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Energy Efficiency Improvement of Industrial Parts Washers Using State Control

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Abstract

In recent years, the energy efficiency topic drastically increased its relevance in manufacturing industry management. One of the most supported strategies to reduce the energy consumed by manufacturing equipment is the machine state control during idle periods, triggering the machine in a standby state with low power request. This approach is aimed at reducing system energy consumption while not jeopardizing the overall production rate and it is referred to as energy efficient control (EEC). Policies implementing EEC techniques are proven to be effective in a manufacturing system but have been tested only for assembly and machining operations. This work is focused on industrial parts washers: widely used machines in manufacturing with significant energy consumption associated. The objective is to demonstrate the applicability and the potential of EEC strategies when applied to washing processes. Proper EEC policies are identified for an industrial parts washer operating in a real production line in the automotive sector. Different scenarios are analyzed and the focus is placed on the effect that these energy efficient actions have on the overall production system in terms of throughput and energy consumption. In this way, the industrial impact of the EEC application on the industrial parts washer is computed by running simulation experiments.

Keywords: Sustainability; Manufacturing Automation; Energy Efficiency; Industrial Parts Washers; Discrete Event Simulation

1. Introduction

Nowadays, energy efficiency is becoming a critical issue in the industrial sector. Recent studies estimate that the industrial field accounts for 42% of global energy consumption, with the majority coming from the manufacturing sector [1]. There are three highly effective strategies for reducing the energy consumption of manufacturing equipment: (i) proper eco-design of machine and process parameters, (ii) energy efficient scheduling (EES) of machines, and (iii) energy efficient control (EEC) of machines. The first approach aims at minimizing the power, material, and resource demands of machine components by utilizing more efficient technologies and identifying proper process parameters, thus reducing energy, resource, and material consumption. This method is well-suited for designing new machines or new production processes but it is not as effective for applying on already existing and operational systems. When companies have already invested significantly in existing and in-use machines in their production lines, it is important to investigate alternative strategies that preserve these investments. In this case, implementing EES and/or EEC strategies is a highly effective way to reduce energy consumption. EES and EEC address the energy efficiency problem from distinct levels. EES is connected with the production activities scheduling, i.e. the detailed plan for the use of the machines to perform a set of production activities called "jobs". The scheduling plan is typically established before it is put into action, assuming that all relevant information is known and certain [2]. On the other hand, EEC provides policies to be applied in real-time during production progress, without deterministic information on the next part arrival to the machine. EEC is focused on machine idle periods. Machines are idle when simultaneously switched

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on but not operating on parts: high energy is consumed to maintain the ready-for-process conditions but no parts are produced. EEC aims to provide effective policies for switching off the machine during idle periods and turning it on again only when production must resume, thereby reducing machine energy consumption without jeopardizing system throughput. This work deals with the EEC approach.

According to scientific literature and industries, EEC policies are usually applied to machine tools executing machining operations, or assembly workstations. However, industrial parts washers are a major contributor to energy consumption in manufacturing plants [3]. The operations required for the overall washing process consume considerable amounts of power and, thus, have a significant energy and material consumption associated with them [4]. It must be noted that machine tools account for more than 30% of the total electricity used in an average manufacturing factory [5] and that a single industrial parts washer has a higher energy consumption than one machine tool [4]. Washing is a key process in any manufacturing line, and, in particular, it becomes essential when producing high-quality components for the automotive sector [3]. Therefore, industrial parts washers are widely used, and reducing their energy consumption could have a significant impact on the overall energy usage of a manufacturing plant.

This work is focused on industrial parts washers. The goal is to analyze whether and how EEC policies can be applied to these machines and what are the resulting effects of this control in terms of energy saving and system productivity. It must be noted that the focus is placed on EEC-based strategies to reduce the energy consumed by these machines since the goal is to evaluate policies to be applied to already existing and operational industrial parts washers. Therefore, different environmental-friendly and effective eco-strategies such as focusing on the design of industrial parts washers process parameters to reduce the associated water depletion are not considered in this work. A real case study is analyzed: EEC is applied to one industrial parts washer operating in a powertrain line from the automotive sector. The industrial impact of EEC application to industrial parts washers in the real system is estimated by running simulation experiments.

While operating in a production system, a machine is subject to (i) a *Base Load* energy consumption to preserve the ready-for-process conditions, as well as to (ii) a *Load Dependent* energy consumption to actually execute processes on the parts [6]. *Base Load* energy can be decreased by reducing the number and duration of machine idle periods. This can be achieved through the proper application of EEC policies to the machine in real-time during production progress, without deterministic information on the next part's arrival to the machine [7]. A complete and recent literature review on EEC in production systems can be found in [8]. The direct counterpart to EEC policies is the *Always On* (*AOn*) policy where machines are kept in ready-for-process conditions even during idle periods, consuming unnecessary energy while not producing parts. Recent research in the field of EEC demonstrates the applicability and potential of this approach for various manufacturing equipment. The first level of analysis considers the EEC for the simplest possible manufacturing system configuration, i.e. a single workstation seen as a single buffer followed by a single machine. Initial examples of EEC applied to the single-buffer-single-machine layout can be found in [9, 10, 11]. Furthermore, more recent studies proposed an adaptive EEC policy for this layout based on machine learning techniques where the EEC is able to self-adapt for varying system parameters [12]. Another related research stream is developed still considering the EEC for the single workstation but when the latter is composed of a common upstream buffer followed by identical machines in parallel. Recent examples in this field can be found in [7, 13], where the authors proposed a model to identify EEC policies for a single parallel-machines workstation and then applied it to more workstations of the same production plant. Nevertheless, the main limitation of single station-related works is that the focus is always placed on the stand-alone workstation, and its interactions with the other machines in the production system are not taken into account. Hence, research also dealt with EEC for the overall production systems where the system under control is modeled as a series of single machines interspersed by single finite capacity buffers. Initial literature analyzing the EEC potential for the overall production systems includes the works developed in [14, 15]. Subsequently, in [16] the authors used work-in-process information to develop effective EEC policies for the entire production line. Most recently, in [17] the authors developed a Gaussian mixture model to predict machines idle periods duration and, consequently, to be able to implement EEC actions during the predicted idle periods. In [18], the authors evaluated the effect of controlling different combinations of machines simultaneous simultaneously in a serial production line for energy efficiency purposes. Furthermore, [19] presents a model to identify a global EEC policy for the overall multi-stage production line with parallel-machine workstations. However, all the literature for EEC in production systems always focused on the control of one or more workstations executing machining or assembly operations, in order to reduce the energy consumed by such processes. This is considered a major limitation since there are no studies assessing the potential benefits of EEC when applied to industrial parts washers that, on the other side, remarkably affect the energy consumption in a manufacturing plant.

1.1. Contribution

The EEC is proven to be an effective way to significantly decrease the energy consumed in a manufacturing system. On the other hand, industrial parts washers require a major amount of energy in order to execute washing operations on parts. Despite this, in the literature, there is no analysis of whether and how the EEC can be useful when applied to industrial parts washers. To fill this gap, this work analyzes the impact that implementing EEC policies on an industrial parts washer has in terms of throughput and energy consumption. The impact is evaluated in a real case of manufacturing system from the automotive sector. Discrete event simulation is used to estimate the controlled system behavior in different scenarios.

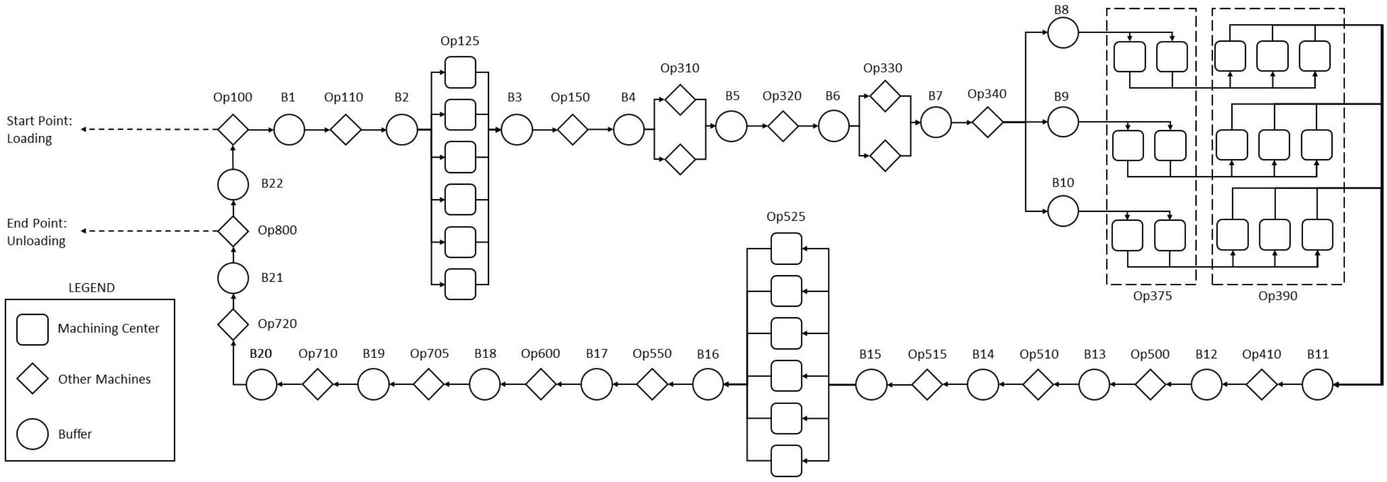

Fig. 1. Layout of the production line under analysis: a powertrain line from the automotive sector composed of 21 workstations.

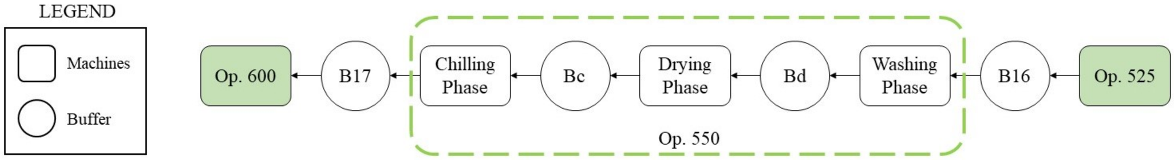

Fig. 2. Industrial parts washer to be controlled, Op.550 of the production line under study.

1.2. Paper Structure

The paper is organized as follows. In Section 2 the system under investigation is described in detail. Moreover, this Section also introduces the concept of EEC policy from an operational point of view, explaining how it works in practice. Section 3 describes the framework used for the performed analysis. Section 4 presents the scenarios analyzed, the simulation model implemented, and, lastly, the numerical experiments carried out, showing the resulting benefits when applying EEC to the industrial parts washer under study. Section 5 closes the work with the respective conclusion and further developments.

2. System Description and Control Policy

2.1. Production System

The industrial parts washer under study is part of a manufacturing system producing components for the automotive sector (the system layout is visible in Figure 1). A conveyor is used to transport pallets in the production system; pallets have the function of carrying around parts that are loaded on pallets in Op.100 and unloaded from them in Op.800, at the end of the line. Each part undergoes twenty-one total operations performed by automated equipment. Each operation is therefore characterized by an upstream buffer of finite capacity collecting parts and one or more machines performing the actual part-processing. It is possible indeed to recognize workstations with identical-parallel machines layout (e.g. Op.125, Op.310, Op.330, and so on) while all the other workstations have a single-buffer-single-machine configuration. In detail, Op.125, 375, 390, and 525 are machining operations and each of them is followed by a washing operation performed in, respectively, Op.150, 410, and 550. All system machines have stochastic processing times. Furthermore, they are subject to failures with respective stochastic time to failure (*TTF*) and stochastic time to repair (*TTR*). First come first serve and blocking after service rules are applied. *AOn* policy is actually applied on all the workstations.

2.2. Industrial Parts Washer Under Analysis

The focus of this work is Op.550, the washing operation performed by an industrial parts washer that is referred to as *tunnel washer*. The tunnel washer performs three consecutive processes on the part: the actual washing, the subsequent drying, and, lastly, the chilling phase to cool down the part. Thus, the overall machine is composed of three devices: a high-pressure pump performing the washing, a heater for drying, and a chiller fan for cooling down. Moreover, the overall machine requires two additional internal buffers, one between the washing and the drying (*Bd*) and another between the chilling and the drying (*Bc*). Hence, each pallet entering the workstation flows through the tunnel washer moved by an internal conveyor and performs the three sequential processes eventually waiting in the internal buffers if the heather or the chiller fan is busy processing another item. This part flow through the workstation leads to the *tunnel washer* name of the industrial parts washer. The complete layout of Op.550 is shown in Figure 2. It is important to note that the speed of the internal conveyor can be controlled and this affects the processing time of each phase. Thus, the tunnel washer can work with adjustable speed. Furthermore, both the heater and the chiller if switched off in a standby state, require a startup time of around 30 minutes to reach the respective operating temperatures required to actually process parts [4]. For this reason, it is unfeasible to apply any EEC policy to the heather and the chiller, since the switch off/on approach would lead to a production stoppage for an excessive amount of time and a consequent significant production drop. On the other hand, the washing phase only needs a reasonable amount of time for the startup and, consequently, it is suitable for EEC policy application. The focus of this work is, therefore, the analysis of the resulting benefits of EEC policies implementation on the device for the washing phase in an industrial parts washer. For the sake of simplicity, from now on in the paper, this washing device is referred to as "washing-phase device".

2.3. Machine States and Power Consumption in Op. 550

All three devices of Op.550, and in particular the washing-phase device under analysis, follow the state model shown in Figure 3.

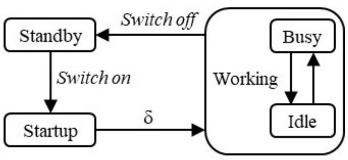

Fig. 3. States and sub-states of the tunnel washer devices under analysis, including the washing-phase device of Op.550 to be controlled.

In the tunnel washer, the washing, drying, and chilling devices are characterized by three main states: *working* (w), *standby* (sb), and *startup* (su). In addition, while *working*, each device is *busy* while actually processing parts and *idle* when in ready-for-process conditions but without actually operating on parts; hence, *idle* (i) and *busy* (b) are two sub-states composing the *working* state. During the *working* state, specifically while *idle*, each device can be immediately switched off and goes into the *standby* state: a lower power request state where only emergency services are active. On the other hand, each device cannot be switched off while *busy*, i.e. part processing cannot be interrupted. From the *standby* state, each device can be switched on and enters in *startup* state. Here the device executes procedures to be suitable for processing so that quality and tolerance requirements can be met. Examples of these operations are the reaching of operating pressure for the washing liquid, the starting phase of the pump, and so on. Once the *startup* phase is over, the device is finally ready to process parts and, consequently, it comes back to the *working* state.

To each mentioned state or sub-state $s = \{w, sb, su, i, b\}$, it is associated with a constant and non-negative power consumption w_s characterizing the respective state or sub-state. This means that w_w is the power consumption associated to the *working* (w) state, w_{sb} is the one associated to the *standby* (sb) state and so on. In particular, w_w, the power requested while in *working* state, is a weighted average of w_b and w_i depending on the amount of time the device spends as busy or idle.

2.4. System Parameters

Evaluating system performance with and without EEC applied requires processing and energy parameters. Op.550 receives parts from Op.525 and releases parts to Op.600; hence, to evaluate Op.550 idle periods (i.e. when the industrial parts washer is starved or blocked) also processing parameters of Op.525 and 600 are required (Table 1). Both Op.525 and Op.600 have normally distributed processing times fitted from real data provided by the company owning the industrial system. On the other hand, the mean processing times for the three phases of Op.550 are provided by the company, while it is assumed that they are exponentially distributed due to a lack of information about the stochasticity of these data.

Table 1. Processing parameters for Op.525, 550, and 660, useful for the EEC to be applied.

Operation	t_p [s]	t_{su} [s]	**Buffer**	K
Op.525	NORM(42,0.2)	-	B16	15
Op.550 - Washing	EXP(36) to EXP(42)	100	Bd	3
Op.550 - Drying	EXP(36) to EXP(42)	~ 1800	Bc	3
Op.550 - Chilling	EXP(36) to EXP(42)	~ 1800	B17	8
Op.600	NORM(42,0.2)	-		

From an energy point of view, to evaluate the eventual saving when EEC policies are implemented, only the energy parameters of Op.550 are required (Table 2). All the reported energy data are provided by the company owning the industrial system under study. The remaining production system parameters are not reported because of a confidentiality agreement with the company.

Table 2. Energy parameters for the three devices of Op.550, useful for the EEC to be applied.

Operation	w_b [kW]	w_i [kW]	w_{su} [kW]	w_{sb} [kW]
Op.550 - Washing	56.25	6.90	8.90	0.50
Op.550 - Drying	59.50	31.10	51.50	25.20
Op.550 - Chilling	33.00	26.15	42.27	0.75

Op.525 is composed of 6 identical parallel machines executing machining operations; when all the 6 machines work at full pace, the processing time t_p of the whole workstation is stochastic and follows a normal distribution with mean parameter equal to 42 seconds, and variance equal to 0.2. The tunnel washer has an upstream buffer $B16$ with finite capacity K equal to 15 plus the two internal buffers Bd and Bc, both with a finite capacity equal to 3. In nominal conditions, the internal conveyor of Op.550 is adjusted to the maximum speed, leading to an exponentially distributed t_p with mean of 36 seconds for each of the three working phases of Op.550. On the other hand, if the internal conveyor of Op.550 is adjusted to the minimum speed, the three phases have a t_p that follows an exponential distribution with mean 42 seconds. Moreover, the washing phase has a startup time of $t_{su} = 100$ seconds, while both the drying and chilling phase have a $t_{su} = 30$ minutes (1800 seconds). In addition, the power requested in the various states or sub-states for each Op.550 phase ($w_s = \{w_b, w_i, w_{su}, w_{sb}\}$) are reported in Table 2. All the phases have remarkable and high power requests in all the states. Lastly, Op.600 is an assembly workstation with an upstream buffer ($B17$) of capacity 8 and one single machine that has a normally distributed processing time with mean and variance equal to, respectively, 42 and 0.2 seconds.

2.5. Energy Efficient Control Policies

EEC policies are applied to the washing-phase device of Op.550. All the policies used in this work are *buffer and threshold based*: the EEC of the washing-phase device is based on its upstream and downstream buffers and, in particular, the device switch off/on is triggered by specific buffers level values. To clarify, this means that each EEC policy is composed of 4 parameters: (i) a threshold defined as n_u^{off} indicating that when the upstream buffer $B16$ reaches this level the washing-phase device must be switched off, (ii) the dual threshold defined as n_u^{on} indicating that when $B16$ is at this level the washing-phase device must be switched on again and, similarly, (iii-iv) two threshold levels (n_d^{off} and n_d^{on}) on the downstream buffer Bd with the same function but looking at the Bd level. A graphical overview of how a *buffer and threshold based* EEC policy works is shown in Figure 4: the washing-phase device is switched off when $B16$ level is equal to n_u^{off} and switched on again only when $B16$ level reaches n_u^{on}; similarly, the washing-phase device is switched off when Bd level corresponds to n_d^{off} and switched on again when Bd level reaches n_d^{on}. It must be noted that n_u^{off} must be lower than n_u^{on} while $n_d^{off} > n_d^{on}$. This choice allows one to switch off the washing-phase device when the latter is or might be soon idle (i.e. starved because $B16$ is empty or with few parts or blocked because Bd is full or with many parts) and to switch on again the washing-phase device when the production must resume ($B16$ is becoming full or Bd is becoming empty).

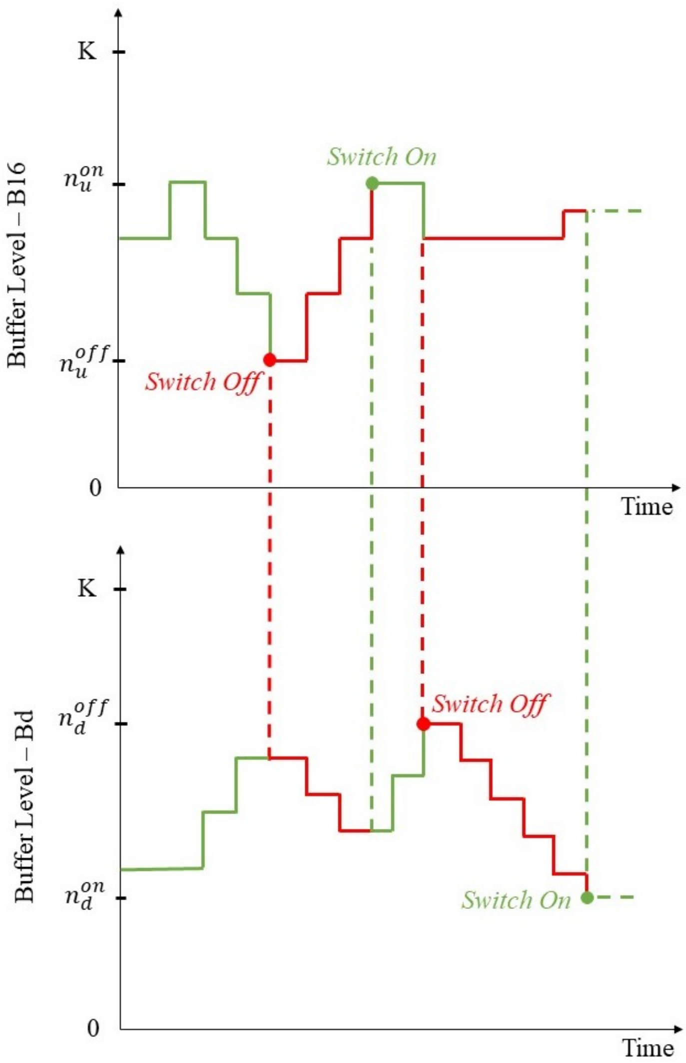

Fig. 4. Graphic example of how a *buffer and threshold based* EEC policy works in practice. The washing-phase device is switched off once $B16$ level reaches n_u^{off} and is switched on again when it is equal to n_u^{on}. Similarly, the washing-phase device is switched off when the Bd level reaches n_d^{off} and switched on again when it is equal to n_d^{on}.

3. Procedure Used for the Analysis

To assess how the EEC affects the performance of the industrial parts washer under study, analysis is performed with the following steps:

- Step 1: Different scenarios are identified, modeling different working conditions of Op.550 in the production system (details in Section 4.1).
- Step 2: For each scenario, all the possible *buffer and threshold based* EEC policies for Op.550 are generated. This means that all the possible combinations of $[n_u^{off}, n_u^{on}, n_d^{off}, n_d^{on}]$ based on $B16$ and Bd capacity are identified (details in Section 4.1).
- Step 3: For each generated policy of each scenario, discrete event simulation is used to estimate the Op.550 performance when this policy is applied. *Matlab (Mathworks, US)* software is used for the simulation experiments.
- Step 4: Numerical results of each experiment are compared with the performance of the system with *AOn* policy implemented, assessing the EEC impact (details in Section 4.2).

All the experiments are characterized by the evaluation of two KPIs: the throughput loss (referred to as "ΔTH" in this paper) and energy saving (referred to as "ΔEN" in this paper). For each case, ΔTH is evaluated as the difference between the system throughput when the *AOn* policy is applied and when the EEC is implemented. Similarly, ΔEN is the difference between the Op.550 energy consumption when the *AOn* policy is applied and the same indicator when the EEC is implemented.

Capacities of $B16$ and Bc are equal to, respectively, 15 and 3; this leads to 846 different possible combinations of $[n_u^{off}, n_u^{on}, n_d^{off}, n_d^{on}]$ while ensuring $n_u^{off} < n_u^{on}$ and $n_d^{off} > n_d^{on}$, and to the same number of possible EEC policies for the washing-phase device. Consequently, for each scenario, 846 different experiments are performed and compared with the same scenario but with *AOn* policy applied to the washing-phase device. In all the experiments, *AOn* policy is implemented on Op.525, Op.600, and both the drying and chilling phases of Op.550. The simulation model is consistent with the system described in Section 2.

The simulation length is the same for all the experiments, corresponding to the production period required to produce 15000 items. The same transient period is imposed for each experiment, corresponding to the production period required to produce 5000 items: this represents an overestimation, for computational-accuracy reasons, of the transient period identified with the Welch method [20]. A single replication is used to estimate the performance of the controlled system at steady state and the Pareto frontier is found by a complete enumeration of candidate solutions. The experimental campaign is carried out on a laptop with 4.90GHz i7 Intel Core and 16GB RAM.

4. Numerical Experiments

4.1. Design of experiments

Six scenarios are studied to assess the effect of EEC application on Op.550. The varying parameters in the different scenarios are the Op.550 internal conveyor speed and the number of functioning machines in Op.525. A complete overview of the analyzed scenarios is shown in Table 3.

Table 3. The 6 identified scenarios, modeling different working conditions of Op.550, where to assess the effect of EEC application.

Scenario	Op.550 Speed Conveyor Speed	Nr of Working Machines in Op.525
1	Maximum	All (6/6)
2	Medium	All (6/6)
3	Minimum	All (6/6)
4	Maximum	5/6
5	Medium	5/6
6	Minimum	5/6

In scenarios 1,2, and 3, all 6 machines of Op.525 are actually working, leading to a processing time for this workstation reported in Table 1 (i.e. normally distributed with mean 42 and variance 0.2 seconds). On the other hand, in scenarios 4,5, and 6, only 5 machines over 6 in Op.525 are actually working, meaning that one machine in the station is under maintenance or because Op.525 is not required to work at full pace for some production periods. In this situation, the processing time of Op.600 follows a normal distribution with a mean of 50.5 and a variance of 0.5 seconds. These values are obtained by fitting from real data provided by the company. For which concerns Op.550, in scenarios 1 and 4, the internal conveyor is set to the maximum speed (exponentially distributed t_p with mean 36 seconds for each of the three working phases), in scenarios 2 and 5 the conveyor speed is at the medium level (exponentially distributed t_p with mean 39 seconds for the three phases), and, lastly, in scenarios 3 and 6 the conveyor flows at its minimum speed (exponentially distributed t_p with mean 42 seconds for each phase). The mean processing time values associated with the three conveyor speeds are provided by the company while the exponential distributions are selected as assumptions due to a lack of information about the stochasticity of these data. Lastly, it must be noted that scenario 1 represents the nominal case, i.e. when the internal conveyor of Op.550 is adjusted to the maximum speed and all 6 machines in Op.525 are working.

In all the scenarios the saturation level of Op.550 is significantly varied. From the literature, it has been proven that EEC leads to higher savings when applied to machine tools characterized by low saturation [19]. Therefore, one of the scopes of this numerical analysis is to assess if similar results can be achieved also for the saturation of industrial parts washers. On the other hand, other insights from the literature related to the EEC of machine tools can be directly applied to the EEC of industrial parts washers. Indeed, studies related to machine tools reveal that higher savings can be achieved through EEC with machining workstations characterized by: (i) high power consumption, (ii) short startup time, and (iii) high buffer capacity [19]. Since these parameters are not strictly related to the machining process but also characterize the industrial washing operation, it is possible to affirm that similar conclusions also hold for industrial parts washers.

4.2. Experimental Results

An EEC policy is said to be effective when leading to a negative ΔEN, i.e. a positive energy saving, with respect to the *AOn* policy. Therefore, the first result to be shown regards how many effective EEC policies is possible to identify for each scenario. Considering as example scenario 1, in Figure 5 it is possible to see the resulting ΔEN and ΔTH for all the 846 EEC policies when applied in this scenario: each point corresponds to one combination of control thresholds, i.e. one of the 846 tested cases where a different EEC policy has been applied. Figure 5 also highlights section where these effective EEC policies are present and how many they are. Similar considerations can be extracted for all the other scenarios and an overview of the number of effective EEC policies in each case is reported in Table 4.

Table 4. Number of effective EEC policies for all the 6 scenarios analyzed.

Scenario	Number of Effective EEC	Percentage of Effective EEC
1	413	48.76%
2	341	40.26%
3	284	33.53%
4	476	56.20%
5	605	71.86%
6	499	58.91%

Furthermore, for each scenario, it is possible to extract the respective Pareto front minimizing energy and maximizing production rate. The 6 Pareto fronts of all the scenarios analyzed are reported in Figure 6. In each Pareto front, two particular solutions can be identified: (i) the *minimum energy consumption case*, i.e. the one leading to the maximum energy saving (minimum ΔEN), and, (ii) the *best constrained solution*, i.e. the one leading to the maximum energy saving while guaranteeing a maximum production rate loss of no more than 1% (i.e., ΔTH of -1%) since the goal is to not jeopardize the system productivity. A summary of the resulting energy savings and throughput losses for the *minimum energy consumption cases* and *best constrained solutions* of each scenario are reported, respectively, in Tables 5 and 6. The tables also show the corresponding yearly absolute energy saving in gigajoules (GJ) and "Barrels of oil equivalent" (or "BOE") for the production system. It must be noted that, only for these 12 instances (i.e. 6 *minimum energy consumption cases* plus 6 *best constrained solutions*), each experiment is replicated (20 replications), and both KPIs ΔEN and ΔTH extracted with a 90% confidence level on the mean value.

Table 5. Experimental results for the *minimum energy consumption cases*.

Scenario	ΔEN [%]	Yearly Sav. [GJ]	Yearly Sav. [BOE]	ΔTH [%]
1	-3.55 ± 0.05	67.7 ± 0.9	11.07 ± 0.14	-2.77 ± 0.01
2	-2.29 ± 0.02	45.9 ± 0.2	7.50 ± 0.03	-1.97 ± 0.03
3	-1.40 ± 0.01	41.2 ± 0.1	6.74 ± 0.02	-2.42 ± 0.02
4	-5.27 ± 0.12	84.1 ± 1.3	13.74 ± 0.21	-2.59 ± 0.07
5	-4.83 ± 0.02	76.4 ± 0.2	12.49 ± 0.03	-2.39 ± 0.04
6	-2.78 ± 0.01	57.6 ± 0.1	9.46 ± 0.02	-2.61 ± 0.02

Table 6. Experimental results for the *best constrained solutions*.

Scenario	ΔEN [%]	Yearly Sav. [GJ]	Yearly Sav. [BOE]	ΔTH [%]
1	-3.36 ± 0.02	45.8 ± 0.2	7.49 ± 0.04	-0.88 ± 0.01
2	-2.09 ± 0.01	33.1 ± 0.2	5.41 ± 0.04	-0.97 ± 0.03
3	-1.35 ± 0.01	23.8 ± 0.1	3.89 ± 0.02	-0.85 ± 0.02
4	-4.87 ± 0.09	62.1 ± 1.0	10.15 ± 0.16	-0.88 ± 0.05
5	-4.66 ± 0.11	59.5 ± 1.2	9.73 ± 0.19	-0.85 ± 0.05
6	-2.61 ± 0.03	38.5 ± 0.3	6.29 ± 0.05	-0.95 ± 0.03

In all the scenarios it is possible to identify a great number of effective EEC policies, indicating that this approach is able to significantly reduce energy consumption also for industrial washing operations. Furthermore, looking at the Pareto fronts, it may be noted how by allowing slight productivity drops, the corresponding saving strongly increases. Considering the remarkable and high power requests for all the phases of the overall washing operation (Table 2), it is important to underline how even a small percentage of saving leads to a significantly reduced consumption in absolute terms for the production system. This is confirmed by all the *best constrained solutions*, showing how while allowing a maximum of 1% decrease in terms of productivity, several tens of gigajoules can be saved. Furthermore, if the maximum 1% throughput decrease is not considered and the *minimum energy consumption cases* are observed, the absolute yearly saving strongly increases. As expected, the saving is higher in scenarios 4,5, and 6, since only 5 machines in Op.525 are functioning. This increases the probability of having Op.550 starved (i.e. idle) and allows more chances to carry out the switch off/on control on the washing-phase device. Moreover, saving also enhances as long as the internal conveyor speed increases: the faster the conveyor, the faster the three phases of Op.550, the higher the probability of having Op.550 starved or blocked (i.e. idle), the higher the number of switch off/on control actions on the washing-phase device. From a practitioner's point of view, the higher the difference in processing time between an industrial parts washer and the upstream/downstream operations, the higher the benefits in terms of energy to be saved. Therefore, this analysis confirms that for industrial parts washers the lower the workstation saturation level the higher the energy savings (as in scenarios 4,5, and 6).

5. Conclusions and Further Developments

In this work, the goal is to analyze possible strategies to improve the energy efficiency of industrial parts washers. Therefore, *buffer and threshold based* EEC policies have been applied to the washing-phase device of an industrial parts washer operating in the automotive sector. The goal of the analysis is to assess the industrial impact that this energy efficient action has on the system. Numerical results are presented, showing that it is possible to identify effective EEC policies for the industrial parts washer in different working conditions. This demonstrates the applicability and potential of EEC strategies also to industrial parts washers. Moreover, if properly selected, it is always possible to identify EEC policies able to decrease energy consumption without jeopardizing the production rate. Finally, from a practitioner's point of view, the higher the probability of having the washing device starved or blocked, i.e. idle, the higher the impact in terms of energy saving.

The principal limitation of this work is related to the stationary system dynamics and the absence of focus on the interactions of the analyzed operations with the surrounding shop floor. To extend this work, an interesting study could be performed by inserting non-stationary system dynamics, i.e. with time-varying behavior. In this case, the introduction of machine learning techniques might be required, to adapt the control to the non-stationary dynamics. Another further development could be the joint control of more workstations in the production systems, assessing the EEC impact when a wider production system, also including industrial parts washers, is controlled. Moreover, it might be also interesting to analyze the patterns present in the obtained solutions for each scenario (as in Figure 5) and to understand what are the causes leading to these patterns and, consequently, which insights might be extracted from them. Lastly, it might be interesting to carry out a sensitivity analysis to deeply assess if there are other input washing-phase device parameters that have the most significant influence on the resulting savings and throughput when EEC is implemented on the industrial parts washers.

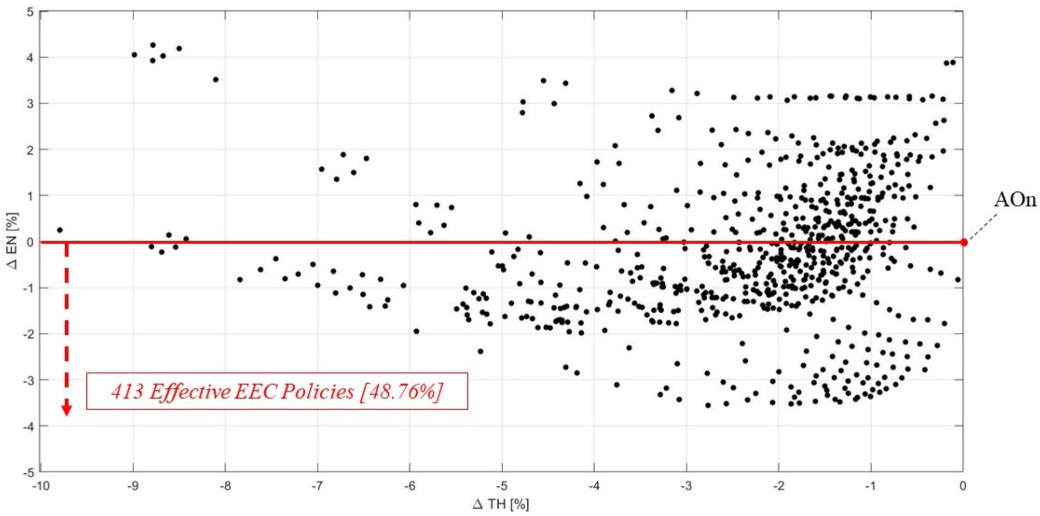

Fig. 5. Resulting energy saving and throughput loss in respect to the *AOn* policy for Scenario 1 analyzed, results for all possible 846 EEC policies are shown.

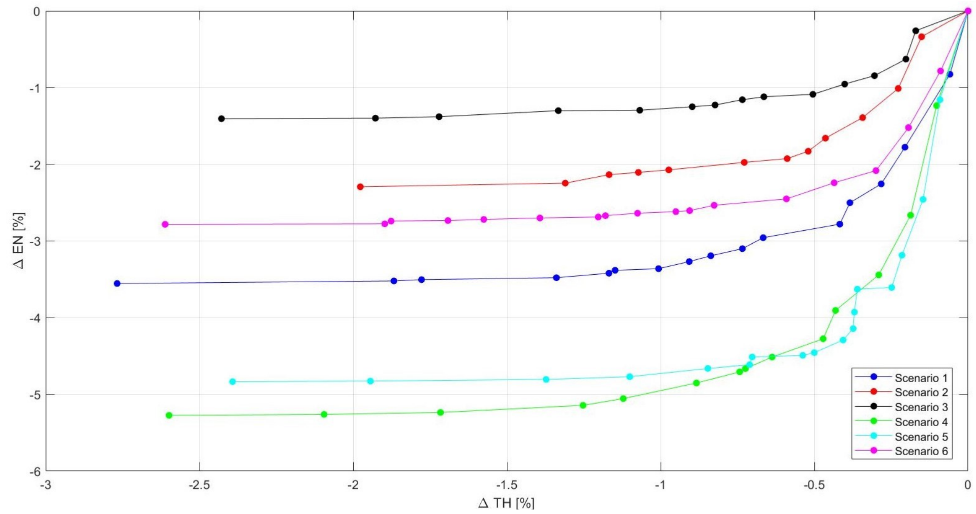

Fig. 6. Pareto fronts of resulting energy saving and throughput loss in respect to the *AOn* policy for all 6 Scenarios.

References

[1] B. P. Center, Annual energy outlook 2020, Energy Information Administration, Washington, DC (2020).

[2] D. Anghinolfi, M. Paolucci, R. Ronco, A bi-objective heuristic approach for green identical parallel machine scheduling, European Journal of Operational Research 289 (2) (2021) 416–434.

[3] M. Bosák, A. Tarča, J. Dugas, K. Klapáková, E. Skrypachov, Increasing effectiveness in automotive manufacturing., Quality-Access to Success 21 (179) (2020).

[4] A. Brus, Validation of energy efficiency requirements for machine tools and industrial washing machines, KTH, School of Industrial Engineering and Management (ITM), Energy Technology Master Thesis (2019).

[5] L. Hu, C. Peng, S. Evans, T. Peng, Y. Liu, R. Tang, A. Tiwari, Minimising the machining energy consumption of a machine tool by sequencing the features of a part, Energy 121 (2017) 292–305.

[6] J. B. Dahmus, T. G. Gutowski, An environmental analysis of machining, in: ASME international mechanical engineering congress and exposition, Vol. 47136, 2004, pp. 643–652.

[7] A. Loffredo, N. Frigerio, E. Lanzarone, M. Ghassempouri, A. Matta, Energy-efficient control of parallel and identical machines: Impact on the overall production system, Procedia CIRP 105 (2022) 739–744.

[8] P. Renna, S. Materi, A literature review of energy efficiency and sustainability in manufacturing systems, Applied Sciences 11 (16) (2021) 7366.

[9] E. T. Duque, Z. Fei, J. Wang, S. Li, Y. Li, Energy consumption control of one machine manufacturing system with stochastic arrivals based on fuzzy logic, in: 2018 IEEE International Conference on Industrial Engineering and Engineering Management (IEEM), IEEE, 2018, pp. 1503–1507.

[10] N. Frigerio, A. Matta, Analysis on energy efficient switching of machine tool with stochastic arrivals and buffer information, IEEE Transactions on Automation Science and Engineering 13 (1) (2015) 238–246.

[11] W. Li, A. Zein, S. Kara, C. Herrmann, An investigation into fixed energy consumption of machine tools, Proceedings of the 18th CIRP International Conference on Life Cycle Engineering (2011) 268–273.

[12] N. Frigerio, C. F. Cornaggia, A. Matta, An adaptive policy for on-line energy-efficient control of machine tools under throughput constraint, Journal of Cleaner Production 287 (2021) 125367.

[13] A. Loffredo, N. Frigerio, E. Lanzarone, A. Matta, Energy-efficient control policy for parallel and identical machines with availability constraint, IEEE Robotics and Automation Letters (2021).

[14] H. Su, N. Frigerio, A. Matta, Energy saving opportunities and value of information: a trade-off in a production line, Procedia CIRP 48 (2016) 301–306.

[15] Z. Sun, L. Li, Dynamic energy control for energy efficiency improvement of sustainable manufacturing systems using markov decision process, IEEE

Transactions on Systems, Man, and Cybernetics: Systems 43 (5) (2013) 1195–1205.

[16] Z. Jia, L. Zhang, J. Arinez, G. Xiao, Performance analysis for serial production lines with bernoulli machines and real-time wip-based machine switch-on/off control, International Journal of Production Research 54 (21) (2016) 6285–6301.

[17] Y. Zhang, Z. Sun, R. Qin, H. Xiong, Idle duration prediction for manufacturing system using a gaussian mixture model integrated neural network for energy efficiency improvement, IEEE Transactions on Automation Science and Engineering (2019).

[18] N. Frigerio, B. Tan, A. Matta, Simultaneous control of multiple machines for energy efficiency: a simulation-based approach, International Journal of Production Research (just-accepted) (2023).

[19] A. Loffredo, N. Frigerio, E. Lanzarone, A. Matta, Energy-efficient control in multi-stage production lines with parallel machine workstations and production constraints, IISE Transactions (just-accepted) (2023) 1–24.

[20] P. D. Welch, The statistical analysis of simulation results, The computer performance modeling handbook 22 (1983) 268–328.