Energetic and Economic Performance Evaluation of Production Systems: Perspective Analysis

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Abstract: Improving the economic as well as the energetic performances of manufacturing systems has become a real challenge for both researchers and industrials. Due to the economic, legislative and environmental pressure, enhancing both economic and energetic performances arouses interest and attracts further efforts. The objective of this paper is to discuss current work done on this subject, analyze the results and propose further perspectives for research in this area towards sustainability. Furthermore, an introduction for an economic and energetic evaluation method for serial production lines is also presented.

Keywords: Energy efficiency, production lines, throughput evaluation, machine performance evaluation, Equivalent Machine Method.

1. INTRODUCTION

The industrial sector represents more than 31% of total world energy consumption according to statistics from the International Energy Agency IEA (2019). Thus, to face these serious situations of increasing energy prices, depletion of global resources and global warming, improving energy efficiency in manufacturing is becoming crucial. The industrial sector is therefore increasingly interested in the issue of energy efficiency for financial, legislative and environmental concerns. Unfortunately, only few work has been done when it comes to study energetic combined with economic efficiency of industrial production lines. Indeed, many research results have been reached in the field of improving energy efficiency for machine tools but there is a significant lack of work in the case of serial production lines.

The aim of this paper is to discuss and analyze current work and progress concerning the study of energetic and economic performances of manufacturing systems, as well as to suggest further perspectives of research in this area. An approach for evaluating both economic and energetic performances for serial production lines is also introduced.

2. LITERATURE REVUE

Improving the economic efficiency of serial production lines has been a major concern since decades. This problem has been widely treated in the literature from the smallest systems to the largest ones. Exact solutions for small systems with two machines and a single buffer were obtained (Dallery and Gershwin, 1992; Li et al., 2006). For larger systems, the complexity being more consequent, approximate solutions are proposed, either based on aggregation (Li and Meerkov, 2003, 2008; Jacobs and Meerkov, 1995b,a), decomposition approaches (Gershwin, 1987a,b, 1989; Choong and Gershwin, 1987; Dallery et al., 1988, 1989), or other proposed analytical methods such as the Equivalent Machine Method (Ouazene et al., 2013). The EMM is an approached analytical method that evaluates the system throughput of a buffered serial production line of unreliable machines with exponentially distributed parameters. The study is based on the analysis of the different states of each buffer using birth-death Markov processes. Thereafter, an equivalent machine replaces each original machine, taking into account the probabilities of blockage and starvation. This allows the evaluation of the throughput of the production line, defined as the bottleneck between the effective production rates of the equivalent machines. This method has been tested on a large benchmark and its relevance has been demonstrated. Indeed, it reduces significantly the state space cardinality of the Markov chain representation of the system and consequently the computational times.

Nevertheless, the current circumstances are pushing researchers and industrials for further performance enhancement. The concern in no more just improving the performances of manufacturing systems economically but also energetically. Further efforts are therefore settled to bring solutions for this problem. However, work done towards the evaluation and improvement of energetic performances of serial production lines is still insufficient, and requires more efforts and advances, according to our non exhaustive literature review. In the following, we summarize our literature review according to several axes of focus to which energy performance evaluation studies have been adressed.

2.1 Generic methods

From a general perspective, Gutowski et al. (2009) used a thermodynamic framework to characterize the material and energy resources used in manufacturing processes. The analysis of different processes allowed to illustrate the relevance of thermodynamics in manufacturing processes analysis. The authors used exergy analysis to identify loss in resources aiming to design more efficient processes. The energy consumption of a manufacturing system is formulated as shown in (1) where $\dot{W}$ is total power used by the process equipment, $\dot{W}_0$ the idle power for the equipment in the ready position, $\dot{m}$ the rate of material processing in (mass/time), and k a constant (J/mass)).

$$\dot{W} = \dot{W}_0 + k\dot{m} \tag{1}$$

On another hand, a novel generic method is proposed by Dietmair and Verl (2009) in order to model the energy consumption behavior of machines and plants based on a statistical discrete event formulation. Authors introduced applications in real-time, tactical and strategic decision making processes for energy consumption minimization of production systems using the modeling framework.

