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Procedia CIRP 29 (2015) 34 – 39
www.elsevier.com/locate/procedia

The 22nd CIRP conference on Life Cycle Engineering

Analysis of an Energy Oriented Switching Control of Production Lines

Nicla Frigerio[a*], Andrea Matta[b]

[a]*Department of Mechanical Engineering, Politecnico di Milano, Milan, Italy*
[b]*Department of Industrial Engineering and Management, Shanghai Jiao Tong University, Shanghai, China*

* Corresponding author. Tel.: +39-02-2399-8559; fax: +39-02-2399-8585. *E-mail address:* nicla.frigerio@polimi.it

Abstract

The implementation of control strategies that reduce energy consumption during the machine idle periods is becoming a challenging goal to achieve energy efficiency in production systems. A general framework for switching the machine off / on has been recently proposed in literature for single machines. This paper studies the performance of a production line when a general policy is applied at machine level. The considered performance measures are the total energy consumed per part and the system throughput. Numerical results are based on discrete event simulation, and a comparison with the most common practices in manufacturing is also reported.

Peer-review under responsibility of the scientific committee of The 22nd CIRP conference on Life Cycle Engineering

Keywords: Production Lines; Energy Efficiency; Switch off/on Control; Simulation

1. Introduction

Energy saving in production plants is becoming more and more challenging to contain the environmental impact of manufacturing, and, nevertheless, to reduce costs. One of the measures for saving energy is the implementation of control strategies that reduce energy consumption during the machine idle periods. This paper studies the performance of a production line when a state control strategy is applied at machine level towards the improvement of energy efficiency.

1.1. Literature Review

The energy required by a machine tool can be significantly reduced applying a state control at machine level. The state control aims at reducing the machine fixed power consumption, which is required even if the production is not requested. Indeed, the machine auxiliary equipment keeps consuming energy during non-productive states. This generates a supply excess that could be reduced by controlling the machine state. Recently, the potential of machine state control during non-productive periods has been highlighted by several researchers. To give some examples, Gadhimi *et al.* estimated up to 26% of energy consumption savings in the analyzed scalping process line by applying a switch-off policy [1]. Weinert and Mose simulated different production scenarios where advanced standby strategies are implemented on production equipment to save energy during short interruptions [2]. The potential saving is shown to be up to 53% of the energy consumed in non-productive periods. Langer *et al.* showed the effectiveness of their energy sensitive Manufacturing Execution System (MES) using a simulation model [3]. The energy control strategies applied reached significant savings (16% - 24%) during the non-productive periods.

In the last years, several research efforts focused on controlling production systems by switching *off* and *on* the machines to minimize total energy consumption when a start-up transitory is needed to resume the service. Chen *et al.* formulated a constrained optimization problem for scheduling machines into on and off modes in a production line [4] [5]. Sun and Li proposed an algorithm to estimate opportunity windows for real-time energy control in a machining line [6]. Random failures of machines are considered, whereas the cycle time and start-up time are deterministic and constant. Frigerio and Matta studied analytically the switching policy for single machines under the assumption of stochastic arrivals, constant start-up

Peer-review under responsibility of the scientific committee of The 22nd CIRP conference on Life Cycle Engineering
doi:10.1016/j.procir.2015.02.177

and no information from the buffer in front of the machine [14]. Under quite general assumptions, they show that the switch-off and switch-on problems are two independent problems and also provide an efficient algorithm to find out the optimal parameters of the policy (i.e., when to switch-off and on). In a different work, they modeled explicitly the start-up time as dependent on the time period the machine stays in a low power consumption state [7]. Furthermore, a framework for energy oriented control of machines that includes buffer information was proposed in [15]. The machine is switched-off according to a time threshold. Then, the machine is switched-on when the queue has accumulated *N* parts or according to a time threshold.

