Sustainable Production and Consumption xx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Sustainable Production and Consumption

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

Research article

Energy saving by switch-off policy in a pull-controlled production line

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ARTICLE INFO

Article history:
Received 21 October 2017
Received in revised form 15 May 2018
Accepted 27 May 2018
Available online xxxx

Keywords:
Energy saving
Production line
Pull control
Buffer level
Simulation

ABSTRACT

The control of the consumption during the machine idle periods can support energy saving policies in manufacturing systems. The strategy to switch-off the machines reducing the energy consumed during the idle periods can lead to important energy saving.

This paper proposes an adaptive control strategy to switch off/on the machines of a production line under pull control policy. The controller of each machine uses the information of the downstream buffer and the satisfaction of the customer order to apply the switch-off policy. The numerical evaluation compares the proposed policy with the approaches proposed in literature considering the trade-off between buffer level and energy saving. The simulations test the proposed policy under different demand profiles and production line configurations. The proposed policy reduces the energy consumption without any effect on the customer performance. The production line balanced or the bottleneck in the last machine leads to the better results.

1. Introduction

The costs and the environmental impact of energy consumption drive the industrial manufacturing to evaluate the energy efficiency (The Cadmus Group, 1998; Deif, 2011). The demand in this sector is relevant, around 40% of the electricity use corresponds to manufacturing activities (U.S. Energy Information Administration, 2016). Studies of the European Association of the Machine Tool Industries (Cecimo, 2009) on the discrete part manufacturing explained how more than 99% of the environmental impacts are due to the electrical energy consumption.

The design and control of manufacturing systems have focused on performance as productivity, quality, inventory control, etc.; but, in the last year's the energy efficiency (costs and environmental impact) becomes critical for manufacturing industries. The energy consumption in a manufacturing system depends on many factors like the equipment technology, the processes and, control strategies.

The machining energy consumption (milling, turning, drilling, and sawing) includes three main parts (Dahmus and Gutowski, 2010; Gutowski et al., 2006): start-up operations (computers and fans, coolant pumps, etc.), runtime operations (tool change, Jog axis, etc.) and material removal operations (machining). The first and second parts are constant independent of the operation, while the third part is variable and depends on the machining operation. The constant power of a machine includes the equipment to ensure the operational readiness of the machine (lubrication system, chip recovery system, etc.). The machining power for cutting depends on many factors of the process like material properties of the workpiece, cutting tools and cutting parameters.

Gutowski et al. (2006, 2007, 2009) and Gutowski (2010) estimated the energy used for the removal material is about 15%, while the major part of the energy is constant and the historical trend seems to be towards more energy-intensive manufacturing processes.

The energy consumed during the standby periods for discrete processes of cutting, such as turning and milling, can be reduced by a switch-off policy of the machine (Li et al., 2011).

Once the machine is completely switched off, a specific time is needed to regain operational readiness. Then, a policy to reduce the energy consumption in discrete processes of cutting is more incisive when works on the constant part. So, the energy saving measures should not sacrifice the availability of the machines.

One of the strategies for saving energy is to control the machine energy state when the machines are idle. The control strategies use some rules to switch off/on the machines to reduce the fixed power consumption (Frigerio and Matta, 2015, 2016).

Gahm et al. (2016) presented a survey of energy-efficient scheduling in manufacturing companies. They underlined how the energy saving in manufacturing companies is relevant, but the energy saving models may degrade the other objectives of the manufacturing companies.

Then, a reasonable trade-off must be found between energy saving and the manufacturing objectives. Beier (2017) presented an overview of energy saving methodologies identifying several research demands. Among them, the more relevant issues for this

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https://doi.org/10.1016/j.spc.2018.05.006
2352-5509/

paper are: "*A quantitative approach for evaluation and methods to enable energy flexibility is required*"; "*reduction of computational complexity*"; "*Integrated evaluation of multiple indicators*"; "*Evaluation of input uncertainties and stochastic influences*".

The research proposed concerns the development of a model to support the switch off/on strategy in a production line. The main focus of the research is to evaluate how the switch off/on strategy impacts on the customer performance in a pull system.

A simulation model tests the proposed model in dynamic conditions to identify in what conditions the switch off/on strategy does not impact on the customer performance.

The proposed model considers the buffer levels (as previous works) but introduces the evaluation of the customer demand profile. A strategy proposed in the literature based on buffer level and in a steady state of the production line is the benchmark for the proposed model.

