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A Queuing Approach for Energy supply in manufacturing facilities

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Abstract. Nowadays increasing energy efficiency is one of the main objectives of manufacturing systems so as to remain competitive despite of the foreseen increase in energy prices for the next years. We propose a novel queuing-based model for the appreciation of the energy consumption on a company base, so as to optimize the total energy costs due to electricity utilization.

We propose an analytical model based on the extension of the $M^{[x]}/M/\infty$ model where arrivals of the queuing model represent the statistical distribution of switch-on of a generic set of machines and departures represent statistical distribution of the resources switch-off. This models can be easily used to assess and establish the contract with the energy supplier under optimal parameters of contractual power, based on its tariff components. Numerical examples are offered to show the applicability of the proposed model.

Keywords: energy efficiency, Energy-aware models

1 Introduction

Manufacturing systems are usually organized in multiple departments and in many of them there are multiple machines and each machine has its own electricity demand pattern over time. This energy requirement is usually different from machine to machine and it depends on the power of the machine and from the relative duration of different state (idle, standby, load level, machining parameters, maximum speed) produced by different product routings which encompass it. The practical problem lies on the fact that a company does not have access to endless amounts of electricity, or that it is already subject to a contract with the supplier, which generally provides a maximum level of supply which, when exceeded, determine substantial penalties to the user.

For this reason, the objective is to create a model, of simple use, able to assist energy managers who, thanks to the model itself, may simulate different production scenarios under different electricity supply contracts, so as to minimize the expected costs. In

particular, the application of the model implies the calculation of the following performance indices:

- probability of exceeding a specific level of power requirement;
- expected average-power requirement;
- economic evaluation and comparison of different electricity supply contracts.

Dietmair and Verl [1] introduced a generic method so as to model the energy consumption behavior of machines based on a statistical discrete event formulation. The parameter information required to characterize the discrete events can be obtained by a small number of simple measurements or by a degree of uncertainty from the machine and component documentation.

Bruzzzone et al. [2] proposes the integration of an EAS module (energy-aware scheduling), within an advanced planning and scheduling (APS) system, incorporating a model to control the shop floor power's peak for a given detailed schedule; unavailability of the actual machine tools power profile and idle energy, requires to assume constant mean power demand for each job. The goal of EAS is to optimise the given schedule from the viewpoint of the energy consumption, while keeping the given assignment and sequencing fixed. The problem is discussed by minimizing the shop floor power's peak, while limiting the possible worsening of the two scheduling objectives (tardiness and makespan minimisation), and modeling it as a Mixed Integer Programming (MIP) problem.

He et al. [3] proposed a modeling method of task-oriented energy consumption for machining manufacturing system. The energy consumption characteristics, driven by task flow in machining manufacturing system, are analyzed, thus describing how energy consumption dynamically depends on the flexibility and variability of task flow in production processes. The results show a valuable insight of energy consumption in machining manufacturing system, so as to make robust decisions on the potential for improving energy efficiency.

Prabhu et al. [4] proposed a queuing models to predict energy savings in serial production lines where idling machines are switched to a lower power state in serial production lines consisting of machines with Poisson arrival and exponential service time.

Prabhu and Jeon [5] extended their previous model and generalize the energy aware queuing model to a re-entrant structure. Moreover, an application to a semiconductor factory is presented.

The paper is organized as follows: section 2 presents the system and the main assumptions. In Section 3, a model is introduced and the energy cost function are presented. In Section 4 a numerical example is offered. Section 5 summarizes the paper content, describing possible future research directions.

2 The system

One of the most important managerial actions to reduce energy costs is the proper fitting of the energy supply contracts with the plant requirements. In particular, these

contracts generally provide the maximum thresholds that, when exceeded, require payment of penalties. For example, in the electricity contract there is a threshold for the maximum power contemporary required by the loads, also defined as “contractual power”. The problem faced in this paper is to determine the appropriate contractual power considering the variability in electricity usage (given by stochastic distribution of loads switch on and switch off), which is generally not predictable a priori. A simple model is then proposed, derived from queuing theory, which allows to model adequately the variability of the electrical energy consumption and to suggest the contractual power more correct adopting a probabilistic approach to the economic optimisation.

