International Journal of Industrial Engineering Computations 16 (2025) 1277–1288

Contents lists available at GrowingScience

International Journal of Industrial Engineering Computations

homepage: www.GrowingScience.com/ijiec

Switch-off policies in job-shop systems including energy price variability

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C H R O N I C L E

Article history:
Received March 28 2025
Received in Revised Format May 12 2025
Accepted June 5 2025
Available online June 5 2025

Keywords:
Switch-off
Energy price
Sustainability
Job-shop
Multi-agent
Simulation

A B S T R A C T

The switch-off approach is one of the practices that supports sustainable manufacturing systems by reducing energy consumption. Manufacturing systems are characterized by two sources of fluctuations: workload due to customer demand and energy price variability. This work proposes a switch-off policy that addresses these fluctuations in job-shop systems using multi-agent architecture. The proposed approach is tested through simulation models and compared to benchmarks in the literature as well as scenarios without a switch-off policy. The performance indices evaluated include throughput, average time in the system, standard deviation of average time in the system, work in process, average maximum items in queues, total waiting time for machines, and total energy costs under different scenarios. The numerical results highlight that the switch-off policy, when considering energy prices and a combination of direct and indirect workload, achieves significant energy savings with minimal degradation of manufacturing performance. These results are particularly relevant under dynamic working conditions of the manufacturing system.

1. Introduction

The introduction of dynamic energy cost rates in manufacturing systems has gained significant importance due to the global energy crisis that peaked between 2022 and 2023 (Skėrė et al. 2023). This crisis has underscored the volatility of energy prices within the European Union, where prices have surged dramatically. Efforts to diversify energy sources have intensified, yet European countries still grapple with high price variability driven by geopolitical and market dynamics. Furthermore, the increasing emphasis on sustainability has motivated numerous companies across Europe to reduce their reliance on fossil fuels. This shift is evident in the growing adoption of renewable energy technologies and the implementation of more stringent energy efficiency measures, reflecting a broader commitment to a greener and more resilient energy landscape. The introduction of renewable energy sources such as wind and solar has an impact on the volatility of the energy price (Maciejowska, 2020). Insights from the World Economic Forum (2023), as noted by Singh et al. (2019), underscore this trend. Amidst these challenges, production companies are increasingly prioritizing environmental concerns, emphasizing sustainable production methods and the integration of renewable energy technologies into their operations, as highlighted by Hegab et al. (2023). Consequently, operational strategies must incorporate energy decisions that align with sustainability objectives. This process requires a tailored approach for each company (Taghavi 2022), ensuring that they can effectively balance their unique operational demands with broader environmental goals. By adopting such individualized strategies, companies can enhance their resilience and competitiveness in an evolving energy landscape. Sustainability, in the context of manufacturing, refers to the ability to meet present needs without compromising the ability of future generations to meet theirs. This encompasses economic viability, environmental stewardship, and social equity. Sustainability in production systems involves designing and managing manufacturing processes to minimize environmental impact while maintaining efficiency. Energy consumption is a key focus, as production systems often require significant power, both during operation and idle states. Strategies like energy-efficient technologies, renewable energy integration, and switch-off policies aim to reduce energy use. Balancing energy savings with productivity is crucial, especially when considering variability in demand and production loads. Sustainable

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ISSN 1923-2934 (Online) - ISSN 1923-2926 (Print)
2025 Growing Science Ltd.
doi: 10.5267/j.ijiec.2025.6.002

production systems contribute to environmental conservation and support long-term economic and operational stability in the manufacturing industry.

This research proposes switch-off policies that integrate both direct and indirect workload considerations along with energy price fluctuations to support decision-making regarding the operational states of machines. The simulation tests conducted encompass various scenarios involving demand, processing time, and energy cost fluctuations. The objective is to determine the conditions under which the switch-off policy can effectively balance the reduction of energy costs with the maintenance of manufacturing performance measures. The proposed switch-off policies aim to optimize machine utilization by dynamically responding to changes in workload and energy prices. By incorporating real-time data and predictive analytics, these policies can make informed decisions about when to switch machines off or on, thus maximizing energy savings without compromising production efficiency. The simulation tests evaluate the impact of these policies under different conditions, such as high and low demand periods, varying processing times, and fluctuating energy prices. This approach aligns with the growing emphasis on sustainability in the manufacturing industry and provides a practical framework for companies seeking to reduce their energy consumption and operational costs.

The manuscript is organized as follows: Section 2 offers a concise overview of the literature on energy reduction in manufacturing by switch-off policies. Section 3 introduces the reference context and the multi-agent architecture. The switch-off policies considering the energy price are described in Section 4. Section 5 provides the design of the experiment and the numerical results analysis. The conclusions and future research paths are discussed in Section 6.

2. Literature review

The drive for energy efficiency in manufacturing systems has prompted extensive research into various strategies aimed at reducing energy consumption. This literature review organizes existing studies into key themes, focusing on switch-off policies and their relevance to job-shop environments under conditions of energy price variability.

Duflou et al. (2012) highlight three critical strategies for enhancing energy efficiency in manufacturing:

- Optimization of Machine Tool Design: Leveraging advancements in technology to improve the energy efficiency of machine tools by minimizing operational inputs and recovering waste energy.
- Enhancement of Process Control: This approach includes precise control over machine operations to reduce energy usage, such as implementing selective shutdowns during idle times and optimizing processing parameters.
- Process/Machine Tool Selection: Choosing the most energy-efficient machine tools and processes, aligning operational choices with sustainability goals.

By adopting these strategies, companies can significantly reduce their energy consumption and environmental impact, thereby contributing to a more sustainable manufacturing industry. Gutowski et al. (2006, 2007, 2009) further emphasize the importance of understanding energy use in manufacturing, noting that only about 15% of energy is directly related to the material removal process, while a significant portion is consumed irrespective of operational activities. These insights underscore the challenges and opportunities in reducing fixed energy consumption (Zhou et al., 2016). Research has shown that implementing switch-off policies can significantly reduce idle energy use in manufacturing operations. Li et al. (2011) illustrate that standby energy consumption during idle periods can be minimized through effective machine switch-off policies, presenting an essential opportunity for energy savings. While several works have proposed switch-off policies for simpler production systems, such as flow line systems (Renna, 2018; Frigerio & Matta, 2018; Frigerio et al., 2024), these studies often fail to address the intricacies of job-shop environments characterized by variable workloads. Zhang et al. (2017) tackle this issue by developing a mixed-integer linear model to minimize energy consumption in flexible job shop scheduling, yet their model requires further adaptation for practical industrial applications. Some works focused on the introduction of dynamic factors supported by multi-agent approaches. Wu and Sun (2018) developed a multi-objective optimization model for flexible job shops focused on minimizing energy consumption and maximizing production efficiency. However, they did not adequately account for dynamic production factors, which are critical for effective decision-making in real-world scenarios. Liu et al. (2018) explored a reconfigurable manufacturing system model aimed at minimizing cycle time, demonstrating potential energy savings. Despite their focus on energy efficiency, their models require additional validation under real industrial conditions. Renna and Materi (2021) took a significant step forward by integrating both direct and indirect workloads into their switch-off policies for job-shop systems. Their simulation studies suggested that considering workload types can enhance energy efficiency and productivity but did not incorporate dynamic energy price fluctuations, which are increasingly relevant in current environments. Frigerio and Matta (2015) investigated the implementation of a switch-off policy, accounting for the stochastic nature of inter-arrival times, machine processing times, and warm-up durations. Although their study focused on a single machine, Loffredo et al. (2024) extended this approach to multi-machine systems. They utilized buffer information to optimize machine transitions between active and standby states, which consume less energy. With stochastic startup times, they aimed to minimize energy consumption while adhering to production constraints. By employing a Markov Decision Process and linear programming, they effectively managed a two-stage system and extended this methodology to more complex systems.

Only one work was proposed in the literature to include energy pricing in the decision-making process. The integration of energy prices into switch-off policy decisions has been addressed by Bokor et al. (2024). Their research found that aligning workload evaluation with energy costs can lead to marked improvements in energy efficiency and production logistics. However, this focus has yet to be expanded to real-time applications in job-shop systems, an aspect this study aims to explore.

One more recent study focused on the finite-capacity buffer.

Jia et al. (2024) analyzed production lines with finite-capacity buffers and machines that switch on/off under specific conditions, focusing on limited production processes. A mathematical model for a three-machine line is developed using the Markov method, extended to multi-machine systems via aggregation. Results enhance sustainable manufacturing system efficiency and competitiveness. Although the literature presents promising findings regarding switch-off policies and energy efficiency, significant gaps remain, particularly concerning the application of real-time energy pricing in job-shop contexts. Most existing models overlook the complexity of incorporating fluctuating energy costs alongside workload dynamics. This study will bridge these gaps by developing a switch-off policy framework within a multi-agent system, aiming for a comprehensive approach that enhances sustainability practices in manufacturing. In response, this paper proposes a switch-off policy derived from Bokor et al. (2024) and an original switch-off policy for job shops that incorporates real-time energy prices. The first research question of this paper is as follows:

RQ1: what is the impact of these switch-off policies, combining workload and energy price, on job shop performance and energy reduction?

Simulations under various scenarios are conducted to address the second research question:
RQ2: which scenarios optimize the trade-off between manufacturing performance and energy savings?

3. Reference context

The manufacturing systems under investigation comprise four machines, each dedicated to a specific task. A total of 24 item types were considered, encompassing all possible combinations of process sequences. These item types are designed to yield results independent of the specific sequence followed. The item enters the manufacturing systems and it is assigned the sequence of the tasks and the processing time for each task. The notation used is described in the following:

	Notation	**Definition**
Indices	j	The index of the Machine j=1,..,J
	i	The index of the item
	h	The index of the hour
Parameters	energyPriceFactor	It is a parameter to compute the energy threshold
	capacityFactor	It is a parameter to compute the workload threshold
	Tav	It is a fixed Tp periods for the average mobile price energy computation
	AverageLongTimePrice	The average mobile of the energy price
	CurrentEnergyPrice(h)	It is the energy price of the hour h
	EnergyThreshold	The threshold of the energy price
	PT_{ij}	It is the processing time of the item i in the machine j
	NQj	Number of items in the queue of machine j
	$CurrentWorkload_j$	The direct workload of the machine j
	machineCapacity (h)	Machine capacity in terms of availability for hour
	workloadThreshold	The threshold of the workload
	$aggregateWorkload_j$	The total workload of the machine j
	$IndirectWorkload_j$	It is the indirect workload of the machine j
	W_1, W_2	They are the weights to combine direct and indirect workload of the machines

3.1 Multi Agent System

The flexible manufacturing system is supported by a multi-agent system architecture composed of three agent types. A Manufacturing System Agent (MSA) oversees the entire system, managing information exchange among the other agents. Each machine is represented by a Machine Agent (MA) responsible for machine operations, including power on/off states. Upon entry of a new part into the system, a Part Agent (PA) is generated to handle part allocation to appropriate machines for task completion. The interaction among the agents consists of the following steps (see Fig. 1):

- The PA analyzes the part's current status, identifies the next required process step according to the part's process plan, and selects the appropriate machine.

- A message is sent to the MA indicating that a part is ready for processing.
- Upon operation completion, the PA determines if the part's process plan is finished or if further operations are needed.
- The MA initiates either a periodic or continuous review of the machine's state.
- The MA requests the current energy price and, if required by the policy, the system's indirect workload from the MSA.
- The MSA provides the MA with the requested energy price and indirect workload data.
- The MA integrates the received information with local machine data (direct workload) to apply the decision model and determine the machine's state.
- The MA awaits the next decision point for the machine's state.

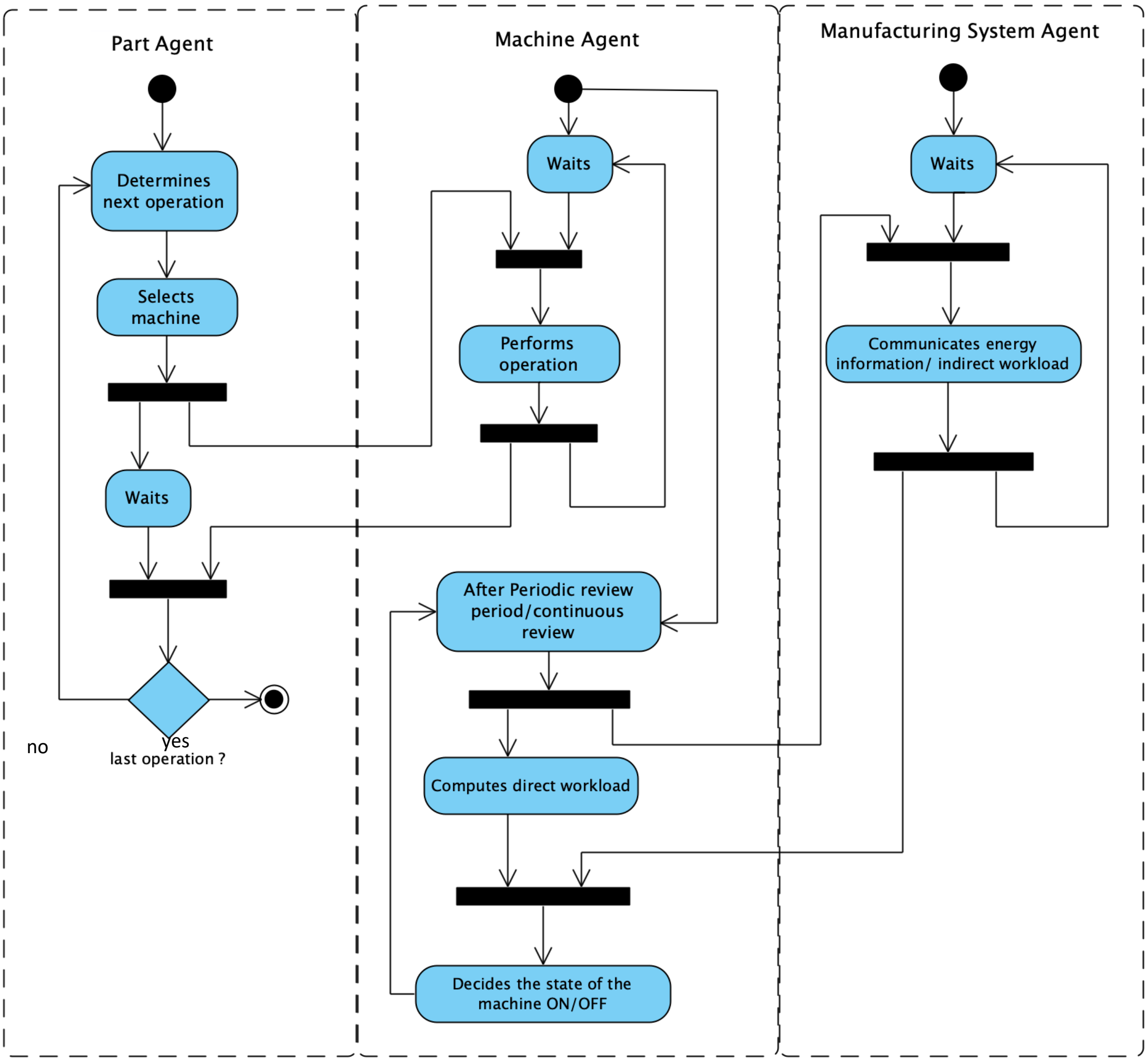

Fig. 1. multi-agent activity diagram interaction

As outlined, the preceding procedure establishes the environmental interactions among the autonomous agents within the network, but does not specify agent decision-making behaviors, commonly referred to as the productive function. This flexibility enables adaptation of the protocol to various agent-based systems with diverse productive functions. The productive function encapsulates an agent's goals and decision-making strategies.

4. Switch-off policy with energy price

As outlined in Frigerio and Matta (2015), machines typically operate within four distinct states: out-of-service (or off), idle (or on-service), warm-up, and working. A visual representation of these states is evident in the machine power load curve depicted in Fig. 2. The objective of switch-off policies is to reduce the energy consumption in standby state. Gutowski et al. (2006) categorized the energy consumption of machine tools into two components: a constant part and a variable part (see Fig. 3). The switch-off policy can significantly reduce the constant part of energy consumption, which, according to Gutowski et al. (2006), accounts for approximately 30% of the total energy usage. This constant part includes energy consumed by auxiliary systems and idle machine states. Furthermore, the increasing trend towards higher levels of automation in machine tools leads to a rise in the constant part of energy consumption. As automation improves, more energy is required to maintain the readiness of automated systems, even when the machines are not actively processing. This makes the implementation of switch-off policies even more critical, as they can mitigate the energy waste associated with these high-automation environments. By effectively managing the switch-off policies, manufacturers can achieve significant energy savings, contributing to both cost reduction and environmental sustainability.

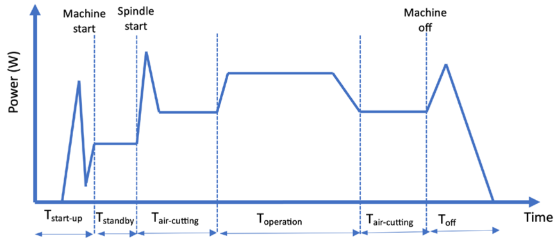

Fig. 2. A schematic diagram of power profile of the milling process

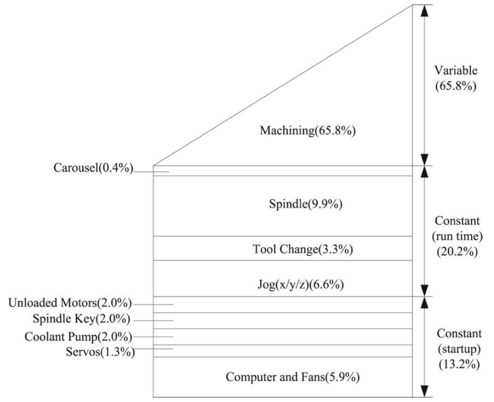

Fig. 3. Energy used of a 3-axis CNC milling machine (Gutowski et al., 2006)

Reducing energy consumption during the non-productive states—namely the idle, off, and warm-up states—is a critical concern. Specifically, powering down the machine during the idle state can significantly contribute to energy savings. The switch off policy can support the control of the machines to improve the energy saving of manufacturing systems.
The control policies tested in this paper include the energy price; The decision model that the agent of each machine applies is the following. Before the decision on the state of the machine, the following parameters needs to be computed:

The MSA provides to the MA the actual hour energy price defined "*CurrentEnergyrPrice(h)*" and the AverageLongTimePrice(Tav) that is the average price over the last *Tp* hours.

- The MA defines the energy threshold as in Eq. (1):

$$\text{EnergyThreshold} = \text{AverageLongTimePrice}(\text{Tav}) \times \text{energyPriceFactor} \tag{1}$$

where,

AverageLongTimePrice(Tav) is the average price over the last *Tp* hours, and energyPriceFactor is a constant fixed.

- Then, the current workload of the items in queue of the machine is computed as follows (Eq. (2)):

$$currentWorkload = \sum_{i=1}^{NQ} PT_i \tag{2}$$

- A workload threshold is computed (Eq. (3)):

$$\text{workloadThreshold} = \text{MachineCapacity}(\text{h}) \times \text{capacityFactor} \tag{3}$$

The machine capacity is the availability in hour; in this research is considered the availability of 100%, therefore the availability is 60 minutes for hour. The decision model is general and it can be included the possibility to reduce the real availability of the machine reducing this value. The computation of the above parameters supports the decision algorithm as follows:

1. The MA controller sets the machine in off state;
2. IF CurrentEnergyPrice(h) is lower than the EnergyThreshold, then the MA controller sets the machine in on state;
3. IF currentWorkload is greater than workloadThreshold, then the MA controller sets the machine in on state;

The MA controller sets the machine in one state when the energy price is lower or the items that are waiting in the queue of machines are characterised by higher workload.

The decision-making process for machine states can follow either a periodic or continuous review approach. In a periodic review, the controller for each machine applies the decision model at fixed time intervals to determine the machine's state.

Conversely, in a continuous review, the controller applies the decision model whenever a part enters or leaves the machine's queue. This control process operates based on local information, specifically the direct workload of the machine, and does not consider the overall state of the manufacturing system. To integrate a broader perspective, indirect workload is included. The aggregate workload of a machine is defined as the sum of its direct workload, which consists of items in the machine's queue, and its indirect workload, which includes items in the queues of other machines that will eventually require processing by the machine in question. By considering both direct and indirect workloads, the decision model provides a more comprehensive understanding of the machine's role within the entire manufacturing system. This holistic approach helps to optimize machine utilization, reduce energy consumption, and improve overall production efficiency. The modified switch-off policy includes the computation of the following parameters. The aggregateWorkload for each machine is compute when an item enters the manufacturing systems by the MSA and provided to the MA (Eq. (4)):

$$aggregateWokload_j = aggregateWokload_j + PT_{i,j} \tag{4}$$

where,

$PT_{i,j}$ is the processing time of the item i in the machine j

The MA computes the indirect workload and the modified current workload as follows (Eq. (5)):

$$indirectWokload_j = aggregateWokload_j - currentWorkload_j \tag{5}$$

Then, it is computed a modified currentWorkload as follows (Eq. (6)):

$$currentWokload_j{}^* = W_1 \times currentWorkload_j + W_2 \times indirectWorkload_j \tag{6}$$

where, W_1 and W_2 are the weights between 0 and 1, with $W_1+W_2=1$

The computation of the above parameters supports the decision algorithm as follows:

1. The MA controller sets the machine in off state;
2. IF CurrentEnergyPrice(h) is lower than the EnergyThreshold, then the MA controller sets the machine in on state;
3. IF currentWorkload* is greater than workloadThreshold, then the MA controller sets the machine in on state;

The models developed are denominated as following:

- **Switch1**; it is the switch-off policy with direct workload controlled by periodic review;
- **Switch2**; it is the switch-off policy with direct workload controlled by continuous review;
- **Switch3**; it is the switch-off policy with direct and indirect workload controlled by periodic review;
- **Switch4**; it is the switch-off policy with direct and indirect workload controlled by continuous review;

The methodology employed in this study aims not only to improve operational efficiency but also to reinforce sustainable practices. By implementing switch-off policies that adapt to real-time energy pricing, this approach contributes to reduced energy consumption and minimized environmental impact.

5. Design of experiments

The switch-off policies were tested using simulation models in dynamic environments to assess their effects on energy savings and manufacturing performance measures. The manufacturing system consists of four machines, each performing a specific technological operation (OP1, OP2, OP3 and OP4). To ensure the results are independent of the particular sequence of operations, all possible combinations are considered (24 for the 4 operations considered). Table 1 presents the 24 possible sequences (denoted with P) that items can follow upon entering the manufacturing system according to the 4 technological operations considered. The sequence assigned to each item follows a uniform integer distribution from 1 to 24, ensuring the results are not dependent on the specific routing of the item. The processing times for each operation in each sequence are either fixed or drawn from a uniform distribution at the start of each simulation replication. The machine queues are managed according to the FIFO (First In, First Out) policy.

The simulation runs for a duration of one year, operating 24 hours a day for 365 days, totaling 8,760 hours. The energy cost for each hour is sourced from the Italian market for the year 2022 (https://gme.mercatoelettrico.org/it-it/Home/Esiti/Elettricita/MGP/Esiti/PUN). The capacity and energy factors, which determine the energy and workload thresholds, are tested around a value of 1. The best results, in terms of energy reduction, are presented in the numerical analysis.

The periods for the computation of the mobile average of the energy costs considered are 4,8 and 12 hours. Finally, in case of periodic review, the periods tested are 6,12,18 and 24 hours.

Table 1
Sequences for each process plan of the items

Sequence	OP1	OP2	OP3	OP4
P1	1	2	3	4
P2	1	2	4	3
P3	1	3	2	4
P4	1	3	4	2
P5	1	4	2	3
P6	1	4	3	2
P7	2	1	3	4
P8	2	1	4	3
P9	2	3	1	4
P10	2	3	4	1
P11	2	4	1	3
P12	2	4	3	1
P13	3	1	2	4
P14	3	1	4	2
P15	3	2	1	4
P16	3	2	4	1
P17	3	4	1	2
P18	3	4	2	1
P19	4	1	2	3
P20	4	1	3	2
P21	4	2	1	3
P22	4	2	3	1
P23	4	3	1	2
P24	4	3	2	1

Table 2
Experimental cases

	Inter-arrival	Energy Price fluctuation	Processing time
Case 1	EXPO (11)	Low	Fixed 10
Case 2	EXPO (11)	High	Fixed 10
Case 3	EXPO (11)	Low	Uniform [8-12]
Case 4	EXPO (11)	High	Uniform [8-12]
Case 5	EXPO (11-13)	Low	Uniform [8-12]
Case 6	EXPO (11-13)	high	Uniform [8-12]

Table 2 reports the experimental classes tested. The first factor is the inter-arrival time of the parts that follows an exponential. A parameter of 11 leads to an average utilization of the manufacturing system of 90%, which allows for the study of switch-off policies under conditions of significant utilization. For cases 5 and 6, the parameter fluctuates between 11 and 13 every 1,000 minutes to examine the impact of variability. The second factor is energy price fluctuation; in scenarios of low fluctuation, the original hourly price extracted from the Italian market is used. For high fluctuation scenarios, a random percentage variability of ±30% is applied to the original price to simulate increased energy price volatility. The third factor is the processing time of each operation in the process plan for each sequence. In cases of low fluctuation, a fixed processing time of 10 is considered for every operation. For high fluctuation scenarios, the processing time follows a uniform distribution between 8 and 12 at the start of each simulation replication. By considering these factors—inter-arrival time, energy price fluctuation, and processing time variability—we can better understand the effectiveness of switch-off policies under different conditions. This comprehensive approach provides valuable insights into the trade-offs between energy savings and manufacturing performance in a dynamic environment. For each experimental class, a sufficient number of replications were conducted to ensure a 95% confidence level and a 5% confidence interval for each performance measure. The performance measures investigated are the following:

- **Throughput of the Manufacturing System (Throughput):** This measures the total number of parts completed during the simulation time.
- **Average Throughput Time in the System (average time in system):** This is the average time that parts spend in the manufacturing system.
- **Standard Deviation of the Average Throughput Time in the System (standard deviation):** This index indicates the stability of the average throughput time in the system.
- **Work In Process:** This represents the average number of parts within the manufacturing system, serving as an indicator of costs.
- **Average Maximum Queue (average Max Queue):** This is the average maximum queue length, highlighting fluctuations in the number of parts waiting in the machine queues.

- **Total Waiting Time:** This measures the total time that machines are in a waiting state, providing an evaluation of energy consumption in this state.
- **Total Costs:** This represents the total energy costs consumed by the machines in both working and waiting states, considering energy consumption in the off state as negligible.

The values of the factors that leads to the better results in terms of energy consumption and manufacturing performance are the following:

- Capacity Factor (CapacityFactor): 0.1;
- Energy Factor (EnergyPriceFactor): 1;
- Average time to compute mobile average cost of energy: (AverageLongTimePrice) 4 hours;
- In case of periodic review approach, the periodic review 12 hours;
- W_1=0.9 and W_2=0.1.

Some relevant trends of the above factors are the following. The capacity factor reduces the manufacturing performance when it increases from 0.1; if this value is greater than 0.3, the results are always the same. The energy factor greater than 1 reduces drastically the manufacturing performance, while lower than 1 reduces drastically the energy saving issue. The first analysis of the numerical results concerns the throughput. The throughput of the manufacturing system does not change significantly when the switch off policies are introduced. This is relevant, because the switch off policies tested keep the same level of throughput as the always on manufacturing system. Table 3 presents the results and percentage differences compared to the always-on (always ON) model used as a benchmark for Case 1. The switch-off policy with periodic review (Switch 1) results in manufacturing performance measures that are closest to the always-on benchmark. This model shows the least reduction in total waiting time and corresponding energy costs in this state. The inclusion of indirect workload (Switches 3 and 4) diminishes the differences between periodic and continuous policies. The periodic review with indirect workload (Switch 3) offers the best trade-off between manufacturing performance and total waiting time.

Table 3
Simulation Analysis Case 1

	Always ON	**Switch1**	**Switch2**	**Switch3**	**Switch4**
Throughput	47740.58	47720.41	47720.19	47734.39	47737.58
Average Time in system	158.85	171.39 (7.89%)	211.55 (33.18%)	178.54 (12.40%)	181.54 (14.28%)
Standard deviation	91.46	93.30 (2.01%)	97.34 (6.43%)	90.77 (-0.75%)	89.79 (-1.83%)
Work In Process	10.80	11.81 (9.35%)	15.58 (44.26%)	12.42 (15.00%)	12.86 (19.07%)
Average Max Queue	21.79	22.53 (3.40%)	24.27 (11.38%)	22.69 (4.13%)	22.55 (3.49%)
Total waiting time	192573.06	150416.68 (-21.89%)	58352.64 (-69.70%)	99964.18 (-48.09%)	93666.49 (-51.36%)

Table 4 presents the results and percentage differences compared to the always-on model used as a benchmark for Case 2. Under these conditions, the periodic switch-off policy with indirect workload (Switch 3) enhances manufacturing performance compared to the other switch-off models, while maintaining a significant reduction in total waiting time. The inclusion of indirect workload improves performance, especially when there is a high fluctuation in energy prices.

Table 4
Simulation Analysis Case 2

	Always ON	**Switch1**	**Switch2**	**Switch3**	**Switch4**
Throughput	47740.58	47722.39	47720.97	47724.29	47720.24
Average Time in system	158.85	202.45 (27.45%)	212.25 (33.62%)	178.25 (12.21%)	181.48 (14.25%)
Standard deviation	91.46	96.39 (5.39%)	96.14 (5.12%)	89.79 (-1.83%)	88.38 (-3.37%)
Work In Process	10.80	14.51 (34.35%)	15.64 (44.81%)	12.38 (14.63%)	12.85 (18.98%)
Average Max Queue	21.79	24.09 (10.56%)	24.21 (11.11%)	22.62 (3.81%)	22.46 (3.07%)
Total waiting time	192573.06	64323.61 (-66.60%)	53028.20 (-72.46%)	96177.23 (-50.06%)	87462.68 (-54.58%)

Table 5 presents the results and percentage differences compared to the always-on model used as a benchmark for Case 3. This case is very similar to Case 2; the switch-off policy with indirect workload (Switch 3) performs better when processing times change dynamically.

Table 5
Simulation Analysis Case 3

	Always ON	Switch1	Switch2	Switch3	Switch4
Throughput	47763.03	47773.37	47765.24	47763.97	47779.18
Average Time in system	181.51	223.89 (23.35%)	224.19 (23.51%)	197.16 (8.62%)	200.75 (10.60%)
Standard deviation	109.99	113.33 (3.04%)	112.52 (2.30%)	105.32 (-4.25%)	106.24 (-3.41%)
Work In Process	12.87	16.73 (29.99%)	16.75 (30.15%)	14.30 (11.11%)	14.63 (13.68%)
Average Max Queue	26.10	28.34 (8.58%)	28.15 (7.85%)	26.60 (1.92%)	26.87 (2.95%)
Total waiting time	194065.92	78971.45 (-59.31%)	69075.40 (-64.41%)	106044.90 (-45.36%)	106044.90 (-48.29%)

Table 6 presents the results and percentage differences compared to the always-on model, which serves as the benchmark for Case 4. The combined effects of energy price and processing time fluctuations did not significantly alter the results compared to Case 3.

Table 6
Simulation Analysis Case 4

	Always ON	Switch1	Switch2	Switch3	Switch4
Throughput	47763.03	47760.04	47742.61	47774.31	47778.84
Average Time in system	181.51	223.85 (23.33%)	228.01 (25.62%)	198.13 (9.16%)	201.44 (10.98%)
Standard deviation	109.99	111.49 (1.36%)	113.56 (3.25%)	106.14 (-3.50%)	105.78 (-3.83%)
Work In Process	12.87	16.72 (29.91%)	17.09 (32.79%)	14.39 (11.81%)	14.69 (14.14%)
Average Max Queue	26.10	27.99 (7.24%)	28.28 (8.35%)	26.81 (2.72%)	26.86 (2.91%)
Total waiting time	194065.92	76194.81 (-60.74%)	59024.93 (-69.59%)	102769.83 (-47.04%)	94235.61 (-51.44%)

Table 7 presents the results and percentage differences compared to the always-on model, which serves as the benchmark for Case 5. Under conditions with inter-arrival time fluctuations, Switch 3 achieves a better trade-off between manufacturing performance and waiting time reduction. However, the differences among the models are less pronounced.

Table 7
Simulation Analysis Case 5

	Always ON	Switch1	Switch2	Switch3	Switch4
Throughput	43778.61	43764.54	43768.98	43775.08	43777.34
Average Time in system	111.18	154.51 (38.97%)	156.51 (40.77%)	136.85 (23.09%)	140.80 (26.64%)
Standard deviation	55.87	65.11 (16.54%)	65.11 (16.54%)	56.90 (1.84%)	56.99 (2.00%)
Work In Process	5.94	9.55 (60.77%)	9.71 (63.47%)	8.08 (36.03%)	8.40 (41.41%)
Average Max Queue	16.60	19.55 (17.77%)	19.43 (17.05%)	17.94 (8.07%)	17.65 (6.33%)
Total waiting time	353603.08	150889.51 (-57.33%)	130742.16 (-63.03%)	168267.63 (-52.41%)	156560.68 (-55.72%)

Table 8 presents the results and percentage differences compared to the always-on model, which serves as the benchmark for Case 6. The inclusion of energy price fluctuations does not significantly alter the results observed in Case 5.

Table 8
Simulation Analysis Case 6

	Always ON	Switch1	Switch2	Switch3	Switch4
Throughput	43778.61	43766.69	43765.11	43775.49	43773.40
Average Time in system	111.17937	155.04 (39.45%)	158.86 (42.89%)	137.36 (23.55%)	141.90 (27.63%)
Standard deviation	55.86938	63.02 (12.80%)	63.06 (12.87%)	56.42 (0.99%)	55.45 (-0.75%)
Work In Process	5.93552	9.60 (61.74%)	9.91 (66.96%)	8.13 (36.97%)	8.49 (43.04%)
Average Max Queue	16.5975	19.48 (17.37%)	19.48 (17.37%)	17.91 (7.91%)	17.67 (6.46%)
Total waiting time	353603.076	144045.88 (-59.26%)	109619.35 (-69.00%)	159142.59 (-54.99)	141203.23 (-60-07%)

From the numerical results above, the following observations can be made:

- Switches 1 and 2, which utilize a direct workload policy, result in a greater reduction in both machine waiting times and associated energy consumption.
- The introduction of an indirect workload policy (Switches 3 and 4) provides a better trade-off between manufacturing performance and energy consumption related to waiting times.
- Implementing an indirect workload policy (Switches 3 and 4) reduces the difference between periodic and continuous review approaches. For these policies, the choice of review approach becomes less significant.

The cost analysis is conducted by examining different power consumption levels of the machines while in the waiting state. Three scenarios are considered, with the power consumption in the working state fixed at 10 kWh. The power consumption during the waiting state is set at 1 kWh (10% of working power), 3 kWh (30% of working power), and 6 kWh (60% of working power). See Figs. (4-6) for a detailed representation of these cases.

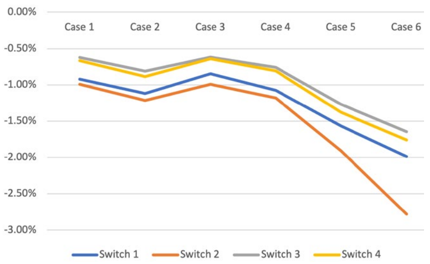

Fig. 4. Energy costs for power working 10 Kwh and power waiting 1 Kwh

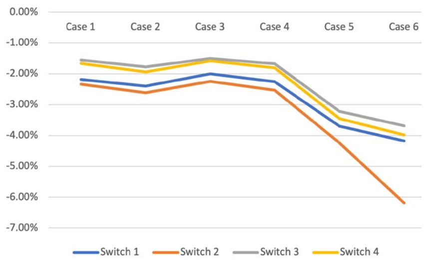

Fig. 5. Energy costs for power working 10 Kwh and power waiting 3 Kwh

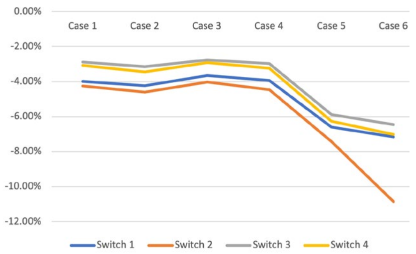

Fig. 6. Energy costs for power working 10 Kwh and power waiting 6 Kwh

From the figures, the following considerations can be drawn:

- The condition of case 6 leads to more reduction of the total energy cost. These conditions concern the fluctuations of inter-arrival, processing time and energy price. Then, the switch off policies work better when the conditions are very dynamic.
- The periodic control policy (switch 2) is the policy that allows the higher reduction of the energy cost.
- The results are very close between periodic and continuous policies when the workload control is introduced (switch 3 and 4).

Generally, the switch off policies can reduce the energy costs when the manufacturing conditions are dynamic and the energy of the waiting state is relevant. Across all six cases, the implementation of switch-off policies demonstrably reduced total waiting times and, consequently, energy consumption compared to the always-on benchmark. Notably, the magnitude of energy savings and the associated impact on manufacturing performance varied significantly depending on the specific scenario and policy adopted. Switches 1 and 2, employing a direct workload strategy, consistently yielded the most substantial reductions in waiting time and energy costs, as evidenced by the percentage differences in Tables 3-8. However, this energy efficiency often came at the expense of manufacturing performance, manifesting as increased average time in system and work-in-process, particularly in cases with higher demand variability (Cases 5 and 6). The introduction of indirect workload considerations (Switches 3 and 4) consistently improved the balance between energy savings and manufacturing performance across all cases. While achieving slightly less aggressive reductions in waiting times than Switches 1 and 2, Switches 3 and 4 notably mitigated the performance degradation. Specifically, Switch 3, utilizing a periodic review with indirect workload, emerged as a robust policy across varying conditions, often offering the best trade-off. This was particularly evident in Cases 2, 3, and 4, characterized by high energy price fluctuation or processing time variability, where Switch 3 maintained a closer throughput and average time in system to the always-on benchmark while still achieving significant energy reductions (Tables 4 and 6). In scenarios with inter-arrival time fluctuations (Cases 5 and 6), while all switch-off policies showed more pronounced performance impacts, Switch 3 and Switch 4 continued to provide a more stable and balanced performance compared to Switches 1 and 2 (Tables 7 and 8). Regarding the review approach, the choice between periodic and continuous review appeared less critical when incorporating indirect workload (Switches 3 and 4). The performance differences between Switch 3 (periodic) and Switch 4 (continuous) were consistently smaller compared to the differences between Switch 1 (periodic) and Switch 2 (continuous) across all cases. This suggests that the system-wide perspective offered by indirect workload diminishes the sensitivity to the review frequency, as the policy becomes more responsive to overall system state rather than just local, immediate queue changes. Conversely, for direct workload policies (Switches 1 and 2), periodic review (Switch 1) generally showed manufacturing performance measures closer to the always-on benchmark, indicating a potentially less disruptive intervention strategy in those contexts, although at the cost of reduced energy savings compared to continuous review (Switch 2). Relating these findings to the existing literature, our results validate and extend the work of Duflou et al. (2012) and Gutowski et al. (2006) by demonstrating the practical effectiveness of switch-off policies in reducing energy consumption in job-shop systems, particularly by targeting waiting states. Our findings build upon and refine the research of Renna and Materi (2021) by confirming the benefit of workload-aware switch-off policies and further highlighting the critical importance of considering *indirect* workload in complex job-shop environments. Moreover, this study significantly expands upon the work of Bokor et al. (2024) by not only integrating energy prices into switch-off decisions but also by empirically testing these policies in dynamic job-shop simulations across a comprehensive range of scenarios incorporating variability in demand, processing times, and energy costs – a level of dynamic evaluation not fully explored in prior research. In contrast to studies focusing on simpler flow-line systems (Renna, 2018; Frigerio and Matta, 2019), our work addresses the complexities inherent in job-shop environments, contributing to a more applicable body of knowledge for real-world manufacturing settings. While the simulation results are promising, it is essential to explicitly discuss the sustainability implications of the switch-off policies proposed in this study. One of the primary sustainability benefits of implementing switch-off policies is the reduction of energy consumption during idle periods. Since a substantial portion of energy consumption in manufacturing arises from non-productive machine states, these policies mitigate that waste. By reducing idle energy consumption, manufacturers can lower their carbon footprint, contributing to a more sustainable operation. A reduction in energy usage directly correlates with a decrease in greenhouse gas emissions, addressing the critical environmental concerns tied to industrial production processes. The integration of sustainability in manufacturing extends beyond environmental and economic dimensions; it also involves social equity. By adopting energy-efficient practices and enhancing operational sustainability, manufacturers can contribute to societal goals of reducing ecological impacts and promoting community health. Reducing energy consumption in manufacturing can lead to lower overall demand for energy supply, which in turn may diminish resource strain on local environments. This can foster community goodwill and a positive public image for companies, aligning with broader societal objectives around sustainability.

6. Conclusions and future development paths

This research introduces a multi-agent architecture designed to implement switch-off policies in manufacturing systems, taking into account variations in energy costs. The proposed switch-off policies are designed to optimize machine states based on current energy prices and machine workloads. Two primary policies are explored: Policy One: This policy considers the current energy price and the direct workload of the machine for local decision-making; Policy Two: This policy incorporates both the current energy price and the combined direct and indirect workloads, providing a comprehensive view of the entire manufacturing system. These policies are managed through two review approaches: periodic and continuous. This results in four distinct switch-off policies. Simulation models are utilized to evaluate these policies against a benchmark (always-on model) under varying dynamic conditions, including fluctuations in processing times, energy costs, and inter-arrival demand. In response to the first research question posed: what is the impact of these switch-off policies, combining workload and energy price, on job shop performance and energy reduction? The numerical results demonstrate that the switch-off policy combining energy costs with direct workload yields the greatest energy savings, although it may lead to worse manufacturing performance. In contrast, incorporating both direct and indirect workloads offers a better trade-off between manufacturing performance and energy savings. Regarding the review approach, periodic review proves to be more effective for policies based on direct workload, while the choice of review approach becomes less critical when both direct and indirect workloads are considered.

The second research question asks: which scenarios optimize the trade-off between manufacturing performance and energy savings? The numerical results highlighted that the increasing the fluctuations factors, the switch-off policies lead to better results, in particular when the demand fluctuations are introduced. The energy consumed in the standby state is crucial to evaluate the introduction of switch- off policies to obtain a relevant energy saving in manufacturing systems. The results of the proposed research, compared to the state of the art, highlight that incorporating energy pricing achieves a good balance between production performance and energy consumption reduction, particularly under variable demand conditions. Additionally, considering the combination of direct and indirect workloads makes the choice between periodic or continuous review policies less significant. This study contributes to the understanding of sustainability in manufacturing by demonstrating that effective switch-off policies can simultaneously optimize economic performance and environmental responsibility. From a managerial perspective, this research offers actionable insights for decision-makers seeking to implement sustainable manufacturing practices. The choice of switch-off policy should be contingent on the specific operational context and priorities. For environments where energy cost reduction is paramount, even at the cost of some performance degradation, direct workload policies (Switches 1 and 2) may be suitable. However, for scenarios prioritizing a balanced approach that minimizes performance disruption while achieving significant energy savings, policies incorporating indirect workload (Switches 3 and 4), and particularly the periodic review policy with indirect workload (Switch 3), are recommended. The figures illustrating energy costs under varying waiting power consumption levels (Figs. 4-6) further emphasize that the economic benefits of switch-off policies are more pronounced when the energy consumption in the waiting state is a significant proportion of the working state consumption, highlighting the importance of machine-specific energy profile analysis for policy implementation.

Future research should investigate the cost implications of performance degradation to better assess the overall benefits of switch-off policies. Another cost of the switch-off policies to study is the possible damage caused to the machines due to the continuous power on/off. Additionally, integrating local renewable energy sources with energy storage systems could significantly reduce reliance on the electric grid, and future studies could explore how switch-off policies can incorporate this factor.

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