Int. J. Production Economics 149 (2014) 164–171

Contents lists available at ScienceDirect

Int. J. Production Economics

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

Energy implications in a two-stage production system with controllable production rates

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ARTICLE INFO

Article history:
Received 14 April 2012
Accepted 24 June 2013
Available online 6 July 2013

Keywords:
Batch sizing
Variable production rate
Energy costs
Two-stage production system

ABSTRACT

Nowadays, it is an essential commitment for firms to reduce energy consumption and therewith energy costs, which frequently account for a large part of the manufacturing costs. This work analyzes a system where a single product is manufactured on a machine and delivered to the subsequent production stage in batch shipments. The production rate at each stage may be varied within given limits. Energy consumption at each stage is strictly related to the production rate set according to a given function that depends on the specific characteristics of the production process. Energy consumption is assumed to occur both during production and during the idle state of the machines. The aim of this work is to propose an analytical model of this system and to minimize the total costs of producing and storing the product, including energy costs. The results of the paper indicate that energy-related costs can be reduced significantly if energy consumption is considered in planning the production process.

1. Introduction

Reducing the use of energy in production is nowadays an important goal for many companies, as lower levels of energy consumption guarantee not only environmental benefits, but also consistent economic savings.

Different approaches can be adopted to reduce energy consumption, which can be differentiated into two main categories: (I) technological interventions and (II) managerial actions. While plenty of works studied how improvements in production technology may reduce energy usage, only a few studies focused on management actions. One of the few works that studied the reduction of energy consumption from a managerial point of view is the one of Artigues et al. (2013), which extended the Cumulative Scheduling Problem (CuSP) to include energy issues. The model developed by the authors was named "Energy Scheduling Problem". Nolde and Morari (2010) analyzed electrical energy scheduling in a steel plant and tried to minimize peak and off-peak energy consumption in production, which are both economically penalized. They used a continuous scheduling model to find a production schedule that minimizes energy cost. Mouzon et al. (2007) analyzed the energy consumption of manufacturing equipment and observed that applying dispatching rules on the decision of turning on and turning off machines allows reducing energy consumption. The authors used a multi-objective mathematical programming model to reduce both energy consumption and total completion time.

Gutowski et al. (2006) showed that the energy consumption of the actual machining process (for example of a milling machine) decreases as the production rate increases. The authors noted that a certain proportion of energy consumption remains constant for varying output rates, which is due to several additional functions the machine offers that are not directly affected by the production rate. They estimated that the electrical energy that is consumed by varying the production rate accounts for only 14.8% of the total energy consumption, while the remaining fraction is consumed by functions such as the centrifuge energy, the cooling, the oil pressure pump, the mist collector, etc. Thus, approximately 85.2% of the energy consumed during production can be considered as independent of the production rate.

The aim of this work is to develop a model of an inventory-production system that explicitly considers energy consumption at the production stages, and to minimize the total cost of this system.

The possible states of the machines considered in this paper are:

– Idle state: the machine is turned on (thus it consumes standby energy), but it does not produce;
– Productive state: the machine produces;
– Switched-off state: the machine is turned off (thus its energy consumption is zero).

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0925-5273/$ - see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.ijpe.2013.06.025

Variable production rates have only infrequently been analyzed in inventory models. Glock (2010), for example, analyzed the total cost of a single production facility that produces and delivers a single item to the subsequent stage in batch shipments. The author assumed that the production rate may be varied within given limits. He studied both the cases of equal- and unequal-sized batch shipments and proposed a solution procedure for the models. Numerical studies showed that deviating from the design production rate of a production facility may reduce inventory carrying cost and thus the total cost of the system. Glock (2011) extended this model to account for a multi-stage production process, reaching to the same conclusion. The case where a variation in the production rate of a machine influences greenhouse gas emissions was analyzed by Jaber et al. (2013). The authors studied a supply chain consisting of a single vendor and a single buyer and assumed that deviating from the 'design production rate' of a machine increases the output of greenhouse gases. The results of the paper indicate that the total cost of the supply chain, including cost related to the emission of greenhouse gases, can be reduced if the system is adequately coordinated. One more paper that presents ideas that are relevant for the model developed in this paper is the one of Glock et al. (2012), who assumed that customer demand is sensitive in the degree of sustainability used in producing a product. The authors assumed that if producing a product leads to a large amount of scrap and a vast amount of greenhouse gas emissions, customer demand for the product decreases. The model thus illustrates that customers can give incentives to companies to produce sustainable products, instead of damaging the environment with their production processes. Since the generation of energy often produces greenhouse gas emissions as well, the works of Jaber et al. (2013) and Glock et al. (2012) are of direct relevance to this paper.

The model presented here also builds on the ideas of Szendrovits (1987), who showed that it can be beneficial to interrupt the production of a batch manufacturing process to reduce inventory carrying cost. However, our work differs from the one of Szendrovits (1987) inasmuch as it assumes that the machine is not necessarily turned off, but that it rather remains in an idle state. In addition, it considers energy-related cost and variable production rates, which are not considered in the paper of Szendrovits. From the authors' point of view, this is a rather promising extension due to its applicability: in practice, productive units are frequently turned into idle states (standby condition) with severe energy requirement, as in the case of furnaces, ladles and milling cages, for example.

The remaining parts of the paper are organized as follows: Section 2 introduces the notations and the description of the system studied. Section 3 formulates the model, and Section 4 presents and discusses numerical results. Section 5 summarizes the findings of this paper and provides suggestions for future research.

2. Notation and description of the system

This work analyzes a system composed of two machines (M1, M2) in series and three stocks (buffers) as depicted in Fig. 1. Two stocks are located between the two machines, where stock point S1 is filled with the products processed by the first machine, which are then transferred to the second machine in equal-sized batch shipments, filling the second stock point (S2). The stock point of finished products (FP) is filled by the second machine, and it is continuously emptied by the demand of the customer (which could be the end customer or another machine, for example). The second machine has a production rate lower than the first one, and the demand rate (d) is lower than the production rates of both machines.

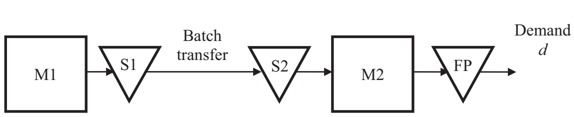

Fig. 1. A two-stage production system with three buffer stocks.

The following notation is used:

d	demand rate [kg/h]
Q	production lot size [kg]
Q_C^*	optimal production lot size [kg] in the case of continuous batch production
Q_I^*	optimal production lot size [kg] in the case of interrupted batch production
m	number of shipments [#]
p_1	production rate of the first machine [kg/h]
p_2	production rate of the second machine [kg/h]
h_b	holding cost of the two stock points between the two machines, S1 and S2, [€/(kg·h)]
h_{FP}	holding cost of the stock of finished products, FP, [€/(kg·h)]
A	setup cost of the system (first and second machine) [€/setup]
S	shipment cost [€/shipment]
W_1	idle power of the first machine [kW]
W_2	idle power of the second machine [kW]
k_1	energy required at the first machine to produce one unit [kWh/kg]
k_2	energy required at the second machine to produce one unit [kWh/kg]
f	multiplication factor for the power required during the setup of a machine
$t_{cycleM1}$	the time between two production cycles of M1
$t_{cycleM2}$	the time between two production cycles of M2
t_{on1}	setup time of machine 1 [h]
t_{on2}	setup time of machine 2 [h]
B	binary variable which is equal to 1 if the first machine stays in the idle state between two successive production cycles, 0 if the first machine is switched off and switched on between two successive production cycles
C	binary variable which is equal to 1 if the second machine stays in the idle state between two successive production cycles, 0 if the second machine is switched off and switched on between two successive production cycles
e	cost of energy [€/kWh].

In addition to what has been stated above, we assume the following hereafter:

1. $p_1 \in [p_{1,}^{min}\ p_1^{max}] \geq p_2 \in [p_{2,}^{min}\ p_2^{max}] > d$, i.e. the production rate of the first machine (p_1) is equal to or higher than the production rate of the second machine (p_2), and both are higher than the demand rate (d); both production rates, due to technological constraints of the specific production process at both stages, are limited to a specific interval set;
2. equal-sized batch shipments are transported between the first and the second stages;
3. shortages are not allowed;
4. the production rates may only be varied before the start of the production process. Once production has been started, it is no longer possible to change the production rate anymore due to technological reasons. This scenario is known as the 'rigid case' in the literature; see, e.g., Buzacott and Ozkarahan (1983), Silver (1990) and Glock (2011).