Another stream of research related to the machine state control during non-productive periods is the queuing theory. Indeed, exhaustive vacation queueing systems can model machines that may become temporary unavailable. The vacation starts at the completion of a busy period (exhaustive vacation) and the service is resumed according to some policies. The simplest resumption policies are the N-Policy and the T-Policy. The N-Policy resumes the service when the queue length accumulates *N* parts. Also the T-Policy is quite intuitive: a customer that arrives to an empty system starts a timer that counts down *T* time units until the machine is activated. The combination of the two policies leads to the hybrid NT-Policy. Detailed surveys have been reported by Doshi [8], Takagi [9], Tian and Zhang [10], Ke et al. [11], Tadj and Choudhury [12], and others. Of particular interest is the work of Teghem, who studied the N-policy single removable server queueing system for the M/G/1/K queue [13]. This work allows to model finite buffer capacity systems with the N-Policy.

A common issue of the works coming from queueing literature is that they do not refer to energy and they require some assumptions that do not properly match with manufacturing systems. Therefore, while the concept of a switching policy can be easily applied to manufacturing, the models cannot be the same queuing models used to evaluate the control policies. Thus, new models to evaluate the performance of manufacturing systems controlled with energy saving policies need to be developed.

1.2. Objective and Contribution

From the literature analysis it emerges that the energy reduction problem has been studied at local level when a single machine can be controlled using local information, such as arrivals and process time information. Also, the information of the buffer level for energy saving purpose is rarely used. The impact on the whole production system performance of controlling one machine has never been discussed yet.

At system level, some switching control strategies have been proposed in the literature, but optimal policy structural properties have never been investigated. For instance, it is not known which machines have to be controlled and which not in a manufacturing system, and how a simultaneous control of the machines may affect the production system performance. Indeed, nowadays, in most of manufacturing systems there is a lack of data in terms of energy consumption and about the savings achievable by properly controlling production equipment.

This paper studies the performance of a production line with finite buffer capacities when a general switching policy is applied at machine level. Production lines are chosen as the subject of the analysis due to the high impact that switching policies may have in terms of machine idle times. Indeed, switching off a machine may cause blocking and starvation to the upstream and downstream machines, respectively. Discrete event simulation is used for performance evaluation, with an ad-hoc template built in Arena software environment for modeling a general machine controlled with a switching policy. In the study a real CNC machining center is considered, experimentally characterized to estimate the power demand in its different states.

Several simulation experiments in different scenarios are presented in this work. A comparison with the common practice in manufacturing is also reported. Briefly, we will show that:

- A general switching policy allows to reach high energy savings without largely compromising production throughput;
- Controlling machines located at the beginning or at the end of a balanced production line makes difference;
- In a balanced production lines where each machine is controlled, the optimal parameter values of the switching policy have a special, and nice, structure.

Since our results were obtained with simulation, there is no claim they are general and valid for any production line. However, this is the first study in which a switching policy is analyzed on a production line, and we think that our considerations will be helpful for many researchers and practitioners.

2. Assumptions

A serial production line with *m* workstations, each composed by a finite input buffer and a single machine working a single part type, is considered. This assumption is valid for machines specialized for one single part-type or for a family of similar items, and for machines working large batches while considering a single batch.

Let $\boldsymbol{x}_i \in S_X = \{1,2,3,4\}$ be the *i*-th machine state according to Frigerio and Matta [14][15]: $x_i = 1$ if out-of-service, $x_i = 2$ if on-service, $x_i = 3$ if warm-up, and $x_i = 4$ if working. In the *out-of-service* state—i.e., the stand-by state— the machine is in a kind of “sleeping” mode and it is not able to produce. In the *on-service* state—i.e., the idle state— the machine is ready to process a part upon its arrival. From the out-of-service to the on-service state the machine must pass through the *warm-up* state—i.e., the transitory start-up state between the out-of-service and the on-service states— where a procedure is executed to make the modules suitable for processing. In this work we refer to this transitory as warm-up. The warm-up duration $T_{\mathrm{wu},i}$ can be a random value because the machine can request different time to reach the proper physical working condition according to system and machine conditions—e.g., room temperature. In the *working* state the machine is processing a part.

