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Procedia CIRP 48 (2016) 301 – 306

www.elsevier.com/locate/procedia

23rd CIRP Conference on Life Cycle Engineering

Energy Saving Opportunities and Value of Information: a Trade-off in a Production Line

Huiting Su[a], Nicla Frigerio[b], Andrea Matta[a]

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

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

Abstract

A general framework for switching the machine off/on has been recently proposed in literature for single machines. However, the amount of information available along the production system is often limited and it might be not trivial to understand which information provides more benefits. This paper studies the performance of a production line when several control policies are applied at machine level. The amount of information at machine level varies and the trade-off with energy reduction is investigated. The considered performance measures are the energy consumed per part and the system throughput. Numerical results are based on discrete event simulation.

Peer-review under responsibility of the scientific committee of the 23rd 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 machine state control strategies that reduce energy consumption during the machine idle periods. These strategies are based on the information the machine can have from the system. This paper studies the performance of a controlled production line when the amount of information at machine level varies.

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 power demand the machine keeps consuming when the production is not requested. Indeed, the machine auxiliary equipment keeps consuming energy during non-productive states. This generates an excess that could be reduced by controlling the machine state, i.e. switching the machine *off*. Recently, the potential of machine state control during non-productive periods has been highlighted by several researchers. For example, Gadhimi et al. [1] estimated up to 26% of energy consumption saving in the analyzed scalping process line by applying a switch-off policy. Weinert and Mose [2] simulated different production scenarios where advanced standby strategies are implemented and the potential saving is shown to be up to 53% of the energy consumed in non-productive periods. However, most of machine tools do not have eco-green functionalities, and in the industrial market there are only few energy-saving control systems available. Most of them have been developed by machine tool builders in order to support the final users. Further, the selection of the policy parameters is not supported by any tool or method and the selection is often experience-based.

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. Mashahei and Lennartson [3] proposed a control policy to schedule off/on mode machine tools in a pallet constrained flow shop under deterministic assumptions. Chang et al. [4] and Brundage et al. [5] estimated the opportunity windows for real-time energy control in machining lines for scheduling machines into on and off modes. This approach considers random failure at machines and assumes the availability of perfect information along the system. Frigerio and Matta [6] studied analytically the switching policy for single machines under the assumption of stochastic arrivals, constant start-up and no information from the buffer in front of the machine. In another work, they considered a policy that includes the upstream buffer occupancy as information [7]. Jia et al. [8] studied serial production lines with Bernoulli machines

Peer-review under responsibility of the scientific committee of the 23rd CIRP Conference on Life Cycle Engineering
doi:10.1016/j.procir.2016.03.147

and finite buffers where some machines can be controlled using buffer information.

The use of simulation which allows an energy simulation of machines under several production scenarios is a powerful method to analyze complex systems. Among the others, Abele et al. [9] proposed a methodology to parametrize and simulate the energy behavior of a machine tool according to its state. Heinemann et al. [10] proposed a hierarchical evaluation tool to analyze the impact of several energy measures on the system performance, e.g., changing lot size, equipment, process parameters. Frigerio and Matta [11] discussed the impact of a machine control on the performance of a production line when a control policy is applied locally at machines.

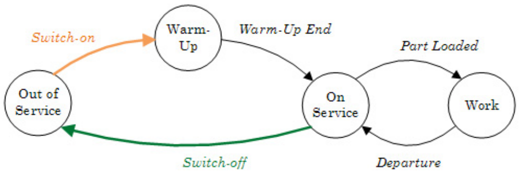

Fig. 1: Machine state model under a switching control policy.

1.2. Objective and Contribution

From the literature analysis it emerges that the machine control 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 buffer occupancy information is used for energy saving purpose. However, the impact of the information the machine has access has never been discussed yet in terms of how different amount of information may affect the controlled production system performance.

This paper studies a production line with finite buffer capacities when several switching policies are applied at machine level: (i) three policies will be proposed at machine level according to the amount of information that might be available, (ii) the value of the information will be discussed in terms of system performance under a certain policy, and (iii) the interaction between two sequential controlled machines will be analyzed because it might cause system deadlocks such that the service cannot be resumed. 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.

