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Modelling Flexible Manufacturing Systems with Power Constraints and Machine Switch on/off

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Abstract - This paper deals with Flexible Manufacturing System in the context of the future's industry. The problem under study is the Flexible Job-shop which models various production systems. This study aims at scheduling operations efficiently by considering a power limitation. To this purpose, each operation has a power profile depending on the machine it is assigned to. Furthermore, in industry, machines are often left idle. This practice could lead to loss in the available power for the manufacturing system, especially when a machine requires a lot of power when it is not processing any operation. Hence, it is proposed to address the benefits of switch *on/off* in the Flexible Job-shop problem with power limitations. A mathematical formulation for this problem is presented in this paper. The results are promising and show that it is possible to schedule efficiently operations with power requirements in a production system.

Keywords - Flexible Job-shop; Power Limitation; Energy Efficiency; Machine Switch *on/off*.

I. Introduction

It is known that the industrial sector worldwide is responsible for consuming more than 50% of the global delivered energy per year [1]. Furthermore, these energy resources represent important expenses for companies hence, better practices should be applied to reduce their consumption. However, these problems are still unsolved, partly because of the gap between research and industrial needs [2]. To provide solutions to these problems, two decisions are possible: technological and/or organisational [3]. Technological measures could lead to strong reductions but are really expensive since they concentrate on new machines or production processes, whereas organisational measures are dedicated to the current system. These organisational measures include scheduling methods which can drastically improve the energy-efficiency of the production system. In the literature, the studies on scheduling with energy-saving objectives mainly concern total energy consumption [4][5][6]. However, another way to reduce costs related to power billings in production systems is to manage the production without exceeding a contracted power load (threshold) [7]. In this last paper, the authors explore a method to schedule efficiently tasks in a steel plant according to a given energy load profile. In this approach, the electrical consumption of the plant is sent to the electricity provider after what the given load profile is accepted or a new one is proposed to the plant owner. The load profile is then sequentially modified until a

definitive one is accepted by both stakeholders. Once a load profile is chosen, penalties are applied for every over- or under-consumption. Respecting this contracted power load has a direct impact in power generation for suppliers as stressed in [8]. Such approaches can be seen as Demand-side Management [9], which consists to manage the load and consumption patterns of end users in order to reduce the production of energy on suppliers' side. With such an approach it is possible for a company to reduce the extra expenses related to the excess of instant power by strictly respecting its contract with the supplier. To this purpose, it is proposed to address the impact of power consumption (PC) on schedules in the context of a Flexible Job-shop manufacturing environment. In this paper, a general model of a Flexible Job-shop scheduling problem (FJSP) is given; its objective is the minimisation of total completion time (makespan) by taking into account the power consumption of operations and a power threshold. Furthermore, machines can be switched *on/off* to assess the performance of a production system including this kind of rules.

The remaining of this paper is as follows: in the next section a brief review of papers related to the field of energy efficient manufacturing is presented. In section 3, the problem and its mathematical model are presented, followed in section 4 by the results on generated instances. Finally, the last section is devoted to the conclusion and research directions.

II. Background and motivations

A lot of industrial problems consisting in minimising the makespan, total tardiness, and other time-oriented objective functions can be found in the literature. Only a few works deal with energy optimisation as an important objective in scheduling of production systems. However, researches concerning "Green Manufacturing" issues are increasing since 2011 [2]. A non-exhaustive review on the reduction of energy and/or power consumption in manufacturing systems through manufacturing scheduling is presented below.

In [10], an optimisation approach for a single machine where the objective is to minimise its energy consumption is explored by the authors. A mathematical formulation in order to minimise both the makespan and the total energy consumption (TEC) is proposed. The model takes into account different states of a given machine: idle, running, *on/off*. In [11], Time Of Use (TOU) pricings are taken into account with consideration of transitions between machine states in a manufacturing system involving one single machine. The authors developed a genetic

algorithm that could be used in extension of a Manufacturing Resource Planning System.

The authors of [12] proposed a mathematical model consisting in minimising the makespan, the carbon footprint and the peak power load in a Flow-shop (FS) with machines having variable speeds. In [13] an approach consisting in minimising power consumption peaks (PC) in a Flexible Flow-shop (FFS) is proposed. This approach uses an Energy Aware Scheduling (EAS) module to adapt a given schedule obtained with an Advanced Planning and Scheduling system. The EAS does not modify the schedule, but optimises it from the energy consumption viewpoint by definition of new starting dates for the operations. The authors of [14] used a Genetic Algorithm (GA) combined with a Simulated Annealing in order to provide solutions to a bi-objective FS problem. Their objectives are the minimisation of the makespan and the TEC. In [15], a time indexed mathematical formulation is proposed in order to minimise the energy expenses under a TOU pricing and the carbon footprint in an eight level FS. An Ant Colony Optimisation algorithm to solve a bi-objective Hybrid FS problem including TOU rates where the objective is to optimise the makespan and the cost of the energy is given in [16].

