Algorithms for robust production scheduling with energy consumption limits

István Módos*, Přemysl Šucha, Zdeněk Hanzálek

Department of Control Engineering, Faculty of Electrical Engineering, Czech Technical University, Czech Republic
Czech Institute of Informatics, Robotics and Cybernetics, Czech Technical University, Czech Republic

ARTICLE INFO

Article history:
Received 8 March 2017
Received in revised form 9 June 2017
Accepted 8 August 2017
Available online 30 August 2017

Keywords:
Robust production scheduling
Energy consumption limits
Uncertainty scenarios
Maximum power demand

ABSTRACT

In this work, we consider a scheduling problem faced by production companies with large electricity consumption. Due to the contract with the electric utility, the production companies are obligated to comply with the total energy consumption limits in the specified time intervals (usually 15-min long); otherwise, the companies pay substantial penalty fees. Although it is possible to design production schedules that consider these limits as hard constraints, uncertainties occurring during the execution of the schedules are usually not taken into account. This may lead to situations in which the unexpected delays of the operations cause the violations of the energy consumption limits. Our goal is to design robust production schedules pro-actively guaranteeing that the energy consumption limits are not violated for the given set of uncertainty scenarios. We consider scheduling on one machine with release times of the operations and total tardiness as the objective function.

To tackle this problem, we first propose a pseudo-polynomial algorithm for finding the optimal robust schedule for the given permutation of the operations. This algorithm is then utilised in three different algorithms for finding the optimal permutation: two exact (Branch-and-Bound and logic-based Benders decomposition) and one heuristic algorithm (tabu search). All the algorithms were experimentally evaluated on random instances with different sizes of the uncertainty scenarios set. Using the tabu search algorithm, we are able to solve large instances within one minute.

1. Introduction

In the domain of scheduling energy-demanding production, it is no longer sufficient to consider only traditional aspects such as due dates, machine capacities, tardiness, and schedule length. To produce efficient schedules, the energy consumption of the operations has to be also considered (Merkert et al., 2015) since significant financial savings could be achieved if the utilisation of the energy is optimised. Although integration of the energy-awareness into production scheduling is getting more and more attention (Biel & Glock, 2016; Mansouri, Aktaş, & Besikci, 2016; Van Den Dooren, Sys, Toffolo, Wauters, & Vanden Berghe, 2016), there is still a gap between industrial needs and academic research (Plitsos, Repoussis, Mourtos, & Tarantilis, 2017).

One of the practical problems addressed in this work is uncertainty during production in relation to the energy consumption limits. Based on the contract with the electric utility, the companies are obligated to comply with the energy consumption limits in every 15 min intervals; otherwise, large penalty fees have to be paid. However, due to the unpredictability of the operation’s preparation time, it often happens that some of the operations are delayed and thus causing the violation of the contracted energy limits. To guarantee compliance with the energy limits, reactive policies are usually employed on the shop floor. However, using only reactive policies may lead to sub-optimal schedules or long downtimes if the schedules are not devised in a robust way (e.g. high and low energy-consuming operations are not alternating).

Therefore, we focus on constructing pro-active production schedules for one machine that guarantee compliance with the contracted energy consumption limits if the operations’ start times are delayed within a pre-determined range; we call this a Robust Scheduling with Energy Consumption Limits problem (RSECLP).

1.1. Motivation for robust scheduling with energy consumption limits

The motivation for our work comes from the manufacturing and production companies with significant electricity consumption. Specifically, we were motivated by a glass tempering process...
during which glass panels are heated to 620 °C in a furnace. In the considered scheduling problem, the furnace is a resource, and the heating of the glass panels represent the operations to be scheduled. Due to technological requirements, heating of the glass panels cannot be interrupted (i.e. preemption is not allowed). Although the production process also contains pre-processing and post-processing stages, we consider only scheduling of the heating stage because it is the most energy-demanding one. However, the pre-processing and the post-processing production stages are not completely ignored since they appear as release times and due dates of the operations, respectively. To ensure the smoothness of the production, it is reasonable to minimise the total tardiness.

According to the negotiated contract with the electric utility, the companies are obligated to keep their power demand below a contracted maximum power demand. Otherwise, the companies pay substantial penalty fees; in the Czech Republic, the penalty is regulated, and it is approximately 10 000 € per consumed MW over the maximum power demand. Energeticky regulacní úřad. The measurement of the demand is taken in every 15 min metering interval of a day, and it is measured as an average power demand during the corresponding metering interval. Since the consumed energy can be computed as a product of the average power demand and the length of the metering interval, an equivalent formulation is that in every metering interval the total energy consumption cannot exceed the maximum energy consumption limit. By considering a proper order of the energy-demanding operations or inserting short idle times, it is possible to design production schedules that do not violate these energy limits, e.g. see Fig. 1.