Two types of information will be considered: the upstream buffer occupancy, and the downstream buffer occupancy. The first policy (Upstream) considers only upstream information and it has been recently investigated by many researchers in the field of energy efficiency improvement of production systems. The second policy (Downstream) considers only downstream information and, together with the third policy (Upstream&Downstream) which uses both information types, have never been addressed in these terms. Actually, Jia et al. [8] studied a policy that uses upstream and downstream information, but they assumed that two sequential machines cannot be controlled. The simultaneous control of more than one machine in a system might cause system deadlocks because of the interactions between machines. Therefore, proper conditions that avoid the system to visit deadlocks must be introduced.

Discrete event simulation is used for performance evaluation. An ad-hoc template has been built in Arena© software environment for modeling a general machine controlled with one of the three switching policy. Since our results were obtained with simulation, there is no claim they are general and valid for any production line. However, this is a preliminary study in which buffer threshold switching policies are analyzed on a production line, and we think that our considerations will be helpful for many researchers and practitioners.

2. Assumption

A serial production line composed of m buffers and m machines working a single part type is considered. The single part type assumption is valid for machines specialized for one single part type or for a family of similar items, and machines working large batches while considering the single batch. Let $x_i \in \mathcal{S}_X = \{1, 2, 3, 4\}$ be the i-th machine state according to Frigerio and Matta [6][11]: $x_i = 1$ if out-of-service, $x_i = 2$ if on-service, $x_i = 3$ if start-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 *start-up* state–i.e., the transitory warm-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 start-up. The start-up duration $T_{\text{wu},i}$ at machine i is a random value because the machine may require different times 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. We assume there is a buffer between two machines with finite capacity K_i, where i is the buffer index. The buffer upstream the machine controls the release of parts, whereas the downstream buffer receives the parts after the completion of the process. The number of parts in each buffer is represented as the integer variable $n_i \in [0, K_i]$. Each machine can be blocked if the downstream buffer is full. Further, blocking before service is assumed. We assume the last machine of the line cannot be blocked and the first machine cannot be starved of raw parts. When a machine is blocked, it is assumed to consume as in the on-service state. The machine processing time $T_{p,i}$ at the machine i is random with mean $t_{p,i}$. The stochastic processes involved in the system are assumed to be independent of each other and stationary and they can be calibrated to model equipment failures. The transition between two states can be triggered by the occurrence of an uncontrollable event or a controllable event.

3. Control Policies and Information Flow

The machine behaviour follows the machine state model in Fig. 1. Whenever a part is loaded from the upstream buffer, the machine passes from the on-service state to the working state. At part departure the machine returns on-service until the next part is loaded or the switch off command is issued. In the latter case, the machine is triggered out-of-service and the service is interrupted. With the switch on command the machine starts the start-up procedure to resume the service. As a consequence, the machine is switched off to save energy and, once in out-of-service, it is warmed up to properly resume the service. The extreme situation in which the machine is always kept on-service is considered as the Always On Policy (AO). The switching commands follow different rules according to the information the control has access to. Therefore, the more the information, the more complex the control.

A control policy that uses only the upstream buffer information is the N-policy. Under this policy, a machine is switched off at completion of a busy period and the service is resumed when N^U parts have accumulated in the buffer. This *Upstream Policy (UP)* allows to switch off the machine when it is idle, therefore, it focuses on the excess generated while the machine is starving but it cannot control the machine while blocked. The control parameter N^U cannot exceed the buffer capacity, or the switch on command will never be issued and the machine would be in deadlock. The Upstream policy has been discussed in some previous works [6] [7] [11].

Similarly, a control policy that uses only the downstream occupancy can be formalized:

Downstream Policy (DP)*: Switch off when the downstream buffer level raises at a threshold N^D_{off}. Switch on as soon as the number of parts decreases below a threshold N^D_{on}.*

If the threshold N^D_{off} exceeds the buffer capacity, the policy degenerates in the AO. In order to avoid machine deadlock, the following condition has to be verified:

$$N^D_{\text{off}} > N^D_{\text{on}} \geq 0 \tag{1}$$

otherwise the switch-on control will never be issued. The DP controls the machine state when blocked, therefore, it focuses on the excess generated while the machine is blocked but it is not working on the machine while starved.