A Job-Shop Problem (JSP) with machines able to process operations with different speeds and energy consumptions is studied in [6]. The authors study the correlation between makespan, energy and robustness of such a production system. According to them, an energy-efficient schedule is more robust and less sensitive to machine breakdowns. Authors of [4] handled minimisation of both the total tardiness and the TEC in a JSP by reducing the non-processing times of machines. A Non-dominated Sorting Genetic Algorithm is used to obtain a set of solutions to the problem. A Flexible Job-shop where the TEC should be minimised is studied in [17]. Their work is motivated by the heterogeneity of machines in flexible manufacturing systems, which could lead to strong improvements in energy efficiency. In [5] a JSP with different states of machines is considered. Several Key Performance Indicators (KPI) for energy-oriented manufacturing are proposed. A multi-objective GA optimises three of these KPI: makespan, TEC, and WEC (Worthless Energy Consumption). Different machine behaviour policies are explored to find the most promising way to improve the criteria.

Actually, few works are dealing with power threshold as an important constraint in scheduling and most of researches try to optimise the TEC or TOU. The objective of the present paper is to propose operational methods to provide schedules respecting a power threshold constraint while considering operations with specific power profiles. In order to address this problem, an improved mathematical model based on [18] is introduced. This model takes into account a power threshold and operations with peak power requirements. It is completely formalised in the following section.

III. Problem definition and mathematical formulation

The purpose of this study is to provide an effective schedule to a Flexible Job-shop problem considering power limitations.

The FJSP problem has been first introduced in [19]. It is formally formulated as follows: a set J of r jobs, $J = \{J_1, \dots, J_r\}$,

must be scheduled on a set M of v machines, $M = \{m_1, \dots, m_v\}$. Each job $\{J_i\}_{i \in [1,r]}$ consists in a number of n_i operations. Hence, n operations must be scheduled with $n = \sum_{i=1}^r n_i$. Each operation is noted $\{O_i\}_{i \in [1,n]}$. An operation O_i is allowed to be executed in any machine of a given set $M_i \subseteq M$. The processing time of an operation O_i on a machine $m \in M_i$ is noted $P_{i,m}$. Furthermore, each operation can be assigned to only one machine at a time. Note that several operations of a same job can be assigned to the same machine. Considering that there is an assignment and a schedule for all the operations, the starting date of an operation O_i is noted s_i . The objective is to minimise the total completion time of all the operations, also called makespan and noted c_{max} . Several assumptions are made for the classical problem, including availability of all machines, no preemption, and release dates of all jobs at time 0.

To better understand the following mathematical formulation, the FJSP can be modelled with a conjunctive-disjunctive graph G as stressed in [20], while power limitations in scheduling problems may be modelled as flows in the graph [18]. An example of an evaluated graph G for the classical Flexible Job-shop problem with operations already assigned to machines is given in Fig. 1.

For ease of understanding, in Fig. 1, operations are already assigned to machines. The objective of this research work is to schedule operations considering their power requirements. Since machines are heterogeneous, the power profile may vary according to the selected machine for processing an operation. In this paper, this power profile is varying along the manufacturing process: (i) at first, a peak power consumption is considered, followed by (ii) a nominal power consumption. Thus, an operation can be viewed as the succession of sub-operations corresponding to each specific power requirement during the production process [21]. The distinction between these two different power consumptions is made by splitting operations into sub-operations. Each operation O_i consists in two sub-operations $O_{i,1}$ and $O_{i,2}$ with durations $P_{i,1,m}$ and $P_{i,2,m}$ and consumptions $W_{i,1,m}$ and $W_{i,2,m}$ respectively. An example of splitting an operation (O_1 from Fig. 1) into two sub-operations, and the power profile related to the machine assignment is given in Fig. 2.

In Fig. 2, power profiles are in exponent of the operations as follows: $O_{i,k}^{W_{i,k,m}}$. Also, it can be seen that the power profile and processing time of the operation O_1 are not the same whether it is assigned to machine M_1 or machine M_2 . Furthermore, since operations must be executed without pre-emption, no-wait arcs are added between sub-operations to ensure these sub-operations to be executed without delay (the negative arcs).

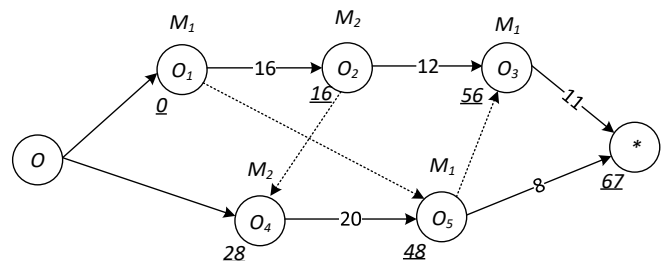


Fig. 1. An evaluated graph for the classical FJSP.