Moreover, we assume every machine has an input buffer with finite capacity K_i controlling the release of parts to the machine. After the completion of the process, the part leaves the workstation. The number of parts in each station is represented as the integer variable $n_i \in [0, K_i + 1]$. The *i*-th machine can be blocked if the downstream buffer (*i+1*) is full. Further, blocking after service is assumed. The last machine of the line cannot be blocked because an infinite buffer is assumed downstream. When the machine is blocked, it is assumed to consume as in the *on-service* state. The interarrival time at the first station is a random variable modeling the time T_a between two part arrivals—where $t_a = \mathbf{E}[T_a]$. Similarly, the machine processing time $T_{p,i}$ at the station i is random with $t_{p,i} = \mathbf{E}[T_{p,i}]$. The stochastic processes involved in the system are assumed to be independent of each other and stationary and they can be calibrated to model failures. The transition between two states can be triggered by the occurrence of an uncontrollable event, e.g., the part arrival, or a controllable event. Since the arrivals are random, the probability of the system being in a certain state is the output of a stochastic process.

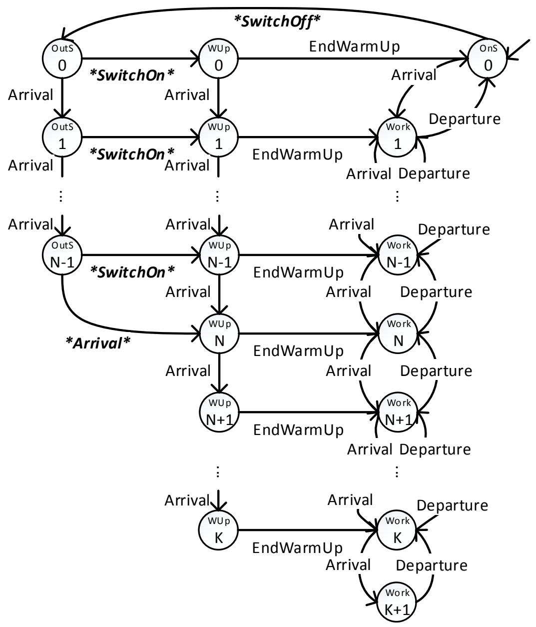

Fig. 1. Workstation state model. The number n_i of parts in the workstation is incremented and decremented by arrivals and departures at the station, respectively. The machine can be in the working state for any value of n_i except when there is no part to work ($n_i = 0$). The system cannot contain more then $n_i = K_i$ if the machine is out-of-service or executing the warm-up because there are only K positions available for holding parts inside the buffer. The system cannot contain more then $n_i = N_i$ if the machine is out-of-service, because the machine is switched on upon the *N*-th arrival.

3. Control Policy

A *TNT-Policy* is applied at machine level such that the machine is switched off after a time interval τ_{off} has elapsed from the completion of the last busy period. The service is resumed when *N* parts accumulate in the buffer or when a time interval τ_{on} has elapsed from the completion of a busy period [15]. As a consequence, the machine is switched off to save energy and, once in *out-of-service*, it is warmed up to resume the service properly. The extreme situation in which the machine is always kept on-service is considered as the *Always On* policy. Moreover, it is not allowed to shut down the machine ignoring the working request, thus a situation where the service is not provided never occurs.

Given *t* as the time passed after the last departure, the control is defined as follows:

$$a_i = \begin{cases} switch-off & if\ x_i = 2 \wedge n_i = 0 \wedge\ t =\ \tau_{off,i} \\ switch-on & if\ x_i = 1 \wedge (n_i = N_i \vee t =\ \tau_{on,i}) \\ do\ nothing & otherwise \end{cases} \quad (1)$$

where $\{\tau_{\text{off},i}; N_i; \tau_{\text{on},i}\}$ are the control parameters for the machine *i*.

