partially renewable resources is denoted by K. When partially renewable resources are utilized, a resource constraint is given over a set of time periods. Let Π_k be an index set associated with a resource $k \in K$, $P_{k,\pi} \in 2^T$ be a subset of time periods for $k \in K$ and $\pi \in \Pi_k$, and $R_{k,\pi} \in \mathbb{Z}^+$ be the capacity of resource k over the set of time periods $P_{k,\pi}$, where $\mathbb{Z}^+$ is a set of non-negative integers. Then, total consumption of resource k over set $P_{k,\pi}$ must not exceed $R_{k,\pi}$. Process time and resource consumption of an activity vary according to modes; the length of process time of activity j under mode m is denoted by $p_{jm} \in \mathbb{Z}^+$, and the amount of consumed resource k per time period for processing activity j under mode m is denoted by $r_{kjm} \in \mathbb{Z}^+$. Note that renewable and non-renewable resources are special cases of partially renewable resources: a renewable resource is represented by introducing a subset $P_{k,\pi} = \{t\}$ for each $t \in T$ and a non-renewable resource is represented by introducing a subset $P_{k,\pi} = T$.

Machines are also a kind of resources in the RCPSP. However, in this study, machines are distinguished from other resources and the set of machines is denoted by B. To represent resource consumption during setup operations, a setup operation is included after each activity. Suppose that two consecutive activities are processed by a machine under modes m_1 and m_2, respectively, then the setup operation requires $p_{m_1 m_2} \in \mathbb{Z}^+$ time periods and $r_{km_1 m_2} \in \mathbb{Z}^+$ units of the resource k. Because we consider a machine scheduling problem, each activity is processed by a machine, and each machine can process only one activity at one time period.