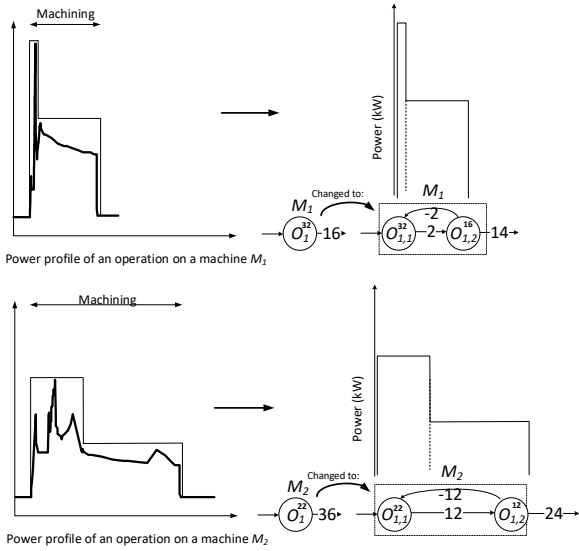


Fig. 2. Example of power profiles depending on the machine assigned to an operation.

For instance, in the top right of Fig. 2, if the starting date of operation $O_{1,1}^{22}$ is set to 0, then $O_{1,2}^{16}$ may start after 2 time units. However because of the negative arc, if $O_{1,2}^{16}$ starts later, let say at 20, then $O_{1,1}^{22}$ will have to start at 18.

Another assumption of the study is the possibility to switch *on/off* (or *off/on*) machines to allow operations to be scheduled earlier by benefitting from the power unused when the machine is shut down. These switch *on/off* operations depend on the order of operations on a machine. As it is not possible to know ahead of the optimisation process the assignment of the operations, and hence, if it is possible to switch *off/on* a machine between two consecutive operations, two additional sub-operations modelling switch *on/off* are added to the already split operation as shown in Fig. 3.

In Fig. 3(B), $O_{1,1}^{32}$ becomes $O_{1,2}^{32}$. The new $O_{1,1}^{16}$ is an operation modelling a possible switch *on*, and the operation $O_{1,4}^4$ models a switch *off*. The switch *on/off* operations require also power in order to be executed. After a machine is turned *on*, it will consume continually the power required to keep it active. For instance, suppose that machine M_1 needs 14 power units at the moment when it is turned *on*, only 2 power units will be returned to the system after $O_{1,1}^{16}$ is ended since the switch *on* procedure requires 16 power units. If the operation $O_{1,4}^4$ is executed it will require 4 power units. However, it will return 18 power units to the system (4 units plus 14 for the power used to keep the machine idle). With these assumptions, it is possible to generate a new graph G' of a problem as in Fig. 4, where the allowed power threshold is fixed at 46. In G' it will be impossible, considering the given assignment, to schedule operations $O_{1,2}^{32}$ and $O_{4,2}^{22}$ at the same moment, as they need 54 power units to be processed which is higher than the power threshold. As can be seen, operations $(O_{1,1}, O_{1,4}) \dots (O_{5,1}, O_{5,4})$ corresponding to switch *on/off* do not have power requirements nor durations. This is because it is not known yet if these operations (*on/off*) are executed or not, even though the machining operations are assigned to a machine. Finally, a solution is obtained by managing the power requirements with flows in the graph.

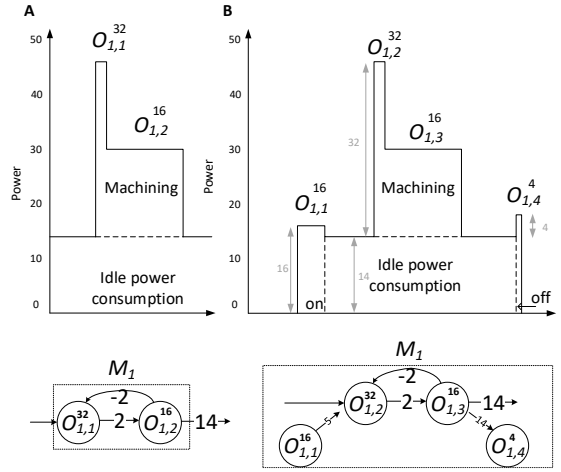


Fig. 3. Example of new added sub-operations for switch *on/off* policies ($O_{1,1}$ and $O_{1,4}$).

It is expected that operations can be scheduled earlier by using the power required to keep machines *on* while they are not in a machining phase. By switching a machine *off* during an idle phase between two operations, more power will be available for processing the other operations. The objective is then to schedule all operations considering a power threshold. This power threshold is a constraint given by the power supplier and it cannot be changed. Hence, when new orders arrive, the enterprise must schedule its production according to the contracted power load. The mathematical formulation of this problem is given as follows, starting with parameters:

Parameters

- V : set of operations;
- i, j : indices for operations;
- J_i : job of operation i ;
- N_i : set of sub-operations for operation i ;
- M_i : set of available machine for operation i ;
- m : possible machine for an operation;
- $P_{i,k,m}$: duration of sub-operation k on machine m ;
- W_{max} : maximum available power (Power Threshold) ;
- $W_{i,k,m}$: power requirement of sub-operation k on machine m ;
- W_m^b : power requirement during idle phases of machine m ;
- H : a large positive number;

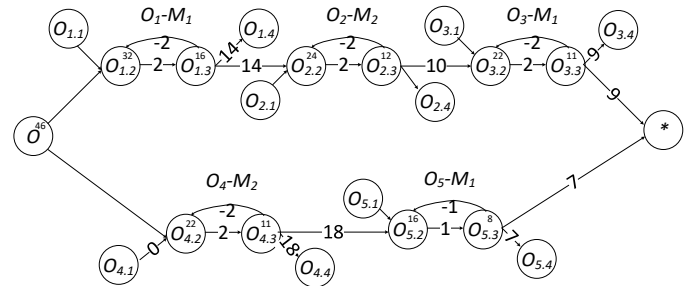


Fig. 4. An example of a non-evaluated graph representing a problem with power profiles for operations and switch *on/off* operations (Former graph in Fig. 1).

Variables

- c_{max} : makespan of the schedule;
- $s_{i,k}$: starting date of sub-operation k of operation i ;
- $p_{i,k}$: processing time of sub-operation k of operation i ;
- $w_{i,k}$: power requirements of sub-operation k of operation i ;
- $w_{i,k}^b$: basis power 'lost', or returned to the system after a switch *on/off*;
- $\varphi_{i,k,j,l}$: number of power units transferred from sub-operation k of operation i to sub-operation l of operation j ($\varphi_{0,0,j,l}$ is for the power units sent from the source node);
- $y_{i,m}$: binary variable equal to 1 if machine m is assigned to operation i , 0 otherwise;
- $x_{i,j,m}$: binary variable equal to 1 if operation i is scheduled before operation j on machine m , 0 otherwise;
- $z_{i,k,j,l}$: binary variable equal to 1 if there is a flow from sub-operation k of operation i to sub-operation l of operation j , 0 otherwise;
- $l_{i,j,m}$: binary variable equal to 1 if there is a switch *off/on* between the end of operation i and the start of operation j , 0 otherwise;

Mathematical Formulation

$$\text{Min } c_{max} \quad (1)$$

Subject to:

Flexible job-shop related constraints:

$$c_{max} - s_{i,|N_i|-1} - p_{i,|N_i|-1} \geq 0, \forall i \in V \quad (2)$$

$$\sum_{m \in M_i} y_{i,m} = 1, \forall i \in V \quad (3)$$

$$p_{i,k} - \sum_{m \in M_i} y_{i,m} p_{i,k,m} = 0, \forall i \in V, \forall k \in \{2,3\} \quad (4)$$

$$2x_{i,j,m} + 2x_{j,i,m} - y_{i,m} - y_{j,m} \leq 0, \forall (i,j) \in V, \forall (i,j) \in V, \forall m \in M_i \cap M_j, J_i \neq J_j \vee i < j \quad (5)$$

$$\sum_{v \in M_i, v \neq m} x_{0,i,v} + y_{i,m} \leq 1, \forall i \in V, \forall m \in M_i \quad (6)$$

$$\sum_{j \in V^*, J_j \neq J_i \vee i < j} \sum_{m \in M_i \cap M_j} x_{i,j,m} = 1, \forall i \in V \quad (7)$$

$$\sum_{i \in V^0, J_j \neq J_i \vee i < j} \sum_{m \in M_i \cap M_j} x_{i,j,m} = 1, \forall j \in V \quad (7)$$

$$\sum_{i \in V, m \in M_i} x_{0,i,m} \leq 1, \forall m \in M \quad (8)$$

$$s_{j,2} - s_{i,|N_i|-1} - p_{i,|N_i|-1} \geq 0, \forall (i,j) \in V, J_i = J_j, i < j \quad (9)$$

$$s_{i,l} - s_{i,k} - p_{i,k} = 0, \forall i \in V, \forall (k,l) \in N_i \setminus \{1, |N_i|\}, k < l \quad (10)$$

$$s_{i,k} - s_{i,l} - p_{i,l} \geq 0, \forall i \in V, \forall (k,l) \in N_i, k > l \quad (11)$$

$$s_{j,1} - s_{i,|N_i|} - p_{i,|N_i|} + H(1 - x_{i,j,m}) \geq 0, \forall (i,j) \in V, J_i \neq J_j \vee i < j, \forall m \in M_i \cap M_j \quad (12)$$