The machine expected energy consumed per part $\boldsymbol{E}[Q_i]$ is the ratio between the *expected power* consumed and the *expected throughput* at the same workstation:

$$\boldsymbol{E}[Q_i] = \frac{\boldsymbol{E}[P_i]}{\boldsymbol{E}[TH_i]} \qquad i=1..m \qquad (2)$$

The expected total energy consumed per part $\boldsymbol{E}[Q_t]$ is the sum of the machine expected energy consumptions:

$$\boldsymbol{E}[Q_t] = \sum_{i=1}^{m} \boldsymbol{E}[Q_i] \qquad (3)$$

Whenever a part arrives when the machine is not available (i.e., $x_i \neq 2$), it consumes w_{q_i} necessary for holding the part in the queue *i*. Further, let w_{x_i} be the power absorbed by the *i*-th machine in state x_i.

Define the workstation state as the vector $y_i = \{x_i, n_i\} \in \mathrm{S}_{\mathrm{Y}_i}$, where S_{Y_i} is the irreducible set of feasible states of the *i*-th workstation in Fig. 1. Therefore, the power consumed by the station *i*-th in state y_i can be defined as:

$$h_i(y_i) = \begin{cases} w_{x_i} + w_{q_i}(n_i - 1) & if\ x_i = 4 \\ w_{x_i} + w_{q_i} n_i & otherwise \end{cases} \qquad (4)$$

As a consequence:

$$\boldsymbol{E}[P_i] = \sum_{y_i \in S_{Y_i}} Pr(Y_i = y_i)\, h_i(y_i) \qquad \forall i = 1..m \qquad (5)$$

$$\boldsymbol{E}[TH_i] = \boldsymbol{E}[T_{p,i}]^{-1} \sum_{\substack{y_i \in S_{Y_i} \\ x_i = 4}} Pr(Y_i = y_i) \quad \forall i = 1..m \qquad (6)$$

The line throughput is defined as the throughput of the *m*-th machine, $\boldsymbol{E}[TH_m] = \boldsymbol{E}[TH]$, and due to the conservation of flow it is $\boldsymbol{E}[TH_m] = \boldsymbol{E}[TH_i], i = 1, \ldots, m-1$.

4. Description of experiments

4.1. Case study

A production line composed by single machine workstations is the system to be analyzed in this work. The machine tools considered are CNC machining centers with 392 dm3 of workspace, five axes, horizontal synchronous spindle, and local chiller. This machine type requires 5.35 kW while on-service, and 0.52 kW when out-of-service. The machine warm-up is characterized by a power consumption of 6 kW and the warm-up time is considered as deterministic with $t_{\text{wu}} = 20$ s. These data have been acquired with dedicated experimental measurements from a real machine configured to operate in a powertrain manufacturing line. The processing times at machines are considered equal and deterministic $t_p = 100$ s.

The power consumed during the working state is not considered in the analysis because it does not affect the selection of the policy parameters, being not dependent on control actions. Each buffer in the line has same finite holding capacity. Since all machines and buffers are identical, the production line is balanced with no bottleneck.

4.2. Simulation model and experiments

The simulation model of the analyzed production lines was developed in Arena®. Since the control policy can be implemented at all the machines of the system, an Arena template (i.e., a library) has been created for modeling a general machine controlled with a switching policy that considers the information from the machine upstream buffer. By using the template, the developer can rapidly build complex simulation models of production systems composed of energy oriented controlled machines. Indeed, the machine parameters can be input using a convenient user interface in which the developer can introduce power data, processing time, warm-up and policy parameters (Fig. 2). The template is composed of 58 blocks and can be easily integrated with the rest of the simulation model using standard instructions in the Arena environment. The developed template is available for use upon writing to the authors.

In our experiments, the control of the analyzed production lines is optimized to find out the optimal parameters that minimize energy consumption. OptQuest is used in order to select a set of near optimal solutions. Simulations in OptQuest were executed for a duration of 230 days and an initial transient identified with the Welch method equal to 139 h. Optimization in OptQuest were launched stopping the algorithm after 100 iterations. Then, these identified solutions have been compared by running longer simulations (1160 days with 139 h of initial transient) to identify the optimal one.

4.3. Scenarios

Two main scenarios are considered in the experiments: *Case A:* line with 3 machines, and *Case B:* line with 9 machines. The buffer capacity is equal to 10 slots at each workstation of the lines.

As far as the Case A, the system can be partially optimized by controlling the state of one machine, i.e. minimizing $E[Q_i]$ at each workstation, or globally optimized by controlling all machines at same time, i.e., by minimizing$E[Q_t]$. The goal is to assess (i) the impact of controlling a specific machine instead of another and (ii) the advantage of controlling the whole production line simultaneously. In such experiments the part inter-arrivals at the first machine are assumed to be exponentially distributed with mean $t_a = 110$ s. Furthermore, to evaluate how the control parameters are affected by the holding power consumption at buffers, the experiments are repeated for different values of w_q. The *Always On* policy represents the reference case for evaluating the impact of the control policies.

Experiments on Case B have the objective to analyze the savings achievable with the simultaneous control on the whole line when the processing time is not deterministic. The starvation/blocking effect of the control will be also assessed. In this scenario, a holding power consumption w_q = 0.1 kW is considered and it is assumed that the first machine is never starved for raw material. As a consequence, the first machine (M1) is kept *Always On*. The processing times are identically distributed and follow a discrete distribution with two values: 100 s in the 95% of the cases and 280 s in 5%. With this distribution, we model in a simplified way failure durations of the length of 3 minutes in addition to the standard processing times of 100 s.

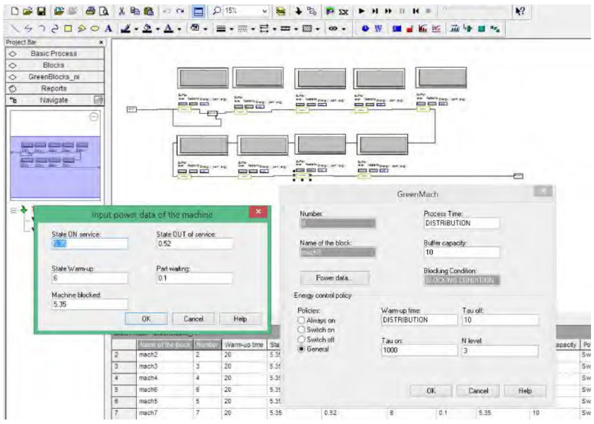

Fig. 2. Production line modelled in ARENA using the template for the workstations. In more details, the user interface allows the customization of the machine tool and the selection of an appropriated control policy.

5. Numerical results

5.1. Case A

The order of magnitude for the duration of an optimization in OptQuest of Case A is 20 minutes on a notebook DELL XPS15 with Intel Core @2.20GHz and 8GB RAM.

Initially, the expected local energy consumed per part $\boldsymbol{E}[Q_i]$ is the objective function to be minimized. The policy is myopically applied at each workstation one-by-one varying the control parameters. Compared to the standard *Always On* policy, a switching policy may decrease the utilization of the controlled machine because the period spent in the out-of-service state can increase. However, the impact on the rest of the system is not easy to evaluate and for this reason the energy consumptions are collected along the line, as well as the line throughput (see Table 1). The optimal control parameters for each machine tool are also reported.

The minimum energy consumed by the first machine (M1) is associated with a control $\{0;6;\infty\}$, whereas on M2 and M3 the optimal control is $\{0;10;\infty\}$. The number of parts in the queue of the controlled machine increases, thus the upstream machines have a higher blocking probability and their energy consumption increases. Moreover, the machine control influences the energy consumed by the downstream machine due to the reduced throughput. As a consequence, the downstream machines, kept on-service longer, increase their consumption. The blocking/starvation effect can be more significant according to buffer capacities, warm-up duration and system variability. A comparison with the *Always On* scenario shows the control achieves significant energy savings regardless the position of the controlled machine.

When all machines are controlled simultaneously, the expected global energy consumed per part $\boldsymbol{E}[Q_t]$ is the objective function to be minimized. As reported in Table 1, the optimal control (*{0;4;∞}{0;10;∞}{0;10;∞}*) performs better than any partial control with -87.45% of average energy reduction and only 0.72% of average throughput losses. The Kruskal-Wallis test between the scenarios confirms the results ($p_{value} > 0.005$). Moreover, the Mann-Whitney test confirms that the combined control obtained by locally optimizing each machine (*{0;6; ∞}{0;10; ∞}{0;10; ∞}*) is sub-optimal. However, some solutions can be statistically equivalent to the optimal solution according to simulation results.

Table 1. Line performance and optimal control (w_q = 0 kW).

	Always On	Control M1	Control M2	Control M3	Control M1,M2,M3
$E[Q_1]$ kJ	62.040	9.010	62.040	62.040	9.407
	±0.190	±0.026	±0.190	±0.190	±0.036
$E[Q_2]$ kJ	62.038	70.761	7.032	62.038	7.502
	±0.188	±0.150	±0.027	±0.188	±0.023
$E[Q_3]$ kJ	62.039	70.761	62.038	6.030	6.454
	±0.188	±0.150	±0.188	±0.018	±0.016
$E[Q_t]$ kJ	186.117	150.533	131.110	130.108	23.363
	±0.566	±0.326	±0.357	±0.396	±0.075
Energy Δ%	***(ref)***	**-19.12%**	**-29.56%**	**-30.09%**	**-87.45%**
	0.008961	0.008832	0.008961	0.008961	0.00889
E[TH] ps/s	±0.000002	±0.000002	±0.000002	±0.000002	±0.000002
	(ref)	(-1.44%)	(0.00%)	(0.00%)	(-0.72%)
$\{\tau_{off}; N; \tau_{on}\}_1$	{∞;*;∞}	{0;6; ∞}	{∞;*;∞}	{∞;*;∞}	{0;4; ∞}
$\{\tau_{off}; N; \tau_{on}\}_2$	{∞;*;∞}	{∞;*;∞}	{0;10; ∞}	{∞;*;∞}	{0;10; ∞}
$\{\tau_{off}; N; \tau_{on}\}_3$	{∞;*;∞}	{∞;*;∞}	{∞;*;∞}	{0;10; ∞}	{0;10; ∞}

Table 2. Line performance and optimal control (w_q = 0.1 kW).

	Always On	Control M1	Control M2	Control M3	Control M1,M2,M3
$E[Q_1]$ kJ	94.801	49.850	94.801	94.801	52,502
	±0.191	±0.142	±0.191	±0.191	±0137
$E[Q_2]$ kJ	62.038	63.487	17.658	62.038	12.088
	±0.188	±0.182	±0.080	±0.188	±0.042
$E[Q_3]$ kJ	62.039	63.490	62.039	17.658	12.088
	±0.188	±0.186	±0.188	±0.080	±0.042
$E[Q_t]$ kJ	218.878	176.827	174.498	174.497	76.677
	±0.358	±0.239	±0.273	±0.273	±0.061
Energy Δ%	***(ref)***	**-19.21%**	**-20.28%**	**-20.28%**	**-64.97%**
	0.008961	0.008939	0.008961	0.008961	0.008920
E[TH] p/s	±0.000002	±0.000002	±0.000002	±0.000002	±0.000002
	(ref)	(-0.24%)	(0.00%)	(0.00%)	(-0.46%)
$\{\tau_{off}; N; \tau_{on}\}_1$	{∞;*;∞}	{0;2; ∞}	{∞;*;∞}	{∞;*;∞}	{0;3; ∞}
$\{\tau_{off}; N; \tau_{on}\}_2$	{∞;*;∞}	{∞;*;∞}	{0;1; ∞}	{∞;*;∞}	{0;1; ∞}
$\{\tau_{off}; N; \tau_{on}\}_3$	{∞;*;∞}	{∞;*;∞}	{∞;*;∞}	{0;1; ∞}	{0;1; ∞}

Assume now the holding power of buffers in the line 0.1 kW. For the Always On case, Table 2 shows the energy consumption of M1 increased from 62.038 kJ to 94.801 kJ because of the parts waiting in the first buffer. Whereas, the energy required by M2 and M3 is unvaried because the line is synchronous and the buffers feeding M2 and M3 are always empty. Once the control policy is applied, the energy consumed for holding parts in the buffers affects the optimal parameters since it is increasing in N. Generally, the service is resumed sooner (N decreases) to avoid the holding power consumption.

5.2. Case B

Before the optimization, we present an interesting numerical fact. Assume the same control is applied to M2 to M9, whenever the control parameter N_i is increased on the machine i, the energy consumed by the upstream machine increases due to the blocking effect. Further, since M1 is kept *always on* (see Section 4), the power consumed by M1 is only due to the blocking condition. Fig. 3 represents one case (red line) where the control of one machine has a greater N with respect to the control parameters *{0;1;∞}* applied to the other machines: particularly the control *{0;10;∞}* has been applied to M5.

The downstream machines are less utilized because of the reduced throughput of the i-th machine, i.e., the starvation effect. As a consequence, the average number of parts in the buffers is reduced and the machine can be switched off more frequently when exhaustive. Nevertheless, the number of warm-up increases, thus the energy consumed by the machines downstream the controlled one may decrease or increase according to this trade-off.

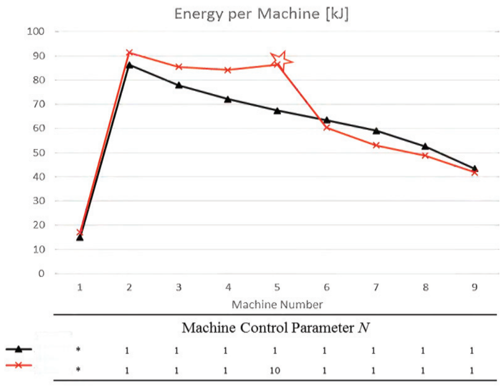

Fig. 3. Energy consumed per machine in Case B when the N-policy is applied at machine level. The control parameter N is reported and the i-th machine controlled with a different parameter is marked with a star.

According to the numerical fact, to increase N at the last machines of the line negatively affect the consumption upstream. Thus, for the case study under consideration, an optimal policy may have the following property:

$$N_i \geq N_j \qquad \forall i \geq j\,; i,j = 1 \ldots m \tag{10}$$

With this additional constraint, the order of magnitude for the duration of an optimization in OptQuest is around 80 minutes.

The system performance under the optimal control are collected in Table 3, as well as the *Always On* referential case. The simultaneous optimal control achieves the 13.37% of energy savings for the whole line, and the throughput is reduced of 0.84%. Particularly, M2 and M3 are controlled with an N-policy where *{0;10;∞}* , whereas M4 – M9 are controlled with an *Off* policy (*{0;1;∞}*). With this control, the machines execute on average 0.04 warm-up procedures per hour. Also in this case, the control is significant according to the Kruskal-Wallis test ($p_{value} > 0.009$).

When a constraint for the minimum target throughput is included in the optimization model, the optimal policy does not change structure. For instance, with a minimum throughput of 0.00894 part/s (0.1% of reduction compared to the *Always On*), the constrained optimal control achieves 8.10% of savings on the total energy consumed. Particularly, M3 to M9 are controlled with an N-policy *{0;1;∞}* and M2 with *{0;5;∞}*, as in Table 4. With this control, the machines execute on average 0.3 warm-up procedures per hour. Compared to the Case A, the energy savings are lower because of the high variability of machines. Indeed, the variable processing times give place to the presence of part in the buffers that do not allow a frequent switch-off of machine.

Table 3. Line with failures: performance and optimal control.

	Always On *(ref)*		Optimal Control		Δ%	Control Parameter
	Average	IC	Average	IC		
$E[Q_1]$ kJ	15.049	±0.372	20.140	±0.434	33.83%	{∞;*;∞}
$E[Q_2]$ kJ	88.116	±0.760	101.204	±0.754	14.85%	{0;10;∞}
$E[Q_3]$ kJ	80.914	±0.599	88.540	±0.449	9.42%	{0;10;∞}
$E[Q_4]$ kJ	75.936	±0.809	58.440	±0.689	-23.04%	{0;1;∞}
$E[Q_5]$ kJ	72.150	±0.530	52.028	±0.713	-27.89%	{0;1;∞}
$E[Q_6]$ kJ	68.751	±0.574	49.595	±0.989	-27.86%	{0;1;∞}
$E[Q_7]$ kJ	64.894	±0.819	48.296	±0.900	-25.58%	{0;1;∞}
$E[Q_8]$ kJ	60.115	±0.556	45.183	±0.621	-24.84%	{0;1;∞}
$E[Q_9]$ kJ	53.362	±0.430	38.714	±0.441	-27.45%	{0;1;∞}
$E[Q_t]$ kJ	**579.286**	**±3.113**	**502.139**	**±2.699**	**-13.32%**	-
E[TH] p/s	0.008949	$\pm 2\cdot 10^{-6}$	0.008874	$\pm 3\cdot 10^{-6}$	-0.83%	-

Table 4. Line with failures: performance and optimal control under a throughput constraint.

	Always On *(ref)*		Optimal Control		Δ%	Control Parameter
	Average	IC	Average	IC		
$E[Q_1]$ kJ	15.049	±0.372	15.772	±0.152	4.81%	{∞;*;∞}
$E[Q_2]$ kJ	88.116	±0.760	90.026	±0.216	2.17%	{0;5;∞}
$E[Q_3]$ kJ	80.914	±0.599	74.148	±1.098	-8.36%	{0;1;∞}
$E[Q_4]$ kJ	75.936	±0.809	69.665	±1.489	-8.26%	{0;1;∞}
$E[Q_5]$ kJ	72.150	±0.530	66.072	±1.095	-8.42%	{0;1;∞}
$E[Q_6]$ kJ	68.751	±0.574	62.460	±1.717	-9.15%	{0;1;∞}
$E[Q_7]$ kJ	64.894	±0.819	58.043	±1.535	-10.56%	{0;1;∞}
$E[Q_8]$ kJ	60.115	±0.556	52.546	±0.577	-12.59%	{0;1;∞}
$E[Q_9]$ kJ	53.362	±0.430	42.890	±0.616	-19.62%	{0;1;∞}
$E[Q_t]$ kJ	**579.286**	**±3.113**	**531.622**	**±6.891**	**-8.23%**	-
E[TH] p/s	0.008949	$\pm 2\cdot 10^{-6}$	0.008941	$\pm 2\cdot 10^{-6}$	-0.09%	-

6. Conclusions

A general framework with three-parameter control policy has been applied to machines in a production line with finite buffer capacities. The template built in Arena software environment allows to study complex system when the machines are controlled. Comparing the controlled line performance with the common practice in manufacturing, we can conclude that:

- A general switching policy achieves significant energy savings without largely compromising production throughput;
- To locally control each machine is sub-optimal, indeed, to control simultaneously the machine achieve the best results;
- The control of one machine influences the energy consumed by the other machines due to blocking and starvation effects;
- In a balanced production lines where each machine is controlled, the optimal parameter values of the threshold *N* may have a special structure such as decreasing;
- Machine variability affects the potential energy savings.

Since our results were obtained with simulation, there is no claim they are general and valid for any production line. Future developments will be devoted to generalize these results for general production line and other systems. A sensitivity analysis for critical parameters is considered as an important extension for policy applicability. Furthermore, multiple low-energy states can be considered, and a multiple-stand-by energy control policy can be studied taking into account different warm-up times for each machine transitory.

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