In this work, we assume the machine may have access to both upstream and downstream buffer occupancy information. Combinations of the UP and the DP can be implemented by maintaining the consistency between off/on rules. This kind of policy focuses on the excess generated while the machine is starved and/or blocked:

Upstream & Downstream Policy (UDP)*: Switch off when starving or when the number of parts in the downstream buffer exceeds a certain threshold N^D_{off}. Switch on when the number of parts in the upstream buffer exceeds a certain threshold N^U and meanwhile, the downstream buffer holds less than a certain number of parts N^D_{on}.*

The control to be applied at machine i according to UDP is:

$$\begin{cases} \text{switch-off} & \text{if } x_i = 2 \wedge (n_i = 0 \vee n_{i+1} \geq N^D_{\text{off},i}) \\ \text{switch-on} & \text{if } x_i = 1 \wedge (n_i \geq N^U_i \wedge n_{i+1} \leq N^D_{\text{on},i}) \\ \text{do nothing} & \text{otherwise.} \end{cases} \tag{2}$$

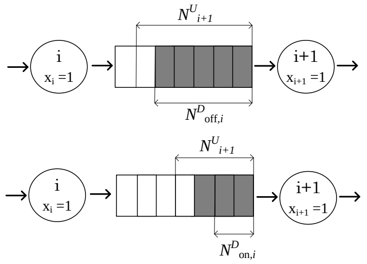

Fig. 2: System deadlocks with UDS policy.

where the vector $\mathbf{a_i} = \{N^U_i, N^D_{\text{off},i}, N^D_{\text{on},i}\}$ is composed by the three control parameters of machine i. In order to avoid machine deadlocks, the conditions described for UP and DP must hold: (i) $N^U_i \leq K$, and (ii) $N^D_{\text{off},i} > N^D_{\text{on},i} \geq 0$. Additional conditions must be further investigated because the occupancy of a buffer is related to the control of two machines. To avoid system deadlocks when two sequential machines are controlled, the control parameters have to satisfy the following conditions:

$$N^D_{\text{off},i} \geq N^U_{i+1} \tag{3}$$

$$N^D_{\text{on},i} \geq N^U_{i+1} \tag{4}$$

Condition (3) avoid the first deadlock in Fig. 2 where both machines i and $i+1$ are out-of-service and the intermediate buffer holds $N^D_{\text{off},i}$ which is the threshold to interrupt the service in machine i. Therefore, machine $i+1$ cannot be switched on because its upstream occupancy never reaches the required level N^U_{i+1} and the system is in deadlock. Condition (4) avoid the second deadlock in Fig. 2 where machines i and $i+1$ are out-of-service and the buffer holds n parts such that $N^U_i > n > N^D_{\text{on},i+1}$. The number of parts n cannot increase, bebecause the part flow is interrupted at machine i, nor decrease because the flow is interrupted also at machine $i+1$. Therefore, machines cannot resume the service and the system is in deadlock.

The machine expected energy consumed per part $\mathbb{E}\left[Q^m_i\right]$ (expressed in $kJ/part$) is the ratio between the expected power consumed and the expected throughput at the same machine:

$$\mathbb{E}\left[Q^m_i\right] = \frac{\mathbb{E}\left[P_i\right]}{\mathbb{E}\left[TH_i\right]} \; [kJ/part] \quad \forall i = 1..m \tag{5}$$

Similarly for the buffer expected energy consumed per part $\mathbb{E}\left[Q^b_i\right]$ with $i = 1..m$. Let w_{x_i} be the power absorbed by the i-th machine in state x_i. Further, let w_{q_i} be the power necessary for holding one part in the queue i, when the following machine is busy. Therefore, the expected power $\mathbb{E}\left[P_i\right]$ consumed by buffer i or machine i depends on the probability of being in each state in the feasible state set. The line throughput is defined as the throughput of the m-th machine, $\mathbb{E}\left[TH_m\right] = \mathbb{E}\left[TH\right]$, and due to the conservation of flow it is $\mathbb{E}\left[TH_m\right] = \mathbb{E}\left[TH_i\right] \; \forall i = 1..m-1$. In the following, the throughput values are expressed in parts per hour (pph). The expected total energy consumed per part $\mathbb{E}\left[Q_t\right]$ is the sum of the machine and buffer expected energy consumptions:

$$\mathbb{E}\left[Q_t\right] = \sum_{i=1}^{m} \mathbb{E}\left[Q^b_i\right] + \sum_{i=1}^{m} \mathbb{E}\left[Q^m_i\right] \; [kJ/part] \tag{6}$$

4. Description of experiments

A production line composed by single machine workstations is the system to be analyzed in this work. We consider a line of 9 identical machines, and each buffer in the line has same finite holding capacity of 10 slots. These homogeneities along the line make difficult—or even not possible— the identification of an energy hotspot, thus it is not trivial to select a machine to be controlled.

The machine tools considered are real CNC machining centers with small-medium workspace-cube and locally chilled. This machine type requires 5.35 kW while on-service, and 0.52 kW when out-of-service. The machine start-up has a power consumption of 6 kW and deterministic duration t_{wu} = 20 s. We acquired these data with dedicated experimental measurements from a real machine configured to operate in a powertrain manufacturing line. The power consumed during the working state (12 − 16 kW on average) depends on the process executed. The power demand of this machine is aligned with data found in the literature and can be representative of a wide range of machine tool commonly used in the manufacturing field. The higher variability is on the working power which is highly dependent on the process, but it is not considered in the analysis because it does not affect the selection of the policy parameters, being not dependent on control actions.

4.1. Scenarios

Two main scenarios are considered in the experiments: scenario B with a balanced line, and scenario M5 with a bottleneck in M5. In both cases, systems are globally controlled, which means controlling all machines at the same time. As far as scenario B, the processing time at all machines is identically distributed and follows 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. In scenario M5, the processing time of machines M1-M4 and M6-M9 is: 100 s in the 98% of the cases and 280 s in 2%. In such a system, M5 is the bottleneck. Two variations of each scenario are considered resulting in four cases in total: cases B/H and M5/H have an holding power consumption w_q = 0.1 kW, cases B/NH and M5/NH have negligible holding power. A power consumption w_q = 0.1 kW represents a high percentage of total demand of cases B/H/AO (Table 1) and M5/H/AO (Table 3). Higher values of w_q are therefore not analyzed in this work.

Experiments are conducted using four policies: Always On (AO), Upstream Policy (UP), Downstream Policy (DP), and Upstream & Downstream Policy (DUP). Actually, UP has the first machine (M1) Always On because it is saturated, while other machines (M2–M9) use UP. DP has the last machine (M9) Always On because it is never blocked, while other machines (M1–M8) use DP. For UDP, M1 is downstream controlled and M9 is upstream controlled for the previous reasons, while M2–M8 are under UDP. We refer to each case with a notation “*scenario/holding/policy*”, e.g., B/NH/AO is scenario B, negligible holding cost, always on policy.

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, a new Arena© template (i.e., a library) has also been created for modeling a general machine controlled with a general switching policy that considers different amounts of information from the environment. By using our 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, start-up and policy parameters.

OptQuest is used to select a set of control parameters (N^U, N^D_{off}, and N^D_{on}) for each controlled machine to minimize the expected total energy consumption of the line. OptQuest automatically chooses the number of replications from 2 to 10, it compares solutions to be significantly different on average (95% of confidence), and it selects the best solution. Simulations in OptQuest were executed for a duration of 10^7 s (about 116 days) and an initial transient identified with the Welch method equal to $5 \cdot 10^5$ s (about 6 days). In order to give more accurate results and to select the best solution, the top solutions identified by OptQuest have been evaluated in longer simulations (20 replications with 10^8 s (about 1157 days — 3 years) simulation length and $5 \cdot 10^5$ s of initial transient. A non–parametric test has been used to compare results and verify whether they were significantly different (Kuskal-Wallis test with $p_{value} < 0.05$).

5. Numerical Results

5.1. Scenario B/H: balanced line with holding power

Compared to B/H/AO, the three control policies (B/H/UP, B/H/DP, and B/H/UDP) achieved significant energy saving. As reported in Table 1, the optimal control for B/H/UP is consistent with the results achieved in a previous paper [11] and saves 11.40% in terms of energy. The saving achievable increses when using downstream information (B/H/DP saves 25.73%). The optimized control for B/H/UDP saves almost 50% compared to B/H/AO—i.e., more than the effect of UP and DP together— and the optimal policy is not the combination of the solutions found for UP and DP.

However, the system expected throughput varies significantly because of the time spent for start-ups, and the variation is more significant for UDP. Therefore, in order to study whether the control policies can still achieve significant energy saving while ensuring a certain throughput, constrained optimizations have also been executed using minimum target levels for the throughput. Compared to the common practice (B/H/AO), the throughput loss for the optimal solutions of cases B/H/UP and B/H/DP are about 0.74% and 2.34%, respectively (see Table 1). Therefore, to compare control policies under the same production constraint, the throughput targets have been set close to these values: namely 0.7% and 2% of throughput reduction. A constraint at 0.1% is also tested. The latter constraint cannot be met in case B/H/UDP, therefore, the solution with the highest throughput is in Table 1.

The plot of energy consumption vs throughput is shown in Fig. 3. Although the optimization is constrained, the saving is still significant. Particularly under the optimal control, DP always performs better than UP, and UDP always results as the best policy among the others. Theoretically, UP and DP are expected to perform similarly, because starvation and blockage are symmetrical along the line— UP switches off the machines when starved while DP switches off the machines when blocked. The reason of this misalignment is in the energy consumed holding parts. DP limits the buffer level at N^d_{off} as detailed in section 3. Therefore, it performs better because it

Table 1: Case B/H: unconstrained and constrained optimal control

	B/H/AO	B/H/UP		B/H/DP			B/H/UDP			
TH Constraint	(ref)	–	-0.1 %	–	-0.1%	-0.7%	–	-0.1%	-0.7%	-2%
$\mathbb{E}[Q^b]$	515.703	497.949	525.316	319.794	497.980	387.959	224.380	518.830	454.744	337.856
$\mathbb{E}[Q^m]$	145.401	87.763	91.202	171.183	93.653	137.658	112.391	34.136	36.020	49.990
$\mathbb{E}[Q_t]$	661.103	585.712	616.519	490.977	591.633	525.616	336.771	552.966	490.763	387.846
	±1.447	±1.792	±1.785	±0.381	±0.869	±0.610	±0.187	±1.614	±0.921	±0.617
$\mathbb{E}[TH]$	32.1372	31.9000	32.1145	31.3834	32.100	31.9104	30.0082	32.099	31.9280	31.5428
	±0.0324	±0.0050	±0.0047	±0.0040	±0.0004	±0.0040	±0.0061	±0.0028	±0.0036	±0.0032
$\mathbf{a}_1$	$\{*,*,*\}$	$\{*,*,*\}$	$\{*,*,*\}$	$\{*,6,4\}$	$\{*,10,9\}$	$\{*,6,5\}$	$\{*,2,1\}$	$\{*,10,9\}$	$\{*,10,6\}$	$\{*,6,2\}$
$\mathbf{a}_2$	$\{*,*,*\}$	$\{9,*,*\}$	$\{1,*,*\}$	$\{*,7,4\}$	$\{*,10,9\}$	$\{*,7,4\}$	$\{1,4,1\}$	$\{1,10,9\}$	$\{2,10,8\}$	$\{1,7,5\}$
$\mathbf{a}_3$	$\{*,*,*\}$	$\{7,*,*\}$	$\{1,*,*\}$	$\{*,7,4\}$	$\{*,10,7\}$	$\{*,10,9\}$	$\{1,6,1\}$	$\{1,10,9\}$	$\{2,10,4\}$	$\{1,10,4\}$
$\mathbf{a}_4$	$\{*,*,*\}$	$\{1,*,*\}$	$\{1,*,*\}$	$\{*,6,5\}$	$\{*,10,9\}$	$\{*,10,9\}$	$\{1,10,9\}$	$\{1,10,9\}$	$\{1,10,9\}$	$\{2,10,6\}$
$\mathbf{a}_5$	$\{*,*,*\}$	$\{1,*,*\}$	$\{1,*,*\}$	$\{*,5,4\}$	$\{*,10,9\}$	$\{*,10,9\}$	$\{1,10,1\}$	$\{1,10,9\}$	$\{1,10,8\}$	$\{1,9,7\}$
$\mathbf{a}_6$	$\{*,*,*\}$	$\{1,*,*\}$	$\{1,*,*\}$	$\{*,7,5\}$	$\{*,10,9\}$	$\{*,10,9\}$	$\{1,10,9\}$	$\{1,10,9\}$	$\{1,10,9\}$	$\{1,10,7\}$
$\mathbf{a}_7$	$\{*,*,*\}$	$\{1,*,*\}$	$\{1,*,*\}$	$\{*,8,4\}$	$\{*,10,9\}$	$\{*,10,9\}$	$\{1,10,9\}$	$\{1,10,9\}$	$\{1,10,9\}$	$\{1,10,7\}$
$\mathbf{a}_8$	$\{*,*,*\}$	$\{1,*,*\}$	$\{1,*,*\}$	$\{*,6,5\}$	$\{*,10,9\}$	$\{*,10,9\}$	$\{1,7,6\}$	$\{1,10,9\}$	$\{2,10,9\}$	$\{1,10,8\}$
$\mathbf{a}_9$	$\{*,*,*\}$	$\{1,*,*\}$	$\{1,*,*\}$	$\{*,*,*\}$	$\{*,*,*\}$	$\{*,*,*\}$	$\{1,*,*\}$	$\{1,*,*\}$	$\{1,*,*\}$	$\{1,*,*\}$

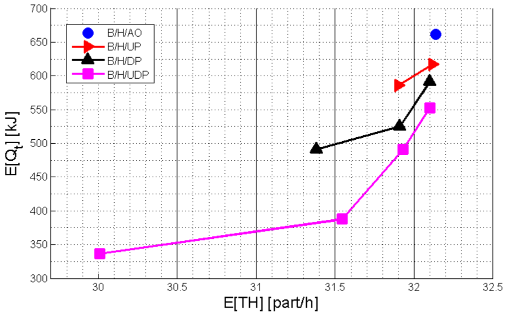

Fig. 3: Total expected energy vs expected throughput of the optimal solutions in case B/H: unconstrained and constrained results.

highly reduces the buffer energy which represents the 78.01% of the total energy consumption when all machines are kept on–service (Table 1). Further, the results in Table 1 show that the machine energy in B/H/DP is higher than that in B/H/UP for both unconstrained and constrained optimizations. However, the total energy in B/H/DP is still much lower than in B/H/UP because of the high holding energy in B/H/UP.

Under a throughput contraint, UDP still performs better than other policies (UP and DP). When the same contraint is applied, UDP saves almost the sum of the amount saved with UP and DP. The reason is that UDP controls the machine both during starvation and blockages since it has access to more information.

5.2. *Scenario B/NH: balanced line without holding power*

The system performance for unconstrained optimizations are collected in Table 2. Although the expected total energy saving achieved with UP and DP are still significantly different (Kuskal-Wallis test $p_{value} < 0.005$), such a difference is much smaller than in B/H. This means that when the holding cost is not a matter in the optimization problem, the UP and DP performs similarly in terms of energy, which is consistent with our expectation. These results hold also in constrained optimizations. The throughput reduction is also lower than B/H. A reasonable explanation is that all control policies result in a raise of buffer level when ignoring holding cost, thus decreasing machine starvation and increasing throughput.

Table 2: Case B/NH: unconstrained optimal control.

B/NH	AO	UP	DP	UDP
$\mathbb{E}[Q_t]$	145.401	85.228	83.309	33.844
	±0.498	±0.451	±0.410	±0.115
$\mathbb{E}[TH]$	32.1372	31.9572	31.88232	32.0022
	±0.0032	±0.0036	±0.0065	±0.0040
$\mathbf{a}_1$	$\{*,*,*\}$	$\{*,*,*\}$	$\{*,10,9\}$	$\{*,10,9\}$
$\mathbf{a}_2$	$\{*,*,*\}$	$\{10,*,*\}$	$\{*,10,9\}$	$\{4,10,9\}$
$\mathbf{a}_3$	$\{*,*,*\}$	$\{2,*,*\}$	$\{*,10,9\}$	$\{2,10,9\}$
$\mathbf{a}_4$	$\{*,*,*\}$	$\{1,*,*\}$	$\{*,10,9\}$	$\{3,10,9\}$
$\mathbf{a}_5$	$\{*,*,*\}$	$\{1,*,*\}$	$\{*,10,9\}$	$\{2,10,9\}$
$\mathbf{a}_6$	$\{*,*,*\}$	$\{1,*,*\}$	$\{*,10,9\}$	$\{1,10,9\}$
$\mathbf{a}_7$	$\{*,*,*\}$	$\{1,*,*\}$	$\{*,10,9\}$	$\{1,10,9\}$
$\mathbf{a}_8$	$\{*,*,*\}$	$\{1,*,*\}$	$\{*,8,0\}$	$\{3,10,9\}$
$\mathbf{a}_9$	$\{*,*,*\}$	$\{1,*,*\}$	$\{*,*,*\}$	$\{3,*,*\}$

A remarkable results is that, the optimal control for the UDP is dominant. The energy saved with UDP is almost the sum of saving with UP and DP—which is aligned with results in section 5.1. Furthermore, it is interesting that the loss of throughput is also the least. The reasons of this result need to be further investigated in the future with more focused experiments.

5.3. *Cases M5/H and M5/NH: unbalanced line*

Also in these scenarios, the three policies achieved significant energy saving as in Tables 3 and 4. Since M5 is bottleneck, the number of parts in buffers upstream the bottleneck is high and machines are mostly blocked. Downstream, the buffer level

Table 3: Case M5/H: unconstrained optimal control.

M5/H	AO	UP	DP	UDP
$\mathbb{E}[Q_t]$	735.423 ±0.821	652.820 ±0.832	406.637 ±0.338	274.067 ±0.171
$\mathbb{E}[TH]$	33.0233 ±0.0048	33.0109 ±0.0067	32.6770 ±0.0033	32.2019 ±0.0073
$\mathbf{a}_1$	$\{*,*,*\}$	$\{*,*,*\}$	$\{*,3,2\}$	$\{*,2,1\}$
$\mathbf{a}_2$	$\{*,*,*\}$	$\{7,*,*\}$	$\{*,5,1\}$	$\{1,4,1\}$
$\mathbf{a}_3$	$\{*,*,*\}$	$\{3,*,*\}$	$\{*,4,3\}$	$\{1,6,1\}$
$\mathbf{a}_4$	$\{*,*,*\}$	$\{3,*,*\}$	$\{*,5,3\}$	$\{1,6,1\}$
$\mathbf{a}_5$	$\{*,*,*\}$	$\{2,*,*\}$	$\{*,10,0\}$	$\{1,10,9\}$
$\mathbf{a}_6$	$\{*,*,*\}$	$\{1,*,*\}$	$\{*,6,4\}$	$\{1,6,1\}$
$\mathbf{a}_7$	$\{*,*,*\}$	$\{1,*,*\}$	$\{*,6,2\}$	$\{1,6,3\}$
$\mathbf{a}_8$	$\{*,*,*\}$	$\{1,*,*\}$	$\{*,6,5\}$	$\{1,10,5\}$
$\mathbf{a}_9$	$\{*,*,*\}$	$\{1,*,*\}$	$\{*,*,*\}$	$\{1,*,*\}$

is low and machines frequently starves. Therefore a policy that works on blocked machine should perform better. Indeed, DP results are around four times that of UP. UDP is still the best policy. The results achieved for M5/NH are consistent with the previous cases. Two alternative policies have been also evaluated for case M5/H. (i) A policy where M1-M5 are always on in order to avoid the starvation of the bottleneck machine and M6-M9 controlled with UP. The total energy consumption of this case is not statistically different from the optimal solution of M5/H/UP (Kuskal-Wallis test with $p_{value} = 0.191$). That means M1–M4 are very rarely switched off and the control applied does not really matter. (ii) A policy which uses DP on M1-M5 and UP on M6-M9. This policy performs better than UP and DP because it apply the policy which is more appropriated on machines having high blocking/starvation.

In scenario M5 (both H and NH) the savings achievable are higher than that in scenario B, beause the non-bottleneck machines are less saturated, therefore the amount of energy exceed is higher. For the same reason, the throughput reduction is lower because the bottleneck machine, that mainly affects the throughput, is almost never switched off.

Table 4: Case M5/NH: unconstrained optimal control.

M5/NH	AO	UP	DP	UDP
$\mathbb{E}[Q_t]$	231.935 ±0.746	135.457 ±0.483	105.724 ±0.340	33.235 ±0.086
$\mathbb{E}[TH]$	33.0233 ±0.0048	33.0046 ±0.0062	32.8690 ±0.0056	32.9206 ±0.0049
$\mathbf{a}_1$	$\{*,*,*\}$	$\{*,*,*\}$	$\{*,9,4\}$	$\{*,10,5\}$
$\mathbf{a}_2$	$\{*,*,*\}$	$\{6,*,*\}$	$\{*,10,9\}$	$\{4,10,7\}$
$\mathbf{a}_3$	$\{*,*,*\}$	$\{4,*,*\}$	$\{*,10,5\}$	$\{7,10,4\}$
$\mathbf{a}_4$	$\{*,*,*\}$	$\{4,*,*\}$	$\{*,10,7\}$	$\{4,10,5\}$
$\mathbf{a}_5$	$\{*,*,*\}$	$\{3,*,*\}$	$\{*,10,9\}$	$\{1,10,9\}$
$\mathbf{a}_6$	$\{*,*,*\}$	$\{3,*,*\}$	$\{*,9,8\}$	$\{3,10,7\}$
$\mathbf{a}_7$	$\{*,*,*\}$	$\{2,*,*\}$	$\{*,7,1\}$	$\{7,10,6\}$
$\mathbf{a}_8$	$\{*,*,*\}$	$\{5,*,*\}$	$\{*,1,0\}$	$\{6,10,6\}$
$\mathbf{a}_9$	$\{*,*,*\}$	$\{5,*,*\}$	$\{*,*,*\}$	$\{4,*,*\}$

6. Conclusion Remarks

Several control policies have been applied to machines in a production line with finite buffer capacities according to the level of information available at machine level. A new simulation template library has been created allowing to study complex systems when the machines are controlled. Comparing the different control policies with the common practice in manufacturing, it is remarkable that:

- All control policies may achieve significant energy saving without largely compromising production throughput. Savings in unbalanced lines are more promising.
- The more information the control have access to, the higher the energy saving.
- DP performs better than UP, because it reduces the number of parts in the buffers. However, when the holding energy is negligible, UP and DP perform similarly.

Since these results were obtained with simulation, there is no claim they are general and valid for any production line. However, the study cases analyzed in this paper are seminal to further analysis. More complex production systems will be investigated in future experiments, once the effect of the policies have been fully understood. Structural properties of the optimal control policies will be further investigated for optimization purposes. A sensitivity analysis for critical parameters is considered as an important extension for policy applicability. Applications of the proposed policies in real manufacturing systems are straightforward, particularly for energy intensive processes.

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