Computers & Operations Research 54 (2015) 218–231

Contents lists available at ScienceDirect

Computers & Operations Research

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

Energy-oriented scheduling based on Evolutionary Algorithms

Markus Rager [a], Christian Gahm [b,*], Florian Denz [b]

[a] Faculty of Electrical Engineering & Computer Science, University of Applied Sciences Ravensburg-Weingarten, PO Box 1261, D-88241 Weingarten, Germany
[b] Chair of Business Administration, Production & Supply Chain Management, Augsburg University, D-86135 Augsburg, Germany

ARTICLE INFO

Available online 17 May 2014

Keywords:
Parallel machine scheduling
Energy efficiency
Resource leveling
Genetic Algorithm
Memetic Algorithm

ABSTRACT

Energy efficiency has become more and more critical for the success of manufacturing companies because of rising energy prices and increasing public perception of environmentally conscious operations. One way to increase energy efficiency in production is to explicitly consider energy consumption during short-term production planning. In many cases, final energy sources (FES) are not directly consumed by production resources and thus have to be transformed by conversion units into applied energy sources (AES), such as steam or pressure, so the relationship between AES and FES has to be considered. Therefore, we present an energy-oriented scheduling approach for a parallel machine environment. These parallel machines require production order and process time specific amounts for AES and the objective is to minimize the demand of FES. This minimization can be achieved by smoothing the cumulated demand of AES to avoid the frequent load alternations that are responsible for the inefficient operation of conversion units. Therefore, resource leveling is used as a surrogate objective for optimization. To solve the resource leveling problem for large problems, a Genetic Algorithm and two Memetic Algorithms are developed. The evaluation of the proposed Evolutionary Algorithms is based on small test instances and several real-world instances. These latter instances are based on an application case from the textile industry, and promising results concerning energy costs and carbon dioxide emissions are reported.

1. Introduction

An analysis of recent trends in manufacturing industries shows that energy efficiency is one of the most important challenges that companies face, which is due to the economic fact of rising energy costs (e.g., for electricity, natural gas, or fuel oil). Managing these costs is crucial – especially in energy-intensive industries such as chemicals, textiles, or food – for corporate success (e.g., [1–3]). An additional reason for manufacturing companies to address energy efficiency is the increased public perception of business operations' ecological impact (cf. [1–3]). With regard to the manufacturing of goods, environmentally conscious operations depend, on the one hand, on an efficient use of resources (e.g., energy or raw materials) and, on the other hand, on minimizing the environmental impact (e.g., carbon dioxide or greenhouse gas emissions in general) during the entire product life cycle. For these reasons, it is necessary to use energy in a more efficient way to stay (or become) competitive.

Energy use during production, and thus energy efficiency, can be influenced by the following two types of measures [4]: technological and organizational. Technological measures focus on efficiency improvements through technical innovations (e.g., new machines or the production process [2]). The main drawbacks of these technological measures are the high costs of development and/or investment. Here, we focus on the organizational measures used to improve energy efficiency, particularly on short-term production planning, i.e., energy-oriented scheduling.

Because (machine) scheduling is the final planning task regarding production processes within a hierarchical supply chain planning system (cf. [5]), the preceding planning tasks (e.g., master planning) determine the decision limits and restrictions (e.g., the available capacity) for energy-oriented scheduling. For that reason, the presented energy-oriented scheduling approach is subject to these limits and restrictions, as is the underlying production system. In terms of the production system, we investigate identical parallel machines, which for example can be found in the energy-intensive textile industry (cf. [4]). We further assume a given order portfolio consisting of production orders that have individual processing times and energy requirements and that have to be processed without interruptions (i.e., preemption is not allowed). Based on this order portfolio and a predetermined (fixed) planning horizon, the preceding planning task determines the number of

* Corresponding author. Tel.: +49 821 5984359; fax: +49 821 5984353.
E-mail addresses: ragerma@hs-weingarten.de (M. Rager), christian.gahm@wiwi.uni-augsburg.de (C. Gahm), florian.denz@wiwi.uni-augsburg.de (F. Denz).

http://dx.doi.org/10.1016/j.cor.2014.05.002
0305-0548/

parallel machines and ensures the feasibility of the temporal and energy conditions. Consequently, the basic scheduling task considered in this contribution is the allocation and sequencing of production orders on identical parallel machines within a fixed planning horizon.

The structure of the paper is as follows. To be able to schedule for energy efficiency, a detailed knowledge of the energy demand and supply characteristics in production environments is indispensable and is therefore analyzed in the following section. Afterward, the surrogate objective of resource leveling is introduced to achieve the desired energy efficiency, and a literature review concerning energy-oriented scheduling and resource leveling is presented. A binary program of the planning problem at hand is formulated in Section 3. The developed solution methods, a Genetic Algorithm and two Memetic Algorithms, are described in Section 4. An evaluation of these solution methods with small academic test instances and a real-world application case is presented in Section 5. The last section provides a brief conclusion and describes future research topics.

2. Energy-oriented scheduling

2.1. Energy demand and supply in production systems

To consider energy efficiency during scheduling in a suitable manner, an analysis regarding the characteristics of energy supply and the energy demand of a production system has to be carried out. This production-oriented analysis reveals two major cases for the provisioning of energy in production systems [4]. Either there is a direct use of final energy sources (FESs) in the production process (cf. case 1 in Fig. 1) or there is the need to convert FESs before their designated application in a production process (cf. case 2 in Fig. 1). An example of the former case is a production system (PS) consisting of machining production units (PUs) that are solely run by electricity. The latter case is accomplished by so-called "conversion units" (CUs). Their duty is to provide the necessary applied energy sources (AESs), such as steam or pressure, to run PUs (PU_1, …, PU_m). A CU centrally provides AESs for several PUs. This case usually occurs when thermal energy is needed in any form to run the production process. Therefore, fossil energy sources are generally burned in CUs centrally to provide heat, which, in turn, ensures the right process conditions needed in industrial chemical processes, for example.

In summary, the initial situation for all considerations in the article at hand is a production environment in which energy is provided centrally. In addition, the energy supply system is built in such a way that AES is produced on demand, i.e., there is no possibility for recirculation or the like.

The consideration of energy is challenging because – in contrast to traditional scheduling approaches – the impact of an allocation is not direct or obvious, and thus, an in-depth analysis of the conversion unit operation's behavior is necessary in the first step. The situation is even more complicated because the energy supply system (including the CU) is often separated from the production system in both a spatial and an organizational context. Because of that separation, there is no adequate information exchange and no coordination of both systems takes place in most cases. In consequence, the CU has to fulfill the cumulated and uncoordinated demand of AES (AESD) of all production units. This often leads to inefficient operation of the CU because the production system only considers the maximum energy supply from the CU as a restriction during scheduling, if it is considered at all. Therefore, scheduling for energy efficiency in production has to consider the cumulated AESD and the economic and ecological effects of this demand on the operation of the CU. This is an additional requirement apart from the traditional task of scheduling that leads to "energy-oriented scheduling".

In general, scheduling seeks an efficient allocation and sequencing of production orders to production units (here, one of the parallel machines) with regard to a certain performance measure (e.g., makespan, maximum tardiness, etc.). To be able to generate an energy-oriented schedule, a new point of view has to be introduced first; production orders have to be distinguished with regard to their AESD, and thus, each order is specified by an individual AESD profile. The demand can either be constant or can vary over time. In contrast to the former case, which is quite easy to model, the latter case requires a more sophisticated approach, which is why production orders are artificially divided up into operations whereby each operation has a certain constant AESD (cf. [4]). In return, the non-preemptive execution of a production order has to be assured by time lags of zero between its operations (i.e., the operations have to be linked by the no-wait constraint; cf. [6,7]). This modeling approach offers the possibility of accounting for the energy characteristics of any type of order (e.g., start-up

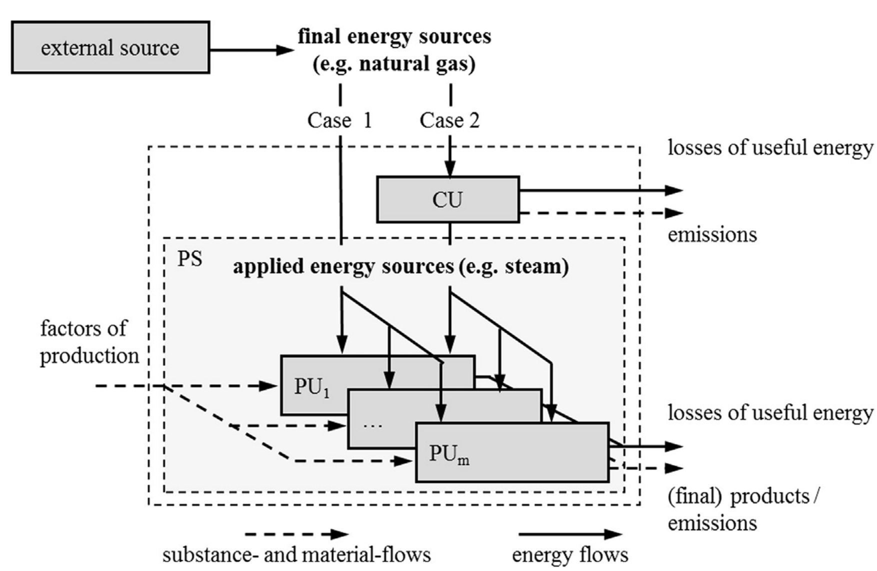

Fig. 1. Energy supply for production systems (following [4]).