The paper is organized as follows. Section 2 discusses the literature review about the switch off policies in production lines. Section 3 introduces the reference context investigated and the proposed model is described in Section 4. The simulation experiments are described in Section 5, while the numerical results are discussed in Section 6. Section 7 provides the conclusions and future research path.

2. Overview of the literature

In recent years, some works were proposed to save energy by switching-off machines with a start-up transitory to resume the machine.

Chen et al. (2013) and Sun and Li (2013) studied production lines with switch-off machines opportunity. Chen et al. (2013) modelled a production line as a Bernoulli serial line with machine startup and shutdown schedule. The numerical results show how the algorithm proposed leads to significant improvement in energy reduction. Sun and Li (2013) evaluated the energy saving opportunity without reducing the throughput of the production line. One of the main limits of these works is the multiple power states of the machines not considered and they did not consider customer demand change.

Chang et al. (2012) examined the energy saving opportunities in an automotive manufacturing system with a serial production line. They evaluated the impact of the energy saving model on the throughput loss. The strategies proposed are simplified and did not consider the change of the manufacturing system state.

Mashaei and Lennartson (2013) proposed mathematical models to support the switch off/on of the machines in a production line. The models proposed work off-line and did not handle the potential uncertain of the conditions. However, the optimization model has a high computational complexity because of the nonlinearity of the energy check and the binary decision variables.

Frigerio and Matta (2015) studied analytically switching models for a single machine assuming stochastic arrivals, constant start-up and no any information from the buffer of the machine. They extended this work to a production line considering several control policies based on the information of the buffers (Frigerio and Matta, 2016). These models did not consider how the control of the machines may affect the production performance, in particular in a pull system.

Cronrath et al. (2016) proposed a model for the analysis of energy consumption in paint shops. A simulation model detects the potential energy saving, but the control of the machines is off-line. Eberspächer et al. (2016) developed a consumption graph-based energy optimization model for industrial manufacturing. The model was tested on a single machine and did not consider the demand scenarios.

Beier et al. (2017) and Giret et al. (2015) presented a survey on the energy saving approaches in manufacturing systems. They identified the detailed research demand. The more relevant for this research are the following: 1) modular approaches to handle the complexity and extend the method to different applications; 2) evaluation of different scenarios; 3) evaluation of the input uncertainty (for example, the uncertain demand as considered in this research).

The works proposed in the literature have the following limits:

- The throughput and energy saving are the main performance measures studied without considering the impact of switch off policy on the other performance.
- The studies proposed focused on the push control and the analytical models analysed the manufacturing system in steady state.
- The demand scenarios and other possible uncertain were not studied.

The research proposed improves the works proposed in the literature on the following issues:

- The performance measures studied include other indices of the manufacturing system; so, the impact of the switch-off policy on the orders' performance is studied.
- The switch-off policy proposed are tested in a pull system to highlight the impact of the policy proposed.
- The policy proposed can handle dynamic conditions as demand changes without setting any parameters a priori.

3. Reference context

The reference context considered is a production line composed of a series of m machines connected in series and separated by buffers. At the end of the production line, a final buffer satisfies the customers' orders. When an order enters, if it is available the final buffer satisfies the order. If not, the order is backordered and will be satisfied later.

The pull production control mechanism is a traditional Kanban control where an output buffer is connected to each machine (that is the input buffer of the next machine).

A Kanban is attached to each part. When an order arrives, the finished part is released to the customer and the kanban attached to that part is transferred upstream for launching the production of a part. If the demand cannot be met from the final buffer, a backorder is generated (Sivakumar and Shahabudeen, 2008). The number of Kanban at each stage is equal to the buffer capacity K.

A machine of the production line can be in the following states (Frigerio and Matta, 2015):

- *Working*: the machine works an item and absorbs the higher power $Pwork_m$;
- *Idle*: the machine can work on an item, but no item is provided from the upstream machine of the line. In this case, the machine absorbs the power $Pidle_m$;
- *Off*: the machine is in the off state cannot work, but absorbs the power of "standby" $Poff_m$;
- *Warm-up*: the machine changes from off to on (Idle or Work) state with a start-up period Twu_m and in this state, absorbs the warm-up power Pwu_m.

It assumed that the raw items are always available from the first buffer of the production line. The input buffer of the other machines has a capacity (K_m); then, if a buffer is full the upstream machine is blocked. Each machine has a stochastic process time Tp_m.

The service level of the customer (the orders satisfied immediately) is the main performance of the production line. The other performance measures considered are the following: