Energy Saving Policies for a Machine Tool with Warm-Up, Stochastic Arrivals and Buffer Information

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Abstract— **One of the measures for saving energy in manufacturing is the implementation of control strategies that reduces energy consumption during the machine idle periods. Specifically, the paper proposes a framework that integrates different control policies for switching the machine *off* when the production is not critical, and *on* either when the part flow has to be resumed or the queue has accumulated to a certain level. A general policy is formalized by modeling explicitly the power consumed in each machine state. A threshold policy is analyzed and the optimal parameter is provided for an M/M/1/K system. Numerical results are based on data acquired with dedicated experimental measurements on a real machining centre, and a comparison with common practices in manufacturing is also reported.**

I. Introduction

Finding technical solutions able to reduce the energy consumption in manufacturing is becoming a challenging goal. One of the most relevant measures for reducing energy consumption at machine level is the implementation of control strategies for the efficient usage of components by minimizing processing time and non-value tasks [1]. This paper proposes a framework for deciding the most suitable energy state for the machine during non productive phases using three control parameters. The machine is switched *off* when the production is not needed because the part flow is interrupted, then it is switched *on* when the production has to be resumed or the machine has to be ready before the arrival of a part.

II. Brief Literature Survey

The power requirement of a machine tool can be divided into two main components. A *Fixed Power*, demanded for the operational readiness of the machine and independent from the process, and a *Load Dependent Power*, demanded to distinctively operate components enabling and executing the main process [2]-[6]. At machine level the state control can achieve significant savings because it aims at reducing the 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. As a consequence, several research efforts focused on the problem of controlling production systems by scheduling startup and shutdown of machines to minimize total energy consumption. Some research studies did not consider any warm-up transitory when the machine tool is switched off. In order to give some examples, Prabhu et al. [8] developed an analytical model by combining an M/M/1 model with an energy control policy. Considering firstly a station, they calculate the time interval for switching the machine off during its idle period, with respect to a target energy waste limit. In this study, the machine switch-off accounts for a certain idling power, but the switch-on is instantaneous once the part arrives. Chang et al. [9] analyzed several real-time machine switching strategies using energy saving opportunity windows in a machining line under random failures. Other research studies considered a deterministic and constant warm-up duration whenever the machine is switched off. Mouzon et al. [10] presented several switch-off dispatching rules for a non-bottleneck machine in a job shop. Chen et al. [11] [12] formulated a constrained optimization problem for scheduling machines *on* and *off* modes in a production line based on Markov chain modeling and considering machines having Bernoulli reliability model. Sun and Li [13] proposed an algorithm to estimate opportunity windows for real-time energy control in a machining line under random failures. Mashahei and Lennartson [14] proposed a control policy to switch off machine tools in a pallet constrained flow shop. The policy aims to minimize the energy consumption under design constraints and considering two idle modes with deterministic warm-up durations. Frigerio and Matta [15] [16] studied analytically several policies to control a machine with deterministic warm-up. The policies are assessed in terms of expected energy consumed and they are optimized under the assumption of general arrival distribution. They also modeled explicitly the warm-up time as dependent on the time period the machine stays in a low power consumption state [17].

Queueing systems where machines may become unavailable for a period of time, due to a variety of reasons, are called in the literature *vacation queueing system*. Excellent surveys on vacation models have been reported by Doshi [18], Takagi [19], Tian and Zhang [20], Ke et al. [21], and, particularly, Tadj and Choudhury [22] focused on the optimization problem. Yadin and Naor [23] proposed firstly the so called *N-Policy* in a queueing system where the machine becomes unavailable after a random closedown time has elapsed from the end of a productive period, and the service is resumed after a random warm-up time when the queue length reaches a threshold N. They also provided an approximate optimal solution that minimizes a cost-based objective function. Baker [24] analysed the model intro-

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ducing exponentially distributed warm-up time for resuming the service. With instantaneous exahustive switch-off, Sikdar [25] analyzed a G/M/1/K queueing system and studied the effects of model parameters on performance indicators. Ke and Wang [26] proposed an algorithm in order to determine the optimal value of N at minimun cost for a G/M/1 finite queueing system. Another intuitive approach is given by the *T-Policy*, where 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* where the machine will be reactivated when either N customers have accumulated in the queue or the first customer arrived has been in the queue for T time units, whichever happens first. A variation of the NT-Policy considers T as the time after the machine switch-off. In order to give some examples, Feyaerts et al. [29] analyzed in the discrete time the effects of an NT-Policy on an M/G/1 queue with a reliable machine and no warm-up. Using fixed N and T, they evaluated performances varying the arrival rate by means of numerical examples. Ke analyzed an M/G/1 system with a random warm-up time and closedown time [28], and he proposed an algorithm to find out the optimal NT-Policy for an M/G/1 system with random warm-up time [28]. A practical problem is used as numerical illustration of algorithm application.

The literature analysis points out a lack of theoretical modeling concerning the machine energy efficient control problem for systems under uncertainty. The problem of vacations queueing system has been deeply developed without referring to energy objective function. Moreover, vacation policies have been assessed without giving a complete analysis on where the policies perform efficiently. A queueing system with a single machine tool where the buffer capacity is finite, the warm-up time is not negligible, and the closedown time is considered as an additional control parameter to be optmized has not been studied yet. This paper studies a general framework for energy oriented control of machine tools in manufacturing, considering a new three-parameter control policy—i.e., the *TNT-Policy*. The machine is controlled by activating a transition from the on-service to the out-of-service state—i.e., *Switch-off command*— based on a time threshold τ_{off}. A second transition from the out-of-service to the warm-up state—i.e., *Switch-on command*— is activated when the queue has accumulated to level N or according to a time threshold τ_{on}. Referring to a real CNC machining center, experimentally characterized to estimate the power demand, an N-Policy is studied as a special case of the TNT-Policy. Specifically, this work considers an M/M/1/K system with a reliable machine tool and warm-up. The optimal conditions are analyzed on the basis of a set of numerical cases built to provide useful guidelines for practical implementation of energy saving control policies. A comparison with the common practices in manufacturing is also reported.

III. Assumptions

A workstation composed by a finite input buffer and a single machine working a single part type is considered as the system to be controlled. 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 the single batch.

The machine can be in one of the following states: out-of-service, on-service, warm-up and working. In the *out-of-service* state—i.e., the stand-by state— some of the machine modules are not ready, indeed, only the emergency services of the machine are active while all the others are deactivated. In this state, the machine cannot process a part being in a kind of "sleeping" mode. The power consumption of the machine when out-of-service is denoted with x_{out}, generally lower compared to that in the other machine states. In the *on-service* state—i.e., the idle state— the machine is ready to process a part upon its arrival. The machine power consumption when on-service, denoted with x_{on}, is due to the activation of all machine modules that have to be ready for processing a part. From the out-of-service to the on-service state the machine must pass through the *warm-up* state, where a procedure is executed to make the modules suitable for processing. The warm-up procedure has duration and power consumption equal to t_{wu} and x_{wu}, respectively. The value x_{wu} is generally greater compared to that in the other machine states. The duration t_{wu} of the warm-up is assumed to be a random value because the machine can request 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 and the requested power changes according to the process.

We assume the machine has an input buffer with finite capacity K controlling the release of parts to the machine. In more details, a part is sent to the machine only during its idle or non productive periods, otherwise, the part has to wait in the queue with a First-Come First-Served (FCFS) service rule—the FCFS assumption does not influence the developed analysis. After the completion of the process the part leaves the system. The number of parts in the system is represented as the integer variable $n \in [0, K+1]$, because, given the buffer capacity K, the system can be either *empty* (i.e., $n = 0$), or *not-empty* (i.e., $0 < n \leq K+1$). If a part arrives when the machine is busy—this can happen when the machine is in out-of-service, on-service, or executing the warm-up procedure— there is a penalty. We express this penalty by the power consumption x_q necessary for keeping a part waiting in the queue. An infinite buffer is assumed downstream the machine.

For simplicity, the machine is assumed to be perfectly reliable, thus failures cannot occur; this assumption can be relaxed without requiring large extensions to the developed analysis. The interarrival time is a random variable t_i with the probability density function (PDF) $f_i(t_i)$ modeling the time T_i between two part arrivals at the station—where t_i is the realization of T_i. Similarly, the machine processing time T_p is random with the PDF $f_p(t_p)$. The stochastic processes involved in the system are assumed to be independent of each other. The transition between two states can be triggered by the occurrence of an uncontrollable event—e.g., the part arrival— or a controllable event. During the idle periods of the machine it is not necessary to keep all the machine modules active, and the machine can be moved, with a proper control, into the out-of-service state characterized by a low power consumption.

IV. TNT Control Policy

A general control policy is now presented describing the system behavior in terms of machine states and transitions. First of all, the number of parts in the system varies according to the part arrivals and departures as represented in Fig. 1. Upon an arrival the value n increases until the station is full ($n = K+1$) and cannot contain more parts. Furthermore, each departure decreases n until the station is empty ($n = 0$). This behaviour is not affected by the control policy applied.

Policy 1 (TNT-Policy): If the buffer is empty, switch off the machine after a time interval τ_{off} has elapsed from the last departure. Then, switch on the machine when the number of parts in the queue reaches a proper level N or after a time interval τ_{on} has elapsed from the last departure—i.e., when $\tau_{on} - \tau_{off}$ has elapsed from the switch-off command.

The behavior of the machine is represented in Fig. 2. From the initial on-service state, two situations may happen: both an arrival occurs and the machine starts working the part, or the time interval τ_{off} has elapsed and the machine is switched off. During the processing time, other parts can enter in the system until the station is full ($n \leq K+1$) and the machine continues processing the parts in the queue until the last part is cleared from the system. Once in out-of-service, the machine is warmed up when the number of parts in the queue exceeds a certain level $N \in [1, K]$. Otherwise, after τ_{on} the machine can be switched on in advance to be ready to process the next part, even if the queue did not accumulate N parts. In order to be time consistent, the switch-on command has to be issued after the switch-off command [16]:

$$\tau_{\text{on}} \geq \tau_{\text{off}} \tag{1}$$

If a part arrives while the machine is in the warm-up state, the part must wait in the queue. The queue level cannot exceed buffer capacity K. When the warm-up procedure ends the machine enters in the on-service state, if the station is empty ($n = 0$), or in the working state, otherwise. The control for Policy 1 is $\mathbf{a_1}$:

$$\mathbf{a_1} = \{\tau_{\text{off}}; N; \tau_{\text{on}}\} \tag{2}$$

that is a vector composed by the three control parameters.

As special cases, four simpler strategies of managing a machine are discussed. Policy 2 to Policy 4 have been analyzed in previous works [15]-[17] and represent situations in which the machine is controlled according to timed-constrained control parameters, i.e., when the threshold level $N = 1$.

Policy 2 (Always on): Stay in the on-service state after the departure of a part.

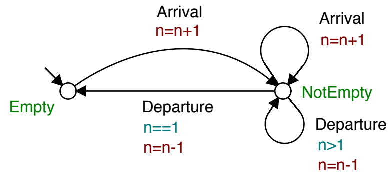

Fig. 1. Station state according to the number of parts in the system n

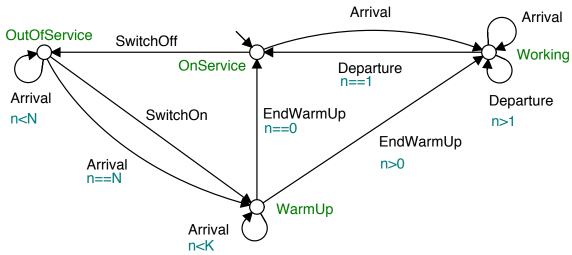

Fig. 2. Machine state model with *TNT-Policy* active

The machine stays in the working state as long as there are new parts available in the buffer and returns on-service when the station is empty. Indeed, for every value of the threshold ($N = *$) the machine is kept on-service because the switch-off command is never issued. The control becomes:

$$\mathbf{a_2} = \{\infty; *; \infty\} \tag{3}$$

Policy 3 (Off): Switch off the machine after the departure of the last part in the station.

As soon as a part enters in the system, the machine starts working and it serves the train of custormers who may arrive while it is engaged. After the last departure, the machine moves immediately to the out-of-service state and returns on-service at the next part arrival. The control is:

$$\mathbf{a_3} = \{0; 1; \infty\} \tag{4}$$

Policy 4 (Switching): Switch off the machine after a time interval τ_{off} has elapsed from the last departure. Then, switch on the machine after a time interval τ_{on} has elapsed from the last departure—i.e., after $\tau_{on} - \tau_{off}$ from the switch-off command—or when a part arrives.

Similarly to Policy 1, the machine is switched off-on according to two time control parameters: τ_{off} for the switch-off, and τ_{on} for the switch-on. Moreover, the machine is warmed up upon the first arrival, if this event occurs first:

$$\mathbf{a_4} = \{\tau_{\text{off}}; 1; \tau_{\text{on}}\} \tag{5}$$

Policy 5 (N-Policy): Switch off the machine upon the departure of the last part in the station. Then, switch on the machine when the queue has accumulated to level N.

Similarly to Policy 3, the machine is switched off as soon as the station empties. But, once in out-of-service, the machine is warmed up only upon the *N-th* arrival:

$$\mathbf{a_5} = \{0; N; \infty\} \tag{6}$$

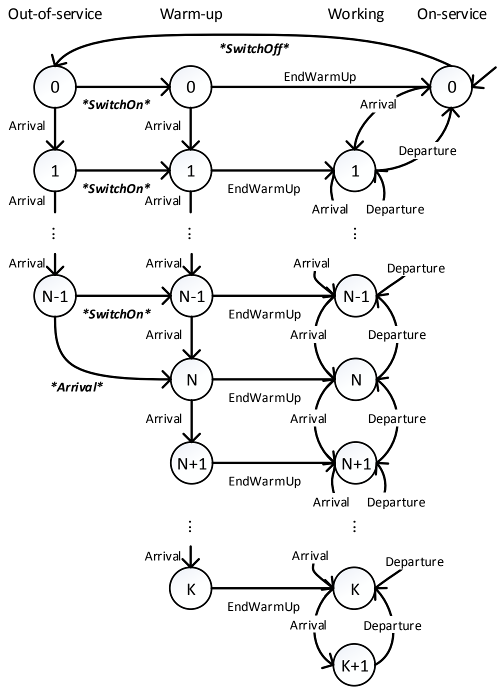

Fig. 3. System state model. The number n of parts in the system is incremented and decremented by arrivals and departures, respectively. The machine can be on-service only if the system is empty. The machine can be in the working state for any value of n with exception of $n = 0$, i.e., when there is no part to work. The system cannot contain more then $n = K$ 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. If the machine is in out-of-service, but not switched on yet, the system cannot contain more then $n = N - 1$, because the machine is switched on upon the *N-th* arrival.

V. System Model and Dynamic Behaviour

In order to properly model the whole system, it is necessary to consider interactions between the machine and the buffer. Indeed, the automata of the machine and the buffer share some events, and the synchronized model contains only the feasible combinations where the system can operate [30].

A. TNT-Policy

The general system state s_j is represented by the duple $s_j = \{m_j, n_j\}$, where m_j is the machine state and n_j the number of parts in the sistem when state j-th. The total number of system states N_s depends on the threshold level N—i.e., $N_s = 2K + 3 + N$. Thus, the power h_{s_j} requested by the system in the state s_j can be calculated as the sum of the machine power requested in m_j, and either the penalty $x_q(n_j - 1)$, when the machine is working, or the penalty $x_q n_j$, otherwise. As a consequence, the total energy consumed by the system is the sum of the product *power* $\times$ *time* for each system state visited within a certain time horizon. When Policy 1 is applied, the machine evolution may follow one of the different paths represented in Fig. 3 depending on the random arrival T_i of the parts. The model is assumed to be ergodic, and a unique stationary state probability vector π exits such that $\pi_{s_j} > 0$ and:

$$\pi_{s_j} = \lim_{u \to \infty} \pi_{s_j}(u) \tag{7}$$

where $\pi_{s_j}(u)$ is the probability of being in state s_j at a certain time instant u. Let be $\mathscr{S}$ the irriducible set of feasible states s_j of the system in Fig. 3, the average power requested by the machine can be calculated as:

$$P_{\text{avg}} = \lim_{u \to \infty} \sum_{s_j \in \mathscr{S}} h_{s_j} \pi_{\mathbf{s}_j}(u) \tag{8}$$

Since the arrivals are random, the probability of being in a certain state is the output of a stochastic process and the expected power consumed by the machine is the objective function to be minimized in this work.

B. N-Policy

Policy 5 represents a way to control the system where the control parameters τ_{off} and τ_{on} are set to *zero* and *infinity*, respectively. As a consequence, the number of system states $N_s = 2K + 2$ is independent from N. Furthermore, the arrival time T_i, the processing time T_p, and the warm up duration T_{wu} are assumed to follow exponential distributions with means $\bar{t}_i$, $\bar{t}_p$, and $\bar{t}_{\text{wu}}$ respectively. Under those further assumptions, the system model becames a Markov chain characterized by the N_s-vector $\mathbf{s}$ composed by the feasible system states s_j in $\mathscr{S}$, and the N_s-*by*-N_s transition matrix $\mathbf{Q}$ [30]. Given the transition matrix $\mathbf{Q}$, the probability π can be calculated as:

$$\begin{cases} \pi\mathbf{Q} = \mathbf{0} \\ \sum_{s_j \in \mathscr{S}} \pi_{s_j} = 1 \end{cases} \tag{9}$$

Since each transition can be associated to an event, it is possible to describe the structure of matrix $\mathbf{Q}$ according to the occurence of three random events: the arrival T_i, the departure T_p, and the warm-up duration end T_{wu}. The arrival increments the number of parts in the system and triggers four types of transition. Firstly, if the machine is working, the system can hold up to $K+1$ parts and the transition (10a) occurs. If the machine is in warm-up, the number of parts in the system is limited by the buffer capacity K and transition (10b) is feasible. When the machine is out-of-service, the arrival can increment the entities in the system up to $N-1$ with transition (10c), or it can switch on the machine with transition (10d). Furthermore, if there are no other parts waiting in the queue the departure empties the system and switches off the machine as in transition (11a). Otherwise, the machine stays in the working state and the transition (11b) occurs. When the warm-up ends, the transition (12) is triggered and the machine goes in the working state without changing the number of parts in the system.

VI. Numerical Results

A real CNC machining center with 392 dm^3 of workspace, five axes, horizontal synchronous spindle, and local chiller—cooling both spindle and axes— is considered. The machine executes machining operations on an aluminum cylinder head for automotive purpose. The machine requires 5.35 kW when

$$q_{i,j} = \lambda_a \quad \text{if} \quad \begin{cases} i = \{\text{working}, n\}; j = \{\text{warm-up}, n+1\} & \forall n = 1..K & (10a) \\ i = \{\text{warm-up}, n\}; j = \{\text{warm-up}, n+1\} & \forall n = 0..K-1 & (10b) \\ i = \{\text{out-of-service}, n\}; j = \{\text{out-of-service}, n+1\} & \forall n = 0..N-2 & (10c) \\ i = \{\text{out-of-service}, N-1\}; j = \{\text{warm-up}, N\} & & (10d) \end{cases}$$

$$q_{i,j} = \lambda_p \quad \text{if} \quad \begin{cases} i = \{\text{working}, 1\}; j = \{\text{out-of-service}, 0\} & & (11a) \\ i = \{\text{working}, n\}; j = \{\text{working}, n-1\} & \forall n = 2..K+1 & (11b) \end{cases}$$

$$q_{i,j} = \lambda_{\text{wu}} \quad \text{if} \quad i = \{\text{warm-up}, n\}; j = \{\text{working}, n\} \quad \forall n = N..K \qquad (12)$$

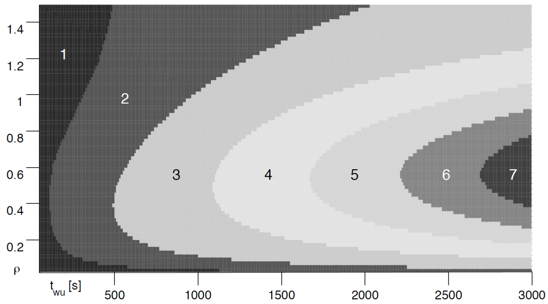

Fig. 4. Contour plot: optimal threshold N^* varying machine utilization and warm-up duration ($K = 10$; $t_p = 100$ s).

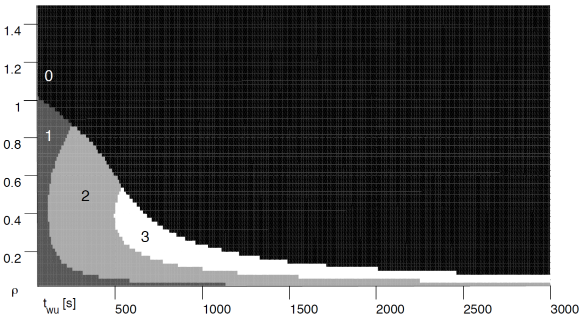

Fig. 5. Contour plot: optimal policy among Always on (label *0*), Off (label $N^* = 1$), and N-Policy (labels $N^* = 2$ and $N^* = 3$) varying machine utilization and warm-up duration ($K = 10$; $t_p = 100$ s).

on-service, and 0.52 kW when out-of-service. The warm-up is characterized by a power consumption of 6 kW and the penalty for part waiting is x_q = 1 kW. The data reported has been acquired with dedicated experimental measurements.

Firstly, the effect of the threshold N over system performances is discussed. Then, the optimal control $\mathbf{a}_5^* = \{0; N^*; \infty\}$ is analyzed varying the buffer capacity K, and the means of the stochastic processes ($\bar{t}_i$, $\bar{t}_p$, and $\bar{t}_{\text{wu}}$).

A. Threshold Level N

In the steady state condition, system performances change according to the threshold N because the probability of being in a certain state s_j changes. In more details, by increasing N, the probability of being out-of-service increases because the system needs more time to accumulate N parts. Indeed, the average number of parts in the system $\bar{n}$ increases because it is composed by a constant contribution due to the M/M/1/K system without control, and the additional queue length, that is increasing with N, due to threshold policy [20]. Parallely, the average waiting time increases due to Little's law. As a consequence, the probability of being in warm-up decreases as well as the probability of having the machine working.

B. Buffer Capacity K

Having an input buffer with a higher capacity, means that system performances tend asyimptotically to the infinite buffer capacity ones. For this reason, the steady state converges to that of an infinite queueing system with same characteristics, as well as the average power requested. As a consequence, the optimal threshold level N^* for the M/M/1/K converges to the optimal value for an M/M/1.

C. Machine Utilization and Warm-Up Time

Let be the buffer capacity $K = 10$ and the mean process time $\bar{t}_p = 100$ s, by varying $\bar{t}_a$ and $\bar{t}_{\text{wu}}$ the optimal parameter N^* minimizing the average power consumed P_{avg} is represented in Fig. 4. The higher the utilization $\rho = \bar{t}_p/\bar{t}_i$, the higher the probability of being in working states; whereas the probability of being out-of-service states is low. As a consequence, given high values of ρ it is advantageous to not fill up the buffer—i.e., to switch-on the machine for low values of N— in order to not waste energy holding parts, even if the system empties rarely. Whereas, if the machine is low utilized, the system empties often and the probability of being in out-of-service states is high. In such a case, the system spends more time to accumulate parts and it is advantageous having low N in order to not waste energy holding parts. A trade-off exists between the energy saved triggering the machine in a low power consuming state, and the energy consumed holding parts and executing the warm-up. Thus, for medium utilized machines, the value N^* is properly set to avoid both high $\bar{n}$ and too frequent warm-up. This analysis holds for different values of warm-up time t_{wu}. Given a certain utilization ρ, if the warm-up time increases the optimal threshold N^* increases. Indeed, the warm-up procedure accounts large time, thus energy. For this reason, once the machine has been switched-off, it is better to wait for more arrivals to increase the time spent in low power consumption states.

D. Always on and Off Policies

Policy 5 degenerates in Policy 3 every time the optimal threshold $N^* = 1$, whereas Policy 5 does not include the possibility to keep the machine always on because the machine is switched off at $\tau_{\text{off}} = 0$. However, it is possible to compare Policy 5 with Policy 2. In Fig. 5 is represented the optimal policy among Policy 2 (label *zero*), Policy 3 (label $N^* = 1$), and Policy 5 (label $N^* = 2$ or $N^* = 3$).

For highly utilized machines ($\rho > 1$), the optimal policy is the *always on* because the production is saturated and the machine should never be switched off. If the warm-up requires very short time or the machine is low utilized, the optimal policy is the *off* (Policy 3) and the threshold is $N^* = 1$. If the mean warm-up time t_{wu} increases, it becomes advantageous to keep the machine on-service even if the machine is not saturated because of the high warm-up energy requested. These remarks are aligned with the analysis in Frigerio and Matta [16] on a single machine without buffer information. For all other cases the optimal policy is the *N-Policy* with a proper value of N^*.

VII. CONCLUSIONS

A general framework with three-parameter control policy applied to a single server has been proposed in this paper. A special case of the TNT-Policy has been studied analytically for exponential stochastic processes. A real case application has showed that the benefits achievable by implementing the threshold policy are significant compared to the common *always on* and *off* policies. Moreover, the optimal control has been provided numerically for different values of the stochastic process means. Future developments will be devoted to analyze Policy 1 by including the possibility of switching the machine with time-based control parameters together with the threshold N. Other perfomance indicators, e.g., throughput and lead time, should also be evaluated in future studies.

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