Queuing theory is capable of providing models (and consequent insights) to predict the systems behavior when they asked for providing services at randomly occurring demand. In a queuing system, entities (data, parts, jobs, etc.) arrive in the system and require some form of service (operations, machining, assembly processes, etc.). When more demand for service occurs at a level larger than resource available for service, a queue is formed. The idea is to model the variability in electricity usage by a queuing system, where the entities are represented by the power devices in the department considered. In particular, the distribution of arrivals describes devices activation, while the distribution of services describes their shutdown. Given the random nature of the two distributions, two exponential distributions are taken. Obviously, this assumption is valid in departments where it is not predictable a priori the consumption of these devices. The arrival and the service rates are thus expressed as power per unit of time. In such a queuing system, the average number of entities represents the average power required useful for determining the contractual power. The queuing system defined is depicted in the following figure.

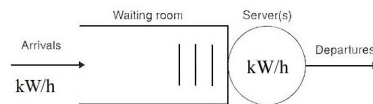


Fig. 1. System considered in the analysis

In order to obtain tractable models, it is assumed that the arrival process and the service process are stationary. Figure 2 shows how the electric power required by a generic machine is variable (for reference see He et al, 2012) because, in general, power varies with respect to the states in which the machine is (state of heating, pressing state, stand-by, etc.). In order to simplify the problem, it may be useful to define the required power constant as shown below. In the next section we present the queuing model proposed.

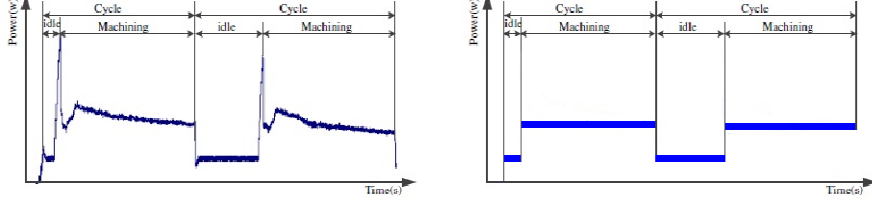


Fig. 2. Variation of the required power in the machine states

3 Model

The model of the queuing theory proposed for the solution of the problem investigated is $M^{[x]}/M/\infty$. In particular, we assume, in addition to the assumption that the arrival stream fits a Poisson process, that the actual number of entities in any arriving module is a random variable X , which takes on the value k with probability w_k , where k is a positive integer, $0 < n < \infty$. Because the Poisson process models the arrival of one - and only one - entity per arrival event, we consider a bulk input. This assumption models the simultaneous activation of multiple devices or the activation of a device at different power levels.

Moreover, we assume infinite services, because every device is activated instantly (i.e., no queue are permitted).

After the definition of the birth-death process and the equations governing the system, using a generating function approach (Gross and al., 2008), it is possible calculate the average number of entities in the system $L = \sum_{k=0}^X (i \cdot p_i)$. This performance is the average power required. Following, we show the rate balance equations related to the states 0-1 and the states 1-2:

$$\lambda \sum_{k=1}^X w_k p_0 = \mu p_1 \quad \rightarrow \quad p_1 = \frac{\lambda}{\mu} p_0 \quad (1)$$

$$\lambda \sum_{k=1}^X w_k p_1 + \lambda(1 - w_1) p_0 = \mu p_2 \quad (2)$$

Using the Little's law and assuming infinite services, the average waiting time in the system is:

$$W = \frac{1}{\mu} \quad (3)$$

In the industrial context, the power required by the department, or company, is always satisfied by the supplier of the electric power, even if this exceeds the predetermined contractual power. Whenever the power required exceeds the threshold, the consumer

will be subjected to a penalty. The objective of this analysis is to verify, in which cases it may be convenient to pay penalties instead of having a greater contractual power and vice versa.