Power related constraints:

$$w_{i,k} - \sum_{m \in M_i} y_{i,m} w_{i,k,m} = 0, \forall i \in V, \forall k \in N_i \setminus \{1, |N_i|\} \quad (13)$$

$$\sum_{j \in V, k \in N_j} \varphi_{0,0,j,k} \leq W_{max} \quad (14)$$

$$\varphi_{0,0,j,l} + \sum_{i \in V} \sum_{k \in N_i} \varphi_{i,k,j,l} - w_{j,l} = 0, \forall j \in V, \forall l \in N_j \quad (15)$$

$$\sum_{j \in V} \sum_{l \in N_j} \varphi_{i,k,j,l} - w_{i,k} \leq 0, \forall i \in V, \forall k \in N_i \setminus \{1, |N_i|\} \quad (15)$$

$$\sum_{j \in V} \sum_{l \in N_j} \varphi_{i,1,j,l} - w_{i,1} + w_{i,1}^b \leq 0, \forall i \in V \quad (16)$$

$$\sum_{j \in V} \sum_{l \in N_j} \varphi_{i,|N_i|,j,l} - w_{i,|N_i|} - w_{i,|N_i|}^b \leq 0, \forall i \in V \quad (16)$$

$$\varphi_{i,k,j,l} \leq H \cdot z_{i,k,j,l}, \forall (i,j) \in V, \forall k \in N_i, \forall l \in N_j \quad (17)$$

$$z_{i,k,j,l} \leq \varphi_{i,k,j,l}, \forall (i,j) \in V, \forall k \in N_i, \forall l \in N_j \quad (18)$$

$$s_{j,l} - s_{i,k} - H \cdot z_{i,k,j,l} - p_{i,k} \geq -H, \forall (i,j) \in V, \forall k \in N_i, \forall l \in N_j \quad (19)$$

$$z_{i,k,j,l} = 0, \forall (i,j) \in V, \forall k \in N_i, \forall l \in N_j, J_i = J_j \wedge (j < i \vee l < k) \quad (20)$$

$$l_{i,j,m} - x_{i,j,m} \leq 0, \forall i \in V^0, \forall j \in V^*, \forall m \in M_i \cap M_j \quad (21)$$

$$x_{i,j,m} - l_{i,j,m} \leq 0, \forall (i,j) \in (0, V) \vee \forall (i,j) \in (V, *), \forall m \in M_i \cap M_j \quad (22)$$

$$p_{j,1} - \sum_{i \in V^0 \vee \sum_{m \in M_i \cap M_j} l_{i,j,m} p_{j,1,m} = 0, \forall j \in V \quad (23)$$

$$p_{i,|N_i|} - \sum_{j \in V^* \setminus i} \sum_{m \in M_i \cap M_j} l_{i,j,m} p_{i,|N_i|,m} = 0, \forall i \in V \quad (23)$$

$$w_{j,1} - \sum_{i \in V^0 \vee \sum_{m \in M_i \cap M_j} l_{i,j,m} w_{j,1,m} = 0, \forall j \in V \quad (24)$$

$$w_{i,|N_i|} - \sum_{j \in V^* \setminus i} \sum_{m \in M_i \cap M_j} l_{i,j,m} w_{i,|N_i|,m} = 0, \forall i \in V \quad (24)$$

$$w_{i,k}^b - \sum_{j \in V^* \setminus i} \sum_{m \in M_i \cap M_j} l_{i,j,m} w_{i,k}^b = 0, \forall i \in V^0, \forall k \in N_i, k = \{1, |N_i|\} \quad (25)$$

The first line (eq. 1) refers to the objective of the problem: minimising the completion time of all operations (the makespan). Constraints (2) give the expression of this makespan. Only the ending dates of processing jobs (i.e.: operations $o_{i,|N_i|-1}$) are considered and not switch *offs* (sub-operations $o_{i,|N_i|}$). Because of constraints (3), each operation must be assigned to one and only one machine. Constraints (4) set the duration of processing sub-operations once a machine is selected. Constraints (5-8) are adapted from the FJSP to have only one output/input arc for each set of sub-operations related to each processing operations. Constraints (5) define precedence constraints of operations, if they are occurring on the same machine. If one of the operation is not assigned to a machine, necessarily, $x_{i,j,m}$ and $x_{j,i,m}$ are valued 0. If both operation are assigned to the same machine ($y_{i,m} = y_{j,m} = 1$), hence, $x_{i,j,m}$ or $x_{j,i,m}$ may be equal to 1. Constraints (6) ensure that, if a machine is assigned to an operation then necessarily the ingoing arcs from the source node 0 to the operation, or the outgoing arcs from the operation to the sink node * and relevant to other machines are set to 0. Constraints (7) ensure that, for all processing operations, only one arc exists between two operations assigned to the same machine, which means that only one arc is entering an operation block (i.e.: all sub-operations of an operation), and only one arc is leaving such a block. Operations 0 can have several outgoing arcs, and no entering arcs; operation * may have several entering arcs but no leaving arcs. Constraints (8) ensure that, there is only one arc per machine going from the source node to all operations. If a machine processes no operation then there is no arcs relevant to this machine at all. Constraints (9-12) are adapted from the FJSP to consider sub-operations. Constraints (9) update starting dates of operations in order to respect the processing order of operations of a job. Constraints (10) ensure no preemption of sub-operations corresponding to a manufacturing process. Constraints (11) stipulate that process order of sub-operations of an operation i must remain the same, which also means that eventual switch *on* (respectively: *off*) are always done before (after) the beginning (end) of a manufacturing process on a machine. Constraints (12) adjust the

starting dates of operations that belong to different jobs but need the same machine operations.

All following constraints (13-25) are specific to the problem under study. Constraints (13) define the power actually needed to process sub-operations of operation i on machine m . The cases $k=1$ or $k=|N_i|$, relevant to switch *on/off* are handled separately in constraints 24. Constraint (14) avoid to exceed the power threshold when processing the operations as it cannot be allocated more energy to the operations than W_{max} . Constraints (15) ensure that the sum of energy flowing from all sub-operations and initial energy node (W_{max} kept in operation 0) is equal to the energy needed to process the l^{th} sub-operation of operation j . Constraints (16) are divided into three different sets. The first one ensures that the sum of energy flowing from the considered sub-operation k to the other ones never exceeds the energy that was used for its processing. Here, all sub operations are considered however, operations $O_{i,l}$ are returning to the system less than what they consume because after a switch *on*, a machine stays idle and needs power anytime (second set); meanwhile, operations $O_{i,4}$ are returning to the system more than what they consume (third set). Constraints (17) ensure that if there is a power flow from the k^{th} part of operation i to the l^{th} part of operation j , then $z_{i,k,j,l}=1$. If $z_{i,k,j,l}=0$, then no flow is possible from the k^{th} part of operation i to the l^{th} part of operation j . Constraints (18) stipulate that if there is no need of a flow from $O_{i,k}$ to $O_{j,l}$ ($\phi_{i,k,j,l}=0$), then necessarily $z_{i,k,j,l}=0$. If $z_{i,k,j,l}=1$ then at least one unit of power goes from $O_{i,k}$ to $O_{j,l}$. Constraints (19) specify that no reverse flow is possible from the l^{th} sub-operation of operation j to the k^{th} sub-operation of operation i , if i and j belong to the same job and the l^{th} sub-operation of operation j is processed after the k^{th} sub-operation of operation i . Constraints (20) adjust the starting dates of sub-operations which need to wait because of a power flow. Constraints (21) detect if a switch *off/on* is possible. Furthermore, if i and j are not in disjunction, then necessarily, no switch *on/off* is possible between these operations. Constraint (22) detect if an operation is the first scheduled on the machine. If so, the machine must be started before processing the operation j . Constraints (23-24) set the processing times and power requirements of the switch *off/on* operations. If $l_{i,j,m}$ is null for any m , hence p and w of these operations are necessarily equal to 0, thus no power flows go *in* or *out* of these operations and they are not deteriorating the makespan either since the processing time is null. Finally, constraints (25) set the basis consumption of machines. This variable is then used in constraints (16) to model the constant consumption of machines if they are switched *on*. Hence, if no switch *off* occur, the $w_{i,k}^b$ variable is like a sink node, and the absorbed power cannot be allocated to other operations unless a switch *off* occur.

All these constraints applied together allow to find schedules with switch *on/off* policies in order to reduce the power consumption of a manufacturing system. Results obtained with this mathematical formulation are given in the next section.

IV. Results and discussion

Results have been computed using CPLEX 12.4 on a set of 10 generated instances. These instances have been generated randomly by considering jobs varying from 2 to 8, number of operations per job between 2 and 6, machines varying from 3 to

5. One or two machines are available to process an operation. Each instance is tested with three different power thresholds. As the impact of switch *on/off* policies is the main purpose of this work, these instances are also tested with and without switch *on/off* policies, which brings to 60 the number of tests performed. For each test, the solver is left running for 5400 seconds. Results are provided in Table I. In this table, **Ins.** refers to the instance tested. **n** is for the number of machining operations in the instance. **W_{max}** is for the different power thresholds tested. **SUP** and **INF** refer to the upper and lower bounds. Solutions with an asterisk(*) are proven optima. **CPU** is the time requested to prove the optimality, whereas **CPU*** is the approximate time for reaching the best found solution. Dashes represent computation times exceeding the 5400s limit, or unavailable solutions.

As can be seen in Table I, switch *on/off* policies have an impact on the quality of solutions. In all instances proven optima, the solutions obtained with consideration of the switch *on/off* policy are always equal or better than the results without considering extinctions of machines (see for example instance Inst_3). This is the expected behaviour however, because the possibility to switch *on/off* machines results in additional binary variables in the mathematical program, computation times are longer in average. Note please that some instances really show the importance of such approaches. For example Inst_4 with a 143 power threshold and switch *on/off* has a makespan potentially better than 251 (the upper bound) whereas the same instance without the switch *on/off* will not reach a solution with a makespan better than 284 (the lower bound).

TABLE I. Results of switch *on/off* policies in a FMS with power considerations

Ins.	n	W _{max}	Without <i>on-off</i>				With <i>on-off</i>			
			SUP	INF	CPU	CPU*	SUP	INF	CPU	CPU*
Inst_1	7	50	49*	49	4	4	49*	49	7	7
		40	52*	52	4	4	52*	52	4	4
		30	83*	83	750	8	83*	83	2666	145
Inst_2	9	54	40*	40	13	13	40*	40	1490	20
		44	41*	41	20	20	41*	41	13	13
		34	77	61	-	150	-	38	-	-
Inst_3	10	77	160*	160	5	5	160*	160	13	13
		67	168*	168	5	5	168*	168	15	15
		57	218*	218	20	20	215*	215	490	60
Inst_4	12	163	270	233	-	80	229	209	-	60
		153	319	221	-	385	230	224	-	1265
		143	313	284	-	2875	251	216	-	3730
Inst_5	12	51	51*	51	15	15	51*	51	20	20
		41	51*	51	21	21	51*	51	30	30
		31	62	61	-	100	62	54	-	375
Inst_6	14	136	224*	224	40	40	221*	221	930	50
		126	240*	240	80	80	237	222	-	4900
		116	248*	248	115	115	249	224	-	630
Inst_7	14	141	233*	233	1740	1640	260	209	-	75
		131	268	241	-	2000	298	212	-	950
		121	-	220	-	-	312	206	-	4400
Inst_8	15	162	286*	286	-	100	285*	285	-	340
		152	316*	316	300	100	296*	296	-	375
		142	341*	341	2000	820	305	300	-	1750
Inst_9	17	146	293	249	-	2825	284	245	-	3450
		136	399	246	-	5250	358	245	-	3500
		126	470	245	-	4750	-	245	-	-
Inst_10	26	59	-	42	-	-	-	43	-	-
		49	-	42	-	-	-	42	-	-
		39	-	42	-	-	-	41	-	-

Also, it has been observed in some cases that the switch *on/off* policies allows to obtain schedules with lower power thresholds, whereas no solutions could be found without the switch *on/off* policies. Furthermore, it appears from these first generated instances that switch *on/off* are very useful for situations where the idle power requirements of machine are high, which is the case of steel and plastic industries for instance. However, this might not be always profitable because of machines that may suffer from lot of switch *on/off* [2]. A constraint to limit the number of switch *on/off* can easily be added to the previous model for such cases.

V. Conclusion

In this study the problem of the Flexible Job-shop with a power limitation and machines with switch *on/off* policies is addressed. Operations have a variable power profile and they must be scheduled without exceeding the power threshold. In this problem, machines can be switched *on* or *off* to benefit from the power loss when they are idle.

Test instances have been generated, where power profiles of operations are limited to two different power consumptions. Exact solutions for these small scale instances can be obtained, but the model is quickly unable to return results for instances with more operations or low power thresholds. In the future, large scale instances based on the instances from the Flexible Job-shop literature will be addressed. These instances may consider wider range of power profiles for operations to better model real world machining processes, and a variable power threshold could be considered. The use of CP optimizer is also a perspective as it is supposed to be better for scheduling problems [22]. Furthermore, it could be interesting to add financial objectives in order to consider penalties for exceeding the power threshold, which could better represent real case situations.

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References

[1] Z. Zhang, R. Tang, T. Peng, L. Tao, and S. Jia, 'A method for minimizing the energy consumption of machining system: integration of process planning and scheduling', *J. Clean. Prod.*, vol. 137, pp. 1647–1662, Nov. 2016.

[2] A. Giret, D. Trentesaux, and V. Prabhu, 'Sustainability in manufacturing operations scheduling: A state of the art review', *J. Manuf. Syst.*, vol. 37, pp. 126–140, Oct. 2015.

[3] J. R. Duflou et al., 'Towards energy and resource efficient manufacturing: A processes and systems approach', *CIRP Ann. - Manuf. Technol.*, vol. 61, no. 2, pp. 587–609, Jan. 2012.

[4] Y. Liu, H. Dong, N. Lohse, S. Petrovic, and N. Gindy, 'An investigation into minimising total energy consumption and total weighted tardiness in job shops', *J. Clean. Prod.*, vol. 65, pp. 87–96, Feb. 2014.

[5] G. May, B. Stahl, M. Taisch, and V. Prabhu, 'Multi-objective genetic algorithm for energy-efficient job shop scheduling', *Int. J. Prod. Res.*, vol. 53, no. 23, pp. 7071–7089, Dec. 2015.

[6] M. A. Salido, J. Escamilla, A. Giret, and F. Barber, 'A genetic algorithm for energy-efficiency in job-shop

scheduling', *Int. J. Adv. Manuf. Technol.*, vol. 85, no. 5–8, pp. 1303–1314, Jul. 2016.

[7] K. Nolde and M. Morari, 'Electrical load tracking scheduling of a steel plant', *Comput. Chem. Eng.*, vol. 34, no. 11, pp. 1899–1903, Nov. 2010.

[8] L. Merkert, I. Harjunkoski, A. Isaksson, S. Säynevirta, A. Saarela, and G. Sand, 'Scheduling and energy – Industrial challenges and opportunities', *Comput. Chem. Eng.*, vol. 72, pp. 183–198, Jan. 2015.

[9] A. Gupta and S. Venkataraman, 'Reducing Price Volatility of Electricity Consumption for a Firm's Energy Risk Management', *Electr. J.*, vol. 26, no. 3, pp. 89–105, Apr. 2013.

[10] G. Mouzon, M. B. Yildirim, and J. Twomey, 'Operational methods for minimization of energy consumption of manufacturing equipment', *Int. J. Prod. Res.*, vol. 45, no. 18–19, pp. 4247–4271, Sep. 2007.

[11] F. Shrouf, J. Ordieres-Meré, A. García-Sánchez, and M. Ortega-Mier, 'Optimizing the production scheduling of a single machine to minimize total energy consumption costs', *J. Clean. Prod.*, vol. 67, pp. 197–207, Mar. 2014.

[12] K. Fang, N. Uhan, F. Zhao, and J. W. Sutherland, 'A new approach to scheduling in manufacturing for power consumption and carbon footprint reduction', *J. Manuf. Syst.*, vol. 30, no. 4, pp. 234–240, Oct. 2011.

[13] A. G. Bruzzone, D. Anghinolfi, M. Paolucci, and F. Tonelli, 'Energy-aware scheduling for improving manufacturing process sustainability: A mathematical model for flexible flow shops', *CIRP Ann. - Manuf. Technol.*, vol. 61, no. 1, pp. 459–462, 2012.

[14] M. Dai, D. Tang, A. Giret, M. A. Salido, and W. D. Li, 'Energy-efficient scheduling for a flexible flow shop using an improved genetic-simulated annealing algorithm', *Robot. Comput.-Integr. Manuf.*, vol. 29, no. 5, pp. 418–429, Oct. 2013.

[15] Y. Zhang, G. H. Huang, and L. He, 'A multi-echelon supply chain model for municipal solid waste management system', *Waste Manag.*, vol. 34, no. 2, pp. 553–561, Feb. 2014.

[16] H. Luo, B. Du, G. Q. Huang, H. Chen, and X. Li, 'Hybrid flow shop scheduling considering machine electricity consumption cost', *Int. J. Prod. Econ.*, vol. 146, no. 2, pp. 423–439, Dec. 2013.

[17] Y. He, Y. Li, T. Wu, and J. W. Sutherland, 'An energy-responsive optimization method for machine tool selection and operation sequence in flexible machining job shops', *J. Clean. Prod.*, vol. 87, pp. 245–254, Jan. 2015.

[18] S. Kemmoe, D. Lamy, and N. Tchernev, 'A job-shop with an energy threshold issue considering operations with consumption peaks', *IFAC-Pap.*, vol. 48, no. 3, pp. 788–793, 2015.

[19] P. Brucker and R. Schlie, 'Job-shop scheduling with multi-purpose machines', *Computing*, vol. 45, no. 4, pp. 369–375, 1990.

[20] S. Dauzère-Pères and J. Paulli, 'An integrated approach for modeling and solving the general multiprocessor job-shop scheduling problem using tabu search', *Ann. Oper. Res.*, vol. 70, pp. 281–306, 1997.

[21] N. Weinert, S. Chiotellis, and G. Seliger, 'Methodology for planning and operating energy-efficient production systems', *CIRP Ann. - Manuf. Technol.*, vol. 60, no. 1, pp. 41–44, 2011.

[22] M. A. Salido, J. Escamilla, F. Barber, A. Giret, D. Tang, and M. Dai, 'Energy efficiency, robustness, and makespan optimality in job-shop scheduling problems', *Artif. Intell. Eng. Des. Anal. Manuf.*, vol. 30, no. 03, pp. 300–312, Aug. 2016.