However, in reality, unexpected events can cause delays of the operations’ start times. In the glass production example, the responsible worker has to carefully put the glass panels on the furnace conveyor, mark the panels and set the furnace parameters before the glass panels are heated. This preparation process may take minutes, and due to various reasons (inexperienced seasonal workers, delays in the preceding production stages, etc.), it might happen that the heating of a glass panel starts later than expected. We call the delayed start time a realised start time, whereas the initial non-delayed start time is referred to as a baseline start time. The issue is that delaying an operation may cause an increase in the energy consumption in some metering interval above the energy limit if the energy demanding operations are started consecutively in the baseline schedule, e.g. see Fig. 2a. In such a situation, the company pays the penalty fee even though the baseline schedule (see Fig. 1) does not violate the energy limits. Therefore, to design robust baseline schedules, these uncertainties have to be considered so that the energy consumption limits are not violated and the penalty fees are avoided.

One possible approach to tackling these uncertainties is to employ reactive scheduling policies, i.e. when the total energy consumption approaches the energy limit, the remaining unfinished operations are delayed until the start of the next metering interval. For example, in Fig. 2b the start time of operation 4 is forcibly delayed by a worker responsible for monitoring the production process. However, relying only on the reactive policies may cause long downtimes in the production if the order of the operations is not chosen reasonably in a baseline schedule. A more viable approach is to combine the reactive policies with a pro-active scheduling, i.e. the baseline schedule is designed in such a way that the hazardous situations are avoided if the deviations of the operations are reasonably small. For example, if the order of the operations from Fig. 1 would be (3, 2, 1, 4), as illustrated in Fig. 3a, then even if operation 2 is delayed by 3 min the energy consumption limits are not violated (see Fig. 3b). However, longer production delays (e.g. furnace breakdown) are still handled by reactive policies or by a complete rescheduling.

1.2. Related work

The related work to the RSECLP can be categorised into two main groups: scheduling with energy constraints and robust scheduling.

The problem of maximum power demand was studied in Fang, Uhan, Zhao, and Sutherland (2013) and Bruzzone, Anghinolfi, Paolucci, and Tonelli (2012), although the models presented in these works do not consider 15-min intervals but rather complying with the maximum power demand at every time instant. Another related problem to the maximum energy consumption limits is the problem of electrical load tracking (Hadera, Harjunkoski, Sand, Grossmann, & Engell, 2015; Hait & Artigues, 2011, 2011; Nolde & Morari, 2010), where the objective is to minimise the absolute difference between the actual and pre-agreed energy consumption over all metering intervals w.r.t. penalty-free deviation range. Contrary to the RSECLP, both over-consumption and under-consumption of the energy are penalised in the load tracking problem.

Robust scheduling is a well-studied problem in the domain of resource constrained project scheduling (Herroelen, Demeulemeester, & Herroelen, 2007). The robustness is obtained either by a robust resource allocation or inserting time buffers between activities. In the domain of the resource constrained project scheduling, the closest problem to the RSECLP is presented in Policella, Cesta, Oddi, and Smith (2007). The goal of this work is to find a partial-ordering of the activities so that if the activities are arbitrarily delayed (w.r.t. to the ordering), the total demand of the resources in every time instant is below the respective capacities. The difference from our problem is that we limit the integral of the operations’ demands w.r.t. the intersection length of the operations with the metering intervals.

A particular interest for us is the modelling using uncertainty scenarios (Cherif, Artigues, & Billaut, 2016; Coban, Heching, Hooker, & Scheller-Wolf, 2016), which are used when the probability distribution of uncertain events is either not known or is uni-

---

Fig. 1. A baseline schedule of four operations (1, 2, 3, 4) on one machine which satisfies the energy consumption limits in every metering interval (1, 2, 3). The energy consumption limits are denoted by the dashed horizontal red lines. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
دریافت فوری متن کامل مقاله

امکان دانلود نسخه تمام متن مقالات انگلیسی
امکان دانلود نسخه ترجمه شده مقالات
پذیرش سفارش ترجمه تخصصی
امکان جستجو در آرشیو جامعی از صدها موضوع و هزاران مقاله
امکان دانلود رایگان ۲ صفحه اول هر مقاله
امکان پرداخت اینترنتی با کلیه کارت های عضو شتاب
دانلود فوری مقاله پس از پرداخت آنلاین
پشتیبانی کامل خرید با بهره مندی از سیستم هوشمند رهگیری سفارشات