In order to compare the cost of energy in case of exceeding or not the power threshold, we define the following objective function. The model is not based on energy consumption, but the probability of being in a given state and thus requiring power at a given level, which is why the formulae that follow are based on these probability distributions. In particular, the objective function is composed by two parts: the first is the evaluation of the cost (expressed as a rate €/h) below the threshold, while the second is the evaluation of the cost (expressed as a rate €/h) above the threshold. The penalty is paid only for the delta of power exceeding the threshold.

$$EEC = \sum_{i=0}^P p_i \cdot \alpha \cdot i + \sum_{i=P+1}^{P_{max}} p_i \cdot \beta \cdot (P_{max} - i) \quad (4)$$

where:

- α is the energy cost below the threshold [€/h]
- β is energy cost above the threshold [€/h]
- P is the threshold [kW]
- P_{max} is the maximum power beyond the threshold [kW]

4 Numerical Analysis

So as to study the behavior of the model, we performed a numerical analysis to investigate how the model parameters influence the optimal solution of the energy model. The scenario considered consists of a production system with machine tools with a required power that can be represented by 4 different batch sizes with linearly increasing probability distribution, the rate of arrivals is equal to 10 kW/h, which is equal to 10 events of 1kW per hour, while the service rate is 35 kW/h.

The average power required L is equal to 12.99 kW. Given a particular energy supply contract two options can be possible:

- adopt a supply contract with 20 kW of contractual power and pay all consumption without incurring any penalty
- adopt a supply contract with 10 kW of contractual power, thus paying at a base fee the power used up to 10 kW and pay a penalty for the exceeding.

According to the formulae shown in the previous section, the expected energy cost for the first case is equal to:

$$EEC(20kW \text{ contract}) = \sum_{i=0}^{13} p_i \cdot 0,2 \frac{\text{€}}{\text{kWh}} \cdot 13kW = 1,61 \frac{\text{€}}{\text{h}}$$

While, if the second option is applied, the result is as follows:

$$\begin{aligned}
& EEC(10kW \text{ contract}) \\
&= \sum_{i=0}^{10} p_p \cdot 0,2 \frac{\text{€}}{\text{kWh}} \cdot 10kW \\
&+ \left(\sum_{i=11}^{13} p_p \right) \cdot 1,5 \frac{\text{€}}{\text{kWh}} \cdot (12,99 - 10)kW = 1,46 \frac{\text{€}}{\text{h}}
\end{aligned}$$

Thus, in this particular case it is more convenient to apply a lower power contract and pay the penalties due to the probability of exceeding the contract power.

Assuming the same scenario above, but at an arrival rate equal to 11 kW/h instead of 10 kW/h, the result changes as follows. Unlike the previous case, the average power becomes very high (35.04 kW instead of 12.99 kW), despite of the value of the arrival rate increased only by one unit (from 10kW/h to 11kW/h). The contractual powers assume the default values of 30kW and 40kW. In the first case the cost per hour is equal to 3.89 €/h, while with a greater contractual power the expected cost is equal to 4.43 €/h.

5 Conclusion

This work faced the problem of the electrical energy supply contract in an industrial environment. The main objective is to properly adjust the contractual power in a manufacturing system composed by several electrical resources and analyze the power consumption probability distribution applying queuing theory. The electrical power demand has been viewed as a physical user (client) that requests access to a system (electrical network) for a certain period of time (thus resulting in the consumption). The mathematical model of a $M^{[x]}/M/\infty$ queue fits this case and it helps in capturing the dynamics of the system. Moreover, using synthetic formulae with probability functions it is possible to look for the most convenient electrical supply contract, given a set of offer available from the suppliers.

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