2.2 Energy efficiency improvement for Bernoulli serial production lines

Su et al. (2016) studied the improvement of energetic performance of Bernoulli serial production lines. They developed an integrated model for improving energy efficiency for buffered lines composed of two machines. The energy consumption of the line was formulated as shown in (2). W_i is the total electrical power consumed, W_{Oi} represents the set-up power needed for the machine to reach 'ready' status, and $k_i\rho_i$ the additional power needed to process parts, where k_i is a constant, and ρ_i the processing rate of machine i.

$$W_i = \sum_{i=1}^{2} W_{Oi} + \sum_{i=1}^{2} k_i\rho_i \tag{2}$$

Recently, Su et al. (2017) extended the study for larger systems with unreliable machines and finite buffers. An integrated model for minimizing energy consumption under a desired production rate was presented (3) and (4), where ρ_i is the machine's processing rate and PR_d is the desired production rate, only the processing energy required to produce is considered in this study. Exact analysis to optimally allocate production capacity for small systems were developed, an aggregation is used for medium systems and finally a heuristic algorithm for larger systems.

$$min\ E = \sum_{i=1}^{K} k_i\rho_i \tag{3}$$

$$s.t.\ PR \geq PR_d \tag{4}$$

2.3 Energy performance improvement for serial production lines using real time data

Methods for the improvement of energetic performance of serial production lines using real time date are also treated. Brundage et al. (2013) developed new energy savings opportunity strategies to maximize energy savings for a serial production line. The method is based on the evaluation of the opportunity window from on-line production data in order to turn off certain machines for energy savings without negatively affecting throughput. Using real time production data, energy efficiency performance indicators are evaluated to identify the least energy efficient machine on the line. The Energy Efficiency Performance Indicator is developed (5), where $W_{i,1}$ is the static part of the energy consumption for machine i and $W_{i,2}$ the dynamic part attributed to random disruptions on the line. This indicator is used within the energy savings opportunity strategy to allow to take the opportunity window for the least energy efficient machine at opportune times, in order to make improvements to the machine towards the increase of the overall energy efficiency of the line.

$$EEPI_i = \frac{W_{i,1}}{W_{i,1} + W_{i,2}} \tag{5}$$

Later, Brundage et al. (2014) incorporated the warm-up time of each machine in the analysis, allowing for more accurate results.

Bajpai et al. (2018) extended previous studies to include economic concerns within the energetic performance evaluation. Performance indices for measuring energy efficiency and also productivity using available sensor data from the production line are developed. These indices capture dynamic nature of manufacturing systems. Authors analyze the energy structure and effects of downtime events on the production line in order to improve the system's performances. They proposed methods for measuring efficiency and highlighting the areas of inefficiency in the system.

Serial production lines with geometric machines were studied by Chen et al. (2015). Transient analysis for energetic performance were presented and discussed.

2.4 Further energy performance improvements for serial production lines

Further solutions for the improvement of serial production lines energetic performances were also proposed. Chen et al. (2011) addressed energy consumption reduction for the simplest Bernoulli system of a buffered two machines line and introduced feedback control of machine start-up with buffer depletion at the end of each shift. Transient analysis were performed in order to achieve performance evaluation formulations and propose effective controllers for machine startup schedule.

Larger systems with warm-up time were considered by Jia et al. (2016). The later extended the previous study and achieved results in both transients and steady state.

Furthermore, idle time reduction for energetic performance improvement was studied by Zhang et al. (2019) who developed a Gaussian mixture model to predict machine idle periods duration for manufacturing systems. The idle time prediction allows to suggest optimal actions considering energy savings while respecting throughput constraint.

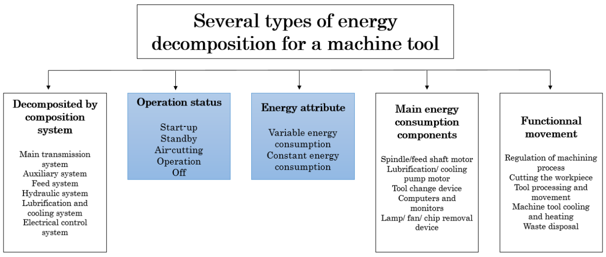

Fig. 1. Energy consumption decomposition (Zhou et al., 2016)

2.5 *Energy performance evaluation and improvement for machine tools*

Although the issue of improving both economic and energetic performances requires further efforts in the case of serial production lines, this concern was widely studied for machines tools, considering models based on machine components or machines tools in a global way.

A comprehensive literature revue concerning energy consumption models and energy efficiency of machine tools was presented by Zhou et al. (2016). Energy efficiency formulations were presented and discussed. The design, scheduling, optimization and assessment based on energy efficiency of machine tools were also introduced. The authors presented several perspectives for energy consumption modeling and decomposition for machine tools according to several axes (see Fig. 1). Classification and prediction methods of energy consumption were presented and over-viewed by Zhao et al. (2017). They also treated strategies for energy consumption reduction in machining processes.

Schudeleit et al. (2016) worked on the development of a metric able to quantify the design of machine tools regarding energy efficiency. Therefore, the total energy efficiency index was developed based on the respective assembly of components. Tuo et al. (2019) developed key performance indicators referred to as 'inherent energy performance' (IEP) indexes focusing on the design and selection of machine tools with the consideration of the main process controls in the usage phase and their interaction. The developed method is based on simplified measurements of basic data in order to calculate the IEP indexes. These indexes are of two types: Energy-consumption function indexes (such as Standby power and idling power function) and Equivalent energy-consumption indexes (such as Equivalent standby power and Equivalent idling power). Each equivalent energy index is represented by the weighted average of powers for different cases times the probability or frequency of each case (see the example of Equivalent standby power formulation in (6)). The main characteristic of these indexes in that of taking into consideration the various process control distributions such as the probability of each spindle revolving speed along with the specific energy demand for each machine tool activity.

$$EP_{sb} = \sum C(P_{sb,i}) P_{sb,i} \tag{6}$$

Word done on sustainability for machine tools has not been resumed to energy efficiency studies only, green performances as a whole were studied by Lv et al. (2019) for CNC (Computer Numerical Control) machine tools. The authors established a model for the evaluation of energy efficiency, carbon efficiency and green degree. Energy efficiency was defined by the ratio of the energy required for the cutting process (material removal energy) and the total energy consumed for the machining process (7).

$$\eta = \frac{E_{cutting}}{E_{process}} \tag{7}$$

The approach for energy consumption evaluation of CNC machine tools was to decompose it by machine states. The later are: start-up state, standby state, no-load state (in which the machine is working without load) and load state (in which the machine is effectively processing). The state energy is defined as the corresponding state power times each state's duration (8,9).

$$E_{processus} = E_{start} + E_{standby} + E_{no-load} + E_{load} \tag{8}$$

$$E_{processus} = P_{start} \times t_{start} + P_{standby} \times t_{standby} + P_{no-load} \times t_{no-load} + P_{load} \times t_{load}$$

$$E_{cutting} = P_{cut} \times t_{load} \tag{9}$$

The energy efficiency as defined in (7) is calculated as a function of machine and process parameters.

Wang et al. (2019) studied the optimization of energy efficiency in machining process and presented a model based on workingstep energy calculation method in Standard for the Exchange of Product model STEP-NC. For the resolution, the authors developed an improved ant colony optimization algorithm.

2.6 *Analysis*

The conducted literature revue reveals the necessity of developing a system of evaluation in which both economic and energetic performances of serial production lines are considered.
On one hand, economic efficiency of serial production lines has been treated over and over in the literature since decades and satisfying results have been reached. However, on the other hand, the issue of energy efficiency evaluation and optimization for serial production lines requires further work. Although, this problem has been largely studied and considerable results have been reached in the case of machine tools, efforts are still necessary for the study, evaluation and optimization of energy efficiency for serial production lines. Therefore, the need for the development of an analytical method that allows to evaluate energy consumption and efficiency of serial production lines taking into account their economic performance.
In the next section, the problem formulation is introduced towards the introduction of our evaluation approach.

3. PROBLEM FORMULATION

The objective is to develop an analytical and computational method that allows the evaluation of both economic

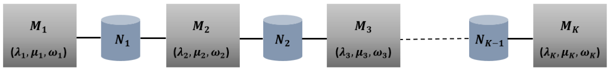

Fig. 2. Serial production line

and energetic performance of a serial production line. The system under consideration consists of K machines (workstations) connected by intermediate storage areas $(K-1)$ buffers (as illustrated by Fig. 2). The system is subject to non-availabilities due to the limited capacity of the buffers and / or the failure and repair rates of the machines. The following assumptions which are frequently used in the literature, address the machines, the buffers, the energy consumption and their mutual interactions:

- The failure state of the machines depends on the operations. A machine cannot fail if it is starved or blocked.
- The first machine cannot be starved and the last machine cannot be blocked.
- The failure and repair times are independent and distributed according to an exponential law.
- Buffer B_i, has a finite capacity N and cannot be down. The transition times between machines and buffers are zero.
- Energy consumption of each buffer B_i is neglected.

4. EVALUATION APPROACH AND RESULTS

The objective is to develop an analytical and computational method able to assess both economic and energetic performance of a buffered serial production line of unreliable exponential machines.

The approach is to evaluate the economic performance using the Equivalent Machine Method (Ouazene et al., 2013), and then assess energetic performance by developing a model based on machine states. The energy evaluation model uses machines and buffers parameters as well as output data from the economic evaluation. Eventually, the method evaluates an economic performance indicator which is the throughput ψ of the line, as well as energy performance indicators which are the energy consumption E and the energy efficiency η of the serial production line. Both performances and therefore indicators are also evaluated for each machine of the line (ρ_i, E_i, η_i) / $\forall i = 1...K$.

The chosen approach to evaluate energy consumption is to assess it per part. Several segmentation methods have been introduced by Zhou et al. (2016) as summarized in Fig. 1. Depending on the needs of the study, the energy consumption of a machine can be evaluated according to several axes. For the conducted study, we have chosen to assess energy consumption according to the machine states.

The problem is then formulated using a discrete time and states Markov chain. The set of states S consists of the different states in which a machine M_i could be: On, Down, Starved, Blocked and Starved&Blocked.

$$S = \{O, D, S, B, SB\}$$

Transition probabilities and then steady state probabilities $(P_{O,i}, P_{D,i}, P_{S,i}, P_{B,i}, P_{SB,i})$ for each machine M_i were evaluated using machines and buffers parameters as well as output data from the economic evaluation.

Next, energy consumption E_i for each machine is formulated. It is evaluated on an horizon using specific energy consumption for each state (10).

$$E_i = P_{D,i}E_{down,i} + (P_{S,i} + P_{B,i} + P_{SB,i})E_{no-load,i} + P_{O,i}E_{Cload,i} + e_{op,i}\rho_i \tag{10}$$

$E_{down,i}$ is the energy consumed in the down state in units of energy, $E_{no-load,i}$ the energy consumed in the idle states (starved, blocked or both) in units of energy, $E_{Cload,i}$ the constant part of the energy consumed in the processing state 'On' (which is assumed equal to $E_{no-load,i}$ in our tests) in units of energy, as well as $e_{op,i}$ which is the specific operating energy consumed per part manufactured in units of energy per part manufactured. These input data are balanced by each state's steady probability at the exception of the specific operating energy $e_{op,i}$ which is multiplied by total number of produced parts that corresponds to the production rate ρ_i of each machine, in order to acquire the energy consumption E_i of each machine M_i. Finally, the total energy consumption E of the production line is evaluated (11) as well as the energy efficiency η.

$$E = \sum_{i=1}^{K} E_i \tag{11}$$

The particularity of the method is its ability to assess both economic and energetic performance as well as to highlight the possible interactions and trade-off between both performances. Conducted tests on a large benchmark from the literature allowed to extract many analysis and findings regarding the behavior of the economic and energetic performance and there mutual interactions. The correlation proved to be not as intuitive as it could be expected. Indeed, although energy parameters were kept constant among the tests due to the absence of adequate energy benchmarks in the literature, the throughout was not directly correlated with neither energy consumption nor energy efficiency. Producing more does not imply consuming more energy. For the tests, the energy parameters were fixed as follows:

$$E_{down,i} = 1 \text{ Unit of energy.}$$
$$E_{no-load,i} = E_{Cload,i} = 10 \text{ Units of energy.}$$
$$e_{op,i} = 8 \text{ Units of energy/part manufactured.}$$

Figure. 3 as an illustrative case, represents the standardized production rate and energy consumption of each machine to the respective maximums. The corresponding tested instance is composed of five machines and four intermediate buffers whose parameters (failure rate λ_i, repair rate μ_i, production capacity ω_i for each machine M_i, and buffer size N_i for each buffer B_i) are given in table 1.

We can effectively notice from that example that although the first machine produces less than the third one, it consumes more energy. The proposed evaluation method allows to conduct several analysis on the behavior of the

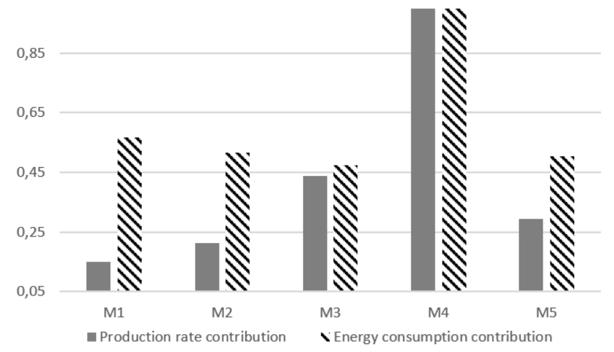

Fig. 3. Production rate and energy consumption for machines of a serial production line (illustrative case)

Table 1. Tested instance parameters

Machine	λ_i	μ_i	ω_i	N_i
M1	0.01	0.45	0.2	5
M2	0.2	0.55	0.5	20
M3	0.5	0.3	2	6
M4	0.4	0.22	2.5	8
M5	0.3	0.4	1	//

economic and energetic performances of serial production lines as well as the corresponding interactions.

5. CONCLUSION

This paper gives an overall review on energy evaluation in both production lines and machining systems. Economic performance evaluation for serial production lines has revealed being largely studied and its results sufficient. As of the energetic performances, this axes remains in need for further work. Indeed, although this issue has been largely studied for machining systems, more efforts are required for the evaluation and optimization of energetic performance of serial production lines. Especially, taking into consideration the economic performance.

Therefore, to fill the gap, it is crucial to develop a method that would evaluate both economic and energetic performance of serial production lines, in order to highlight areas of correlation and the mutual interactions between both axes of performance. The approach for the development of the method for a buffered serial production line with unreliable exponential machines is therefore introduced. This proposed solution allows the evaluation of key performance indicators able to asses performances in terms of throughput, energy consumption and energy efficiency of the production line. In addition, the numerical tests brought-out important findings regarding the trade-off between economic and energetic performance of serial production lines.

In the future, the focus will be on the improvement of the method and its extension upon different production system types. Furthermore, practical case studies aiming for the development of an energy benchmark would allow to bring more accurate analysis especially considering energy